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REVIEW ARTICLE

REVIEW OF IDENTIFIED SHORTCOMINGS IN AQUIFER VULNERABILITY ASSESSMENTS

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ABSTRACT

Several studies have successfully carried out aquifer vulnerability evaluations using a combination of geophysical and biogeochemical methods. Unfortunately, some identified shortcomings have often led to inaccurate assessments. This review attempts to identify some of these drawbacks and suggest better ways to improve upon analysis and interpretation of results. Articles reviewed were sourced publicly and subjected to systematic analysis based on fundamental principles. The outcomes of each analysis were discussed, among which was a study that applied Ohmega Resistivity meter to acquire Self-Potential (SP) data without specifying the nature of electrode used. The result indicated large SP readings ≥200mV attributed to high fluid flow. According to analysis, when copper stakes are used, spurious SP readings occur in contrast to lower SP values of roughly 10 mV when suitable non-polarizable electrodes of Cu/$CuSO_4$ porous pots are utilized to collect SP data. The review made clear the importance of providing detailed explanation of the nature of materials used. Another study solely collected samples for groundwater quality assessments during dry season, ignoring the effects of seasonal variation on water parameters. This must have had an impact on the results of the investigations. Research examined the aquifer problems in Gosa area of Abuja, utilizing only the Vertical Electrical Sounding (VES) technique. The study suggested basaltic intrusion as probable cause of borehole failures in the area. A different research which incorporated VES and data from the hill-shaded Shuttle Radar Topography Mission (SRTM), suggested insufficient interconnectivity within the fractures as conditions controlling groundwater occurrence in the area. The study illustrated the need for integrating geophysical methods for effective target detection. To map the infiltration of leachate into the subsurface, a study applied only the VES technique. Studies, however, showed that the VES method only provided average resistivity readings, suppressing some features. The study suggested the combination of VES and 2-D imaging for more accurate results. Another study obtained data via the ADMT Groundwater Detector. At the interpretation stage, the author interpreted ADMT data as VES, which was perceived as inaccurate as their principles and methodologies are different. Another study was noted to have presented results without categorizing the Aquifer Protective Capacity (APC) rating in percentages (%). It was assessed that a framework that accurately categorized the APC of each transversal using common statistics guidelines would have made it simpler to understand and aided decision-making. Future research is advised to take some of the noted flaws into account in order to enhance data processing and interpretation.

KEYWORDS

Groundwater vulnerability assessment, aquifer, water contamination, geophysical and biogeochemical methods, data collection, data processing and presentation

1. INTRODUCTION

Availability of basic water needs is a necessary foundation for economic development and progress (Sharma, 2023; Vinciguerra, 2023; JD and Alan, 2023; Bacha et al., 2023). However, industrial growth and an unchecked rise in rural-urban migration have led to increasing rate of production of various wastes, from industrial to municipal. This has negative impact on human health through groundwater contamination (Wang et al., 2023; Roy et al., 2023; Lozano et al., 2023; Salhi et al., 2023; Takunda and Steven, 2023; Vinti et al., 2023; Junior et al., 2023; Obasi et al., 2023). Urban waste materials are typically improperly disposed of in open landfills. Hence, they pose a serious threat to community health, environmental contamination, and underground water resources, as they become point sources of pollution (Alao, 2023; Juarez et al., 2023; Marín-Angel et al., 2023; Oliveira et al., 2023; Triassi et al., 2023; Ogarekpe et al., 2023).

Many studies have combined geophysical and biogeochemical techniques to conduct aquifer vulnerability evaluations due to the significance of high-quality water for human health. However, some identified procedural shortcomings have often led to inaccurate assessments of results. This review attempts to identify some of these drawbacks and suggest better ways to improve upon analysis and interpretation of results. The specific objectives of this review include (a) reviewing previous aquifer vulnerability assessments and possibly identify shortcomings; and (b) discussing the identified drawbacks and recommend ways to prevent future re-occurrence.

2. FUNDAMENTAL PRINCIPLES OF GEOPHYSICAL AND BIOGEOCHEMICAL METHODS

Geophysical methods are dependent on measuring physical properties of

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rocks (e.g., Boateng et al., 2023; Deng et al., 2023; Tóth et al., 2023; Adam et al., 2023; Ernenwein, 2023). The quality of the data determines the level of resolution from a particular geophysical approach. (Naseer et al., 2023; Abdollahizad et al., 2023; Sun et al., 2023; An et al., 2023). Moreso, the suitability of a geophysical method for a given situation depends on differences in subsurface properties and the sensitivity of the measurement equipment (Lin et al., 2023; Sanuade et al., 2023). So, identifying them relies heavily on the traits or qualities that set them apart from the surrounding media (Hao et al., 2023). These characteristics define the most effective geophysical technique to use in a survey (Wang et al., 2023). Magnetic Susceptibility, Electrical Conductivity or Resistivity, Radioactivity, Electrical Polarizability Density, and Seismic Velocity are among the characteristics that are of importance in the majority of geophysical investigations (Eeva et al., 2023; Pulinets et al., 2023).

3. Geophysical Methods

There are two types of geophysical survey methods: those that employ the Earth's natural fields and those that involve introducing intentionally created energy into the subsurface. (Ghorbani et al., 2023; Kadam et al., 2023). Hence, geophysical survey techniques can be split into two categories: those that exploit the Earth's natural fields and those that call for the subsurface insertion of artificially generated energy (Sakhare et al., 2023). In general, natural field methods are less expensive to conduct than artificial source methods and can provide information about Earth properties to a significantly higher depth (e.g., Carletti et al., 2023; Liu et al., 2023; Ghorbani et al., 2023). However, it has been noted that utilizing a single geophysical technique is typically insufficient for target detection as identical geophysical anomalies may be connected to an anomaly source with various physical characteristics, occurrence patterns, and sources of anomalies of different types (Ernenwein, 2023; Abdollahizad et al., 2023). In order to uncover and define hidden targets for a better interpretation of detected anomalies when examining aquifer vulnerability to pollution, integration of geophysical methodologies is therefore required. For the detection of a desired target, two (and occasionally three) geophysical techniques are needed (Obasi et al., 2023; Ghorbani et al., 2023).

4. Biogeochemical Methods

The main causes of groundwater pollution are infiltration of contaminants through the soil at waste disposal sites and the percolation of fluvial water (e.g., Alao, 2023; Srivastava et al., 2023; Bhatt et al., 2023; Mineo, 2023). The susceptibility of an aquifer depends on its thickness, lithology, and overburden despite the fact that Earth materials serve as a natural filter to percolating fluids (Obasi et al., 2023; Ossai et al., 2023; Akiang et al., 2023; Preene and Roberts, 2023). Due to the long residence lengths, clay-like beds that are limiting and silts make excellent aquitards and are therefore protective barriers against surface and near-surface pollution (e.g., Mohammed et al., 2023; Guo et al., 2023; Abd El-Dayem et al., 2023). Seldom do pollutants or contaminants that have been introduced into the environment stay where they were first released. Four fundamental processes—advection, molecular diffusion, mechanical dispersion, and adsorption—transmit contaminants across porous media (Steiakakis et al., 2023; Yusuf et al., 2023; Guo et al., 2023). The most crucial transport process that influences how chemicals behave in soils and how they are distributed in the soil water ecosystem is adsorption. (e.g., Pan et al., 2023; Darnault et al., 2023; Sharma et al., 2023; Song et al., 2023).

Biogeochemical methods entail the systematic measurement of the biochemical properties of a naturally occurring material (Gupta and Singh, 2023; Ogarekpe et al., 2023; Olatinsu et al., 2023). The purpose of the measurements is the location of geochemical anomalies or of areas where the biochemical pattern indicates the presence of contaminants in the vicinity. Biogeochemical methods are applied to investigate the quality of groundwater through the assessment of level of contaminants present in analyzed water samples to ascertain whether there lie within global permissible limits (Obiri-Nyarko et al., 2023; Maqsood et al., 2023; Ogarekpe et al., 2023; Olatinsu et al., 2023). The following parameters are measured: heavy metals (Fe, Zn, Mn, Pb, and Cd), oxidative parameters, including total dissolved solids (TDS), total suspended solids (TSS), pH, total hardness, electrical conductivity, iron content, nitrate, sulfate, temperature, and turbidity, as well as biological, chemical, and oxygen demand (BOD), major anions, selected halide ions, nitrogen, and phosphorus, microbiological components (faecal streptococci and coliform bacteria, such as Escherichia coli) (Rabeh, 2023; Patriarca et al., 2023; Mir et al., 2023; de Oliveira et al., 2023). It also involves applying multivariate statistical analysis (MSA) to examine the relationships between the examined water quality indicators and sample points, as well as evaluating potential sources of dissolved ions through the calculation of hydro-chemical data and ionic ratios.

5. Survey Techniques

The most appropriate approaches for assessing the susceptibility of aquifers are determined to be electrical resistivity methods because leachate, a liquid created from degraded waste, has a higher conductivity due to the presence of dissolved salts (Akiang et al., 2023; Sarti et al., 2023; Udosen, 2022). Moreover, leachate being frequently more electrically conductive than the pore fluids nearby, some studies, as detailed in the next section, have integrated various geophysical and biogeochemical methodologies to undertake aquifer risk assessments because it is typically insufficient to apply only a single geophysical method for detection of the intended target (Durdağ et al., 2023; Egbelehulu et al., 2020; Mohammed et al., 2023; Ismail and Ahmed, 2023; Vespasiano et al., 2023; Sivakumar et al., 2023). A typical case is the simultaneous measurement of Self-Potential (SP), VLF-EM and resistivity methods (VES, 2-D, and 3D electrical imaging) and the application of standard biogeochemical methods for the effective interpretation of observed anomalies (Ghimire et al., 2023; Khan et al., 2023; Akiang et al., 2023; Sarti et al., 2023).

6. Review of Related Literature

The concept of water pollution simply means contamination of water due to any external material (Ukah et al., 2020). In other words, water pollution is the introduction of something to natural water which makes it unsuitable for human consumption. Numerous studies have acknowledged the crucial role of quality water to economic progress and development. Gleick stated that it is implicitly and openly endorsed by international law, declarations, state practice, that access to basic water is a fundamental human right (Gleick, 1998). Ndimande claimed that all society's life revolves around water (Ndimande, 2022). He cited a number of problems that have hampered the equal distribution of high-quality water and have also restricted the constitutional right to water, including population increase, pollution, and inadequate allocation and distribution methods. He used the Alfred Duma Local Municipality in South Africa as a case study, where the majority of women felt oppressed, disenfranchised, and left out of the decision-making process over access to quality water.

Assessing the availability of quality water for drinking purposes, identified the two principal water resources required for sustaining life and the environment as surface water and groundwater (Mgbenu and Egbueri, 2019). They noted that even while water makes up around 71% of the planet's resources, access to clean water for drinking, residential use, and industrial use is limited, particularly in poorer nations. That human-made elements, such as domestic, agricultural, and industrial activities, as well as improper waste management, are the primary causes of the restricted supply of high-quality water, both in rural and urban areas. A group researchers demonstrated that the biggest dangers to the quality of water and biodiversity are inappropriate solid waste management and a lack of wastewater treatment plants (Stevanović et al., 2021). Although the Adriatic Coast, which is located between the Italian and Balkan peninsulas, has relatively abundant surface and groundwater resources, they reported that demand for water is constantly rising due to the growth of tourism, intensive farming, and urbanization, particularly along the Coast.

Some researcher investigated the possibility of heavy metal pollution of the groundwater around an open dumpsite in Olubunku, Ede North, Southwestern Nigeria, using PQWT Electromagnetic Groundwater Detector (PQWT-300S) and Buck Scientific AAS (Isah et al., 2023). As and Hg in the samples were read colorimetrically using a Niesa Spectrophotometer. Findings showed that the water-bearing rock is located at the boundary between the fresh basement and the well-fractured basement. According to the HPI scale, all of the samples include levels of Cd, Hg, Pb, As, and Co that are higher than the permissible limit for water. The water is not contaminated with Ni or Cr, according to the low scale of Ni and Cr. The maximum permissible concentrations of Co, Ni, Cd, Pb, and Hg are found in the soil, whereas As and Cr are extremely low and hence, do not provide a hazard.

A group researchers applied spectrophotometric method, geo-hydrological and field mapping techniques to evaluate the main hydro-chemical constituents of groundwater resources and the fracture system that influence the migration, flow direction and subsequent transport of contaminants in the mining areas of Abakaliki, Ebonyi State (Obasi et al., 2023). The results show that some wells have levels of SO_4^{2-}, Cl^-, As, Mn, Pb, Cd, Fe, Hg, and Se that are higher than the recommended threshold for drinking water set by the World Health Organization and the Standard Organization of Nigeria. Higher quantities are seen in wells located within mining zones and further downstream, according to the geochemical element distribution. This is caused by the fact that not all fractures are connected.

Alao assessed the impacts of dumpsite leachate on soil and groundwater quality around an open dumpsite for mining located at Goni-Gora, Kaduna State, applying physico-chemical and geophysical methods for water analysis (Alao, 2023). While physical drilling reveals soft subsoil, the results suggest the presence of heavy metals, and the geophysical result is characterized by low resistivity values, demonstrating a good match. The leachate plums, which had infiltrated the ground up to the water table, may have affected the soil and aquifer systems inside and around dumpsites based on the soft soil, the presence of heavy metals, and the low resistivity values.

Some researchers evaluated the hydrogeochemical facies, heavy metal pollution and irrigation indices, and their impact on human health in North Tripura district, India (Roy et al., 2023). Results of heavy metal indices suggest above 80% samples are at high risk due to high Fe contamination. The results of a health risk assessment study suggest that due of hazardous levels of Fe and As, children are more at risk than adults for both cancer and other diseases. To understand interactions between all ions and trace metals as well as likely hydrogeochemical processes in groundwater, multivariate statistical methods are used. 77% of the samples match the criterion for irrigation appropriateness, according to Wilcox and USSL plot results.

Some researchers assessed the aquifer systems at Owode–Onirin in Lagos, southwest Nigeria using VES, CST and hydro-geochemical analysis from 4 handmade wells and 1 borehole (Olatinsu et al., 2023). Interpreted 1-D and 2-D resistivity data yields a maximum of five geoelectric layers. The aquifer unit within the study region is represented by coastal plain sand from either the second or third geoelectric layers. A freshwater aquifer was identified beneath two places with resistivity ranging from 115 to 127 m at depths between 17.6 and 19.2 m, despite the fact that low aquifer resistivity (21 m) indicates severe salty water intrusion. High water salinity is supported by high average total dissolved solids (856 mg/L) and electrical conductivity (1712 μS/cm) values. High levels of sulfate (average: 752.31 mg/L) and bicarbonate (122.0–640.5 mg/L), as well as a high overall hardness (270–715 mg/L) relative to alkalinity (100–525 mg/L), all point to a hard groundwater state. Mean Phosphate concentration (1.30 mg/L) is far above 0.035 mg/L set by the United States Environmental Protection Agency (EPA) and is likely to produce cloudy water with low oxygen content.

In other study they has assessed the pollution level of the Asa River, Ilorin, Kwara State, Nigeria, using standard methods as stipulated by United States Environmental Protection Agency (Adeyinka et al., 2023). OCP concentrations were below the World Health Organization and European Union drinking water guidelines. The hazard quotient (HQ) was used to evaluate the health risk assessment for both children and adults and it was discovered that for the targeted OCPs, it was more than unity (> 1). For humans, the associated cancer risk for OCPs varied from low to significant. Except for HCH, the negative ecological impacts of OCPs have been shown to be extremely unlikely to occur.

A group researchers examined the effect of air pollution on the soil and consequently on the medicinal herbs grown on such soils using atomic absorption spectroscopy (AAS) (Akinlade et al., 2023). Chromium, cadmium, and lead concentrations were found to be greater at the contaminated location while nickel concentrations were found to be higher at the unpolluted site. For the Moro and Fasina sites, respectively, cadmium has the highest transfer ratio among the four metals (0.39 and 0.34) while lead has the lowest (0.21 and 0.25). In a similar vein, Carica papaya has the lowest transfer ratio (0.30) and Chromolaena odorata has the highest (0.34). (0.28). In conclusion, it is clear that the dangerous metals are slowly building up in the polluted site and may eventually poison the herbs.

Other researchers assessed groundwater quality, ecological richness, and HR in the coastal districts of West Bengal, India, by applying field-based CD, GWQI, ERI, and HRI techniques (Biswas et al., 2023). The results indicated that between 40 and 50 percent of the two chosen coastal districts' GW are of low to very bad quality, the GW's environment is in danger, and there is a significant risk to human health throughout both the dry and wet seasons. The Wilcox and USSL figure demonstrated that around 50 % of the GW aquifers in West Bengal's coastal districts are unsuitable for irrigation and consumption. Researchers, decision-makers, and water scientists might benefit from the study's findings in managing and lowering groundwater vulnerability in coastal zones in a sustainable way.

Chris and Anyanwu studied the Isaka–Bundu tidal swamp area in the Niger Delta, which is an impacted mangrove creek located along the Bonny River, exposed to pollution pressures (Chris and Anyanwu, 2023). The ecological risks (Er) of toxic metals in the sediments and water of the Isaka–Bundu tidal mangrove swamp followed a decreasing order (Cu > Zn > Cd > Cu > Pb > As). The results showed that although the Isaka-Bundu tidal mangrove swamp's toxic metals can be stated to have an exceptionally high ecological risk (PERI 600), the sediment pollution load index (PLI) was higher than in all three stations under study, indicating extremely toxic pollution. The enrichment evaluation reveals that the analyzed stations have a low potential ecological risk for Pb and a moderate potential ecological risk for Cd. Significant toxic metal pollution in the Isaka-Bundu tidal mangrove swamp is proof of the illicit activities carried out in the Niger Delta.

A group researchers investigated the impact of continual discharge of untreated abattoir effluents on the water quality of River Benue (Omoni et al., 2023). Three major abattoirs (Wurukum, Wadata and Northbank) in Makurdi, Nigeria, and their polluting strength in river upstream and downstream were measured and compared. All sampling sites indicated an increased bacterial population while Salmonella spp. and Escherichia coli were the predominant bacteria among the ten genera identified in water upstream and downstream. Faecal coliforms increased from upstream to downstream in two sampling sites (Wurukum and Wadata). Strong positive correlations were observed between upstream and downstream samples for pH, EC, turbidity, TSS, DO, COD, SO_4^{2-}, TC, and Shigella spp. WQI revealed that all sampling locations were heavily polluted and unsuitable for drinking purposes (WQI > 300) based on both the physico-chemical and bacterial parameters. However, merely looking at physico-chemical characteristics, particularly upstream at both Wurukum and Northbank sampling sites (WQI 50), the sampling sites revealed outstanding water quality. The elevated concentration of a few physio-chemical parameters and the bacterial loads reported in the river downstream have been attributed to anthropogenic activities in the area around the river.

A group researchers assessed the groundwater potential within the sedimentary basin of Ughelli situated in the Niger Delta region of Nigeria, using a geoelectric survey, geophysical logging, pumping test and water quality analysis (Anomohanran et al., 2023). The result of the geophysical well log revealed that the electrical conductivity and total dissolved solid of the groundwater are 180 µS/cm and 120 mg/L, respectively. These values and the results of the laboratory analysis revealed that the values of the various parameters determined are within the permissible limit of the World Health Organization. The results of the pumping test also showed that the well's specific yield and the aquifer's transmissivity are, respectively, 87.8 and 463.8/day. These findings show that the aquifer is abundant and strong enough to survive intensive pumping. As a result, it is recommended that groundwater development be promoted in the area under study.

Ammar and Kamal employed Direct Current (DC) resistivity and time-domain electromagnetic (TEM) methods to distinguish between saturated and dry zones and in an evaluation of groundwater resources in the western desert of Egypt (Ammar and Kamal, 2023). In the decay (voltage) curves, the last parts of the early stage and the intermediate stage refer to the shallow aquifer, while the late stage indicates the deep aquifer. The effect of ramp-off time was studied. The first and last diffusion depths, as well as the shallow, unrecorded depths of the high current diffusion speed, were calculated. The sedimentary basin was defined using the TEM method, and the maximum penetration depth was about 1300 m. It was established by comparing the results of the two approaches that the TEM method is sensitive to both shallow and deep conductive and resistive zones, but the resistivity method is sensitive to just shallow conductive and resistive zones.

Ogundana and Falae employed VES techniques using Schlumberger array electrode configuration to study the groundwater potential and vulnerability of selected locations around Ifedore LGA of Ondo State (Ogundana and Falae, 2023). The results showed that the general trend of groundwater potential within the study area is low as indicated from the hydraulic conductivity, transmissivity and porosity. The generated groundwater potential map of the area can be used in designing appropriate groundwater exploration and management within the area.

A group researchers applied VES and chemical analyses to assess the characteristics and hydrochemistry of shallow lateritic aquifers of northern Kerala, India (Sandeep et al., 2023). The spatial distribution maps of various resistivity layers indicate that the northern and north-western parts of the study area are favourable for groundwater exploration through open wells. The geochemical analysis indicates that the groundwater in the lateritic aquifers is slightly acidic in nature. The US salinity diagram indicates that all the groundwater samples belong to the category of low salinity and low sodium hazard. The ions in the groundwater mostly originate from rock-water interaction and a few samples belong to the category of precipitation dominance. However, the type of parent rock does not exhibit a significant relationship with groundwater chemistry.

Some researchers evaluated the groundwater condition in Enugu North, Southeastern Nigeria, using VES Resistivity survey (Ossai et al., 2023). The contour maps were generated using Surfer software package version 15 which showed the variation of overburden parameters. Due to the low geo-physically based protection index values of the aquifer layers and the weak to fair GPI rating, which suggests that the aquifer can be shielded from intruding contaminants, the research area was generally regarded as having a good protective level.

A group researchers analyzed the Ovogovo area's groundwater's exposure to contamination, in Nsukka West, Enugu State, using VES sounding in twenty (21) locations (Omeje et al., 2023). According to a statistical summary of the DRASTICLu and SINTACSLu models, soil media and recharge pose the highest risk of aquifer contamination, whereas topography, land use, and the composition of the aquifer pose the lowest risk. Depth to water table and land use were identified as the most sensitive parameters in the area's vulnerability assessment by the results of single parameter sensitivity and map removal analysis for the modified models.

A group researchers carried out a profiling of antibiotic resistance and potential discovery of ampicillin-resistant genes in Escherichia coli in the city of Osogbo, Southwest, Nigeria, using forty groundwater samples (20 each from wells and boreholes) (Titilawo et al., 2023). Grab sampling was done using 1L sterile plastic bottles, isolation of E. coli was performed using pour plate technique on eosin methylene blue agar and their identities confirmed by polymerase chain reaction (PCR) using uidA gene. For everyone who strongly relies on this source of water for various purposes, the presence of multidrug-resistant E. coli and the TEM-H resistant gene in the groundwater poses a serious hazard. To protect the public's health, proper groundwater monitoring and antibiotic resistance surveillance are advised.

Egirani and Chidi performed Organo-Contaminant GIS Analysis to identify the cause of high fever and gastrointestinal problems in those who have consumed groundwater in Aluu, Delta Region, Nigeria (Egirani and Chidi, 2023). A total of 10 water and sediment samples were collected at a depth of 45 m from 10 boreholes within Aluu and analyzed in triplicate. The air-dried sediments were subjected to particle size measurements using a particle size analyzer. The chemical analysis of the water samples was carried out using the American Public Health Association Method (APHA). Total petroleum hydrocarbon concentration ranged from 0.033 mg/L to 0.88 mg/L, whereas iron content ranged from 2.98 mg/L to 0.48 mg/L and total hydrocarbon content from 1.65 mg/L to 3.41 mg/L, respectively. The World Health Organization's permissible limits were exceeded by the pollutants that were bonded to sediments and water. The properties of the borehole sediment played a key role in regulating the entry of contaminants into the groundwater.

Some researchers also collected potable groundwater samples (hand-dug wells and boreholes) in the Bosso community of North Central Nigeria and assayed for radon concentration (Kolo et al., 2023). Water samples taken from hand-dug wells and boreholes had mean 222 Rn activity of 9.81 1.85 Bq/L and 24.78 2.48 Bq/L, respectively. Intake and inhalation of waterborne radon from the two groundwater sources result in average whole-body committed effective doses of 0.026 mSv/y and 0.067 mSv/y for hand-dug wells and boreholes, respectively. These values are below the safety threshold of 0.1 mSv/y advised by the European Union.

In other study, researcher modelled groundwater potential in a typical schist belt region in Osun State, Southwestern Nigeria, using electrical resistivity, aeromagnetic, remotely sensed data, and multi-criteria decision analysis (MCDA) (Olubusola et al., 2023). Within the research area, 80 vertical electrical soundings (VES) were taken using the Schlumberger setup. Very low, low, moderate, and high zones were identified as the four distinct groundwater potential zones. The accuracy of the groundwater potential map was verified using data from boreholes and static water level measurements throughout the study area.

A group researchers examined the suitability of the water for irrigation and drinking in Ambagarh Chowki Chhattisgarh, India, by examining various physico-chemical parameters (Lal et al., 2023). With the exception of one sample, the drinking water quality index (WQI), which ranged from 12.22 to 185.56, indicated that the majority of the groundwater was fit for human consumption. Groundwater hydro-geochemistry was assessed using correlation, Piper, Gibbs, and other geochemical analyses. According to the Piper trilinear diagram, 90% of the groundwater that was sampled was of the Ca (Mg)-HCO3 type. The various ions in groundwater are the result of mineral weathering caused by silicate and carbonate weathering of rocks and water.

Some researchers applied VES sounding using Schlumberger array to investigate groundwater protection in Awgbagba region in southwestern Nigeria (Adeniji et al., 2023). In the research area, the Dar-Zarrouk parameters showed 70% evidence of poor/weak groundwater protection potential, suggesting contaminants may soon infiltrate from the topsoil to the subsurface. In other study, researchers has applied geospatial and analytical hierarchical process (AHP) techniques in the Edo north region, in Nigeria to identify zones of groundwater occurrence and distribution with high precision (Ozegin et al., 2023). The recharge capacities were divided into four zones on the groundwater potentiality map made in a GIS environment: very low 561 Km^2 (17%), low 1989.9 (60.3%), moderate 627 Km^2 (19%), and high 122.1 Km^2 (3.7%). The eastern and northern portions of the research area appear to have moderate to high potential for recharge and storage, according to the GIS model and RS data.

In a study, monitored the pollution loads in the Kalpakkam coastal zone of India in terms of physico-chemical characteristics of sediment (Pandion et al., 2023). The investigation took place at 12 sampling points around the Kalpakkam coastal zone for one year beginning from 2019. T The three-way ANOVA test revealed significant differences between the population means at the 0.05 level. Principal component and cluster analyses revealed a strong correlation with all variables throughout all seasons, suggesting pollution from both anthropogenic and natural sources. The study found that nutrient contamination has a negative impact on the environment of the coastal region of Kalpakkam.

A group researchers employed SP, DC-Resistivity, and DC-TDIP techniques to assess the state of the groundwater located in the Western Desert, along the Cairo-Assiut desert road, Egypt (Ammar et al., 2023). The findings demonstrated the significance of resistivity, chargeability, and SP values in defining the fault zone, separating dry from saturated sediments, identifying the source of surface water seepage, classifying the depths of high, medium, and low groundwater accumulation, and determining groundwater flow and permeability. Some researchers investigated soil pollution and aquifer susceptibility caused by leachate percolation in a major dumpsite in Calabar using the VES and ERT approach (Akiang et al., 2023). According to the studies, the region has a high protection capacity rating. It also demonstrated the northeasterly direction of the leachate flow.

A group researchers examined some physicochemical characteristics, metal concentrations (Pb, Cd, Cu, Zn, Fe, and Mn), and the general water quality from Bomadi Creek in the Niger Delta of Nigeria, over two seasons (Iwegbue et al., 2023). In accordance with established protocols, water samples were collected at specific locations throughout the river's flow and processed for analysis. The complete pollution index results showed that the Creek was severely polluted, with turbidity, Cd, and Fe suggested as the main causes of the degraded water quality. Water samples were taken throughout the course of the river at defined points and processed for examination in accordance with established protocols. The Creek was badly contaminated, according to the full pollution index values, with turbidity, Cd, and Fe being the main contributors to the poor water quality. The risk analysis found that drinking the water posed harmful non-carcinogenic and carcinogenic risks to humans. Children are at greater risk than adults are. Therefore, remediation is needed since the water is deemed unfit for drinking and other residential uses.

Some researchers used electrical resistivity tomography (ERT), sediment characterization, and temporal monitoring techniques, in order to identify potential groundwater recharge zones, at IIT Kanpur, India (Mishra et al., 2023). The existence of potential zones made up of highly permeable strata within a depth range of 6–48 meters was determined by the correlation of 2-D ERT models with borehole lithology and depth-wise fluctuation of hydraulic parameters. In addition, time-lapse ERT study was used to monitor the activity of the designated prospective zones. Comparing time-lapse 2-D ERT models revealed a notable decrease in post-monsoon resistivity profiles, which suggests an increase in saturation levels brought on by rainwater penetration.

In other hand, some researcher studied evaluated the environmental hazards and health-related risk of Arsenic (As), Cadmium (Cd), Zinc (Zn), Manganese (Mn), Copper (Cu), Colbat (Co), Cranium (Cr), Nickel (Ni), and Lead's (Pb) in an abandoned landfill system at Obio/Akpor LGA, Rivers State, using United State Environmental Protection Agency model (Afolabi et al., 2023). The Concentration of the elements descended as follows; Mn > Zn > Cr > Pb > Cu > Ni >Co > As > Cd and exceeded the WHO permissible limit. With the exception of Cd (3.67, 426), the Enrichment Factor (EF) and Potential Ecological Risk (ER) showed no enrichment and low risk, and moderate enrichment and extremely high ecological danger, respectively. Except for Mn in children, which had a value of 1.69 x 100 on the hazard index (HI) scale, there was no evidence of a significant risk of a non-carcinogenic effect for either adults or children.

A group researchers investigated a novel time-lapse electrical resistivity tomography strategy to evaluate the impact of STE infiltration on the water pathways of two planted loamy-soil trenches located in a Fluvisol region in southwestern France (Delgado-Gonzalez et al., 2023). The system was monitored for 3 years using discontinuous monitoring of electrical resistivity tomography during four saline tracer tests. The findings demonstrate that: 1) the new methodology has successfully highlighted the evolution of water pathways in the soil over time; and 2) such evolution is consistent with reeds root distribution in the trenches, which appears to be influenced by water quality, such as sludge losses and TSS. Higher pollution levels (7.2 mg TSS/L, 45 mg COD/L, plus episodic sludge release) near the bottom of the second infiltration trench could cause roots to grow close to the surface, which could reduce the infiltration capacity. The significance of long-term flow pathway monitoring in comprehending the hydraulic behavior of infiltration surfaces submitted to STE is brought out in this work.

7. Review of Related Works and Discussions

The following related works were scrutinized, analyzed, and discussed:

7.1 Article 1

Researchers combined 2-D electrical resistivity and self-potential (SP) methods to locate anomalous electrical conductivity around the Goronyo dam in Sokoto State, Nigeria in order to determine the condition of the embankment of the earth dam (Augie et al., 2022). The study applied Ohmega Resistivity meter as the instrument for measuring Self-Potential (SP) data from the study lcation. However, the result revealed large range of SP values (≥ 200 mV) which were attributed to high fluid flow which could have possibly resulted in high moisture content (Ammar et al., 2023; Zhang and Furman, 2023). This according to the study, caused the seepage of water leaking through the zones.

7.1.1 Discussion

In the material and method section of the paper, the authors did not provide detailed description of the nature of electrode used (e.g., polarizable or non-polarizable) to collect the SP data. This would have helped to assess the source of the spurious SP values (≥200 mV). This is deemed to be a significant procedural flaw because a thorough explanation of the type of electrodes used would have allowed this review to identify the origin of the big SP data, enabling reproducibility and repeatability of results. Therefore, it is determined that the usage of copper stakes rather than the non-polarizable electrodes of Cu/CuSO4 porous pots is most likely to blame for the wide range of SP values obtained in the study.

For instance, in a study conducted at an artificial dam constructed at Thuyloi University, Vietnam, to track water leakage across the structure dam using Self-Potential method by they observed that the values of the electrical potential measured using copper stakes was about 120 mV (Thanh et al., 2020). However, when Cu/CuSO4 porous pots were used, these values were lower (around 10 mV). The work by offered a detailed description of the electrodes utilized and explained the high SP values by pointing out that copper stakes substantially induce electrical polarization (Thanh et al., 2020). It further observed that when copper stakes are hammered into ground, the electrical potential may not have a consistent value for up to five minutes. This according to study, is because copper stakes, when rubbed against soil, produce an electrical charge that takes some time for metal electrodes to discharge and reach equilibrium. The study found that using copper stake electrodes causes significant errors in measuring SP and has an impact on how data are interpreted.

The non-polarizing electrodes are therefore used in SP measurements to avoid a reaction at the soil-electrode interface that could cause localized effects (Strobel et al., 2023; Roy, 2022). The non-polarizable electrodes are often fashioned of cylindrical, partially glazed ceramic pots with an unglazed bottom to maintain porosity and promote ion mobility between the pots and the earth. Each pot contains a salt solution that is saturated, and a metallic electrode is submerged in each pot. The combinations are employed as electrodes, such as copper rods in copper sulfate solutions, lead rods in lead chloride solutions, and silver rods in silver chloride solutions. However, a widely used method uses copper rod submerged in a copper sulphate solution since it is generally available and least expensive (Roy, 2022). The non-polarizing electrode is essentially an electrochemical cell that maintains electrical contact by ions moving from the soil to the electrode through the tiny pores in the porous pots that contain a particular type of electrolyte. A study of this kind is advised to give a clear description of the techniques utilized to avoid ambiguity, including the type of electrode that was employed (polarizable and non-polarizable) to identify the root of errors in order to ensure that outcomes may be repeated and reproduced (Bazyleva et al., 2021; de Ruijter et al., 2020).

7.2 Article 2

Some researchers evaluated the presence and distribution of various heavy metals (e.g., Pb, Cd, Co, Cr, and Ni) and their possible sources in the shallot fields of Brebes Regency, Central Java, Indonesia, through a field survey and a series of laboratory and statistical tests (Dewi et al., 2021). They analyzed total concentration of heavy metals from 184 sampling points of the shallot fields in Brebes Regency, Central Java, Indonesia, during dry season from August to October, 2019. The study concluded that based on the concentration of heavy metals, the shallot fields in Brebes Regency, Central Java, were classified as uncontaminated soils.

7.2.1 Discussion

Only samples from the dry season were collected for the study. The concentration of physical, chemical, and biological aspects of soil and water samples, including heavy metals, are deemed to be climate and season dependent (Rodrigues-Honda et al., 2023; Moll-Mielewczik et al., 2023; Pandion et al., 2023; Ganiyu et al., 2018). In previous studies conducted by all demonstrated the impact of seasonal and spatial variation on the assessment of groundwater quality parameters (Pandion et al., 2023; Yenigun et al., 2021; Badmus et al., 2021; Ganiyu et al., 2018). So, it is important to think about sampling both during the dry and wet seasons, as this must have had an impact on the results of the investigations.

7.3 Article 3

In a studied, examined the aquifer issues in Gosa area of Abuja, North-central Nigeria, utilizing solely the VES technique (Omeje et al., 2013). According to the study's findings, the failure of the borehole in the area was most likely caused by intrusion of basalt which broke the strata that contained the aquifer. Another study in the same Gosa neighborhood in Abuja, Nigeria, using a combination of VES and data from the hill-shaded Shuttle Radar Topography Mission (SRTM), which examined the factors influencing groundwater occurrence in the area, concluded that while fractures exist in the Gosa area, they do not have enough connectedness (Omeje et al., 2014). Dry wells were observed in the area, which was interpreted as the result of insufficient interconnectivity of fractures having a negative impact on the permeability of the fractured zone. The study demonstrated that failure of boreholes in the Gosa is most likely due to the lack of interconnected fracture zones, thick overburden, and low fracture densities (Omeje et al., 2014).

7.3.1 Discussion

These two separate studies demonstrated the usefulness of combining two or three geophysical methods to properly characterise the hydro-geological properties of the Goas area. While the study by which applied only a single geophysical method (VES method), attributed basaltic intrusion which shattered the aquifer bearing rocks as the probable cause of borehole failure in the area, the second study by that combined both conventional VES surveys with SRTM imagery on the other hand, concluded that there were a lot of dry wells in the area because of insufficient interconnectivity of fractures, which negatively impacted the permeability of the fractured zone (Omeje et al., 2023; Omeje et al., 2014). According to the second study, linked fractures should be the desired structural characteristic (target) for enhancing the study area's aquifer potential. The research suggests that using a single geophysical method for target detection is insufficient since a geophysical anomaly may be connected to an anomaly source with different physical characteristics, a different mode of recurrence, a different pattern, and a different nature. Thus, it is advised to employ integrated geophysical approaches.

7.4 Article 4

A group researchers applied VES method to detect the level of groundwater pollution within Oru and Ikoto dumpsites in Ogun State, Nigeria (Talabi et al., 2018). The result showed that the leachate present in VES 4 can infiltrate into the groundwater table through the highly porous and permeable material in the subsurface layer of the location.

7.4.1 Discussion

The study applied only VES technique to map and delineate the infiltration of leachate into the Earth subsurface in the area of study. However, research conducted by compared the effectiveness of VES and the 2-D imaging to define a subsurface plume of hydrocarbon contamination water in southeast of Karbala City, Iraq (AL-Menshed and Thabit, 2018). They demonstrated that the VES technique provided only the average resistivity values obtained and therefore suppresses some details, while the 2-D imaging on the other hand, provided more detailed view of subsurface behavior of contaminants, as it shows the location of the infiltration of the plume in the Earth subsurface.

In the study, they concluded that higher sensitivity values in the 2-D imaging technique provided higher lateral and vertical resolutions in the inverted model, thus, the contact between the uncontaminated zone and underground plume and the shape of that contact is clearly delineated. They also showed that the vertical sensitivity decreases with depth with the VES, so the contact between the contaminated and uncontaminated zones are not clearly delineated when it becomes deeper. Similarly, in another study compared the effectiveness of VES and 2-D imaging methods (AL-Zubedi and Thabit, 2014). They demonstrated that although, the VES method provided information for larger depth than 2-D, the 2-D show presence of hydraulic connection. They observed that the inverse models of 2-D imaging reveal the lateral and vertical variations of the resistivity within each horizon for shallow depths, and hence, reflects the changes in the lithology or leachate infiltration. The study presented above suggests that comparable studies in the future should combine VES and 2-D/3-D imaging for more accurate groundwater pollution evaluations as a more thorough perspective of the subsurface behavior of pollutants was obtained by the 2-D/3-D imaging.

7.5 Article 5

Nwankwo and Udo examined the impact of a dumpsite's contamination on a groundwater aquifer at a landfill in Choba Town around the University of Port Harcourt environs, Rivers State, Nigeria, using ADMT 200S Digital Terameter, which is a ground sensor (Nwankwo and Udo, 2021). The technique remotely transfers current, voltage and geometric data obtained by the instrument to a digital computer which utilizes the AIDU Resistivity Software to measure bed resistivities and generate high resolution real time 2-D and 3-D contour maps. The study observed that Digital ADMT 200S Terameter and ground sensor significantly minimized the operational difficulties that would have been encountered from the use of conventional VES method that involves extensive layout of cables. The results showed that contaminant leachate plume percolated through the dumpsite and infiltrated the clay beds without a direct contamination of the delineated aquifers.

7.5.1 Discussion

The study's interpretation of the ADMT method's data acquisition as vertical electrical sounding (VES) was noted during the interpretation stage, a method that has been determined to be incorrect. The VES method, according to assumes that current always penetrates deeper with increasing current electrode spacing (Chungam et al., 2023; Moulds et al., 2023; Akpaneno and Abdulwahab, 2020). For near-horizontal strata of formation below, the electrical sounding infers a change in resistivity with depth from a certain point on the ground. Measurements of the VES apparent resistivity is conducted at various electrode spacings, all centered around a common point (Minagawa et al., 2023; Moulds et al., 2023). Depths rise with increasing electrode array size. For VES, the Schlumberger array is frequently employed, with the potential electrode dipoles (M and N) remaining fixed and the current electrode dipole being moved (A and B). The interpretations are usually aided by softwares such as IPI2Win, MS Excel and surfer.

The ADMT Groundwater Detector and PQMT, both new groundwater detectors, share comparable ideas and processes as opposed to the principles and procedures of VES. A groundwater detector uses the benign conductivity of groundwater, the excitation effect, radioactivity, and other physical qualities, according to the PQMT website, to determine the location of groundwater, its depth, the water table line, and its output, among other details. After measuring the natural earth electromagnetic field at a variety of different frequencies produced by the law of change, the ADMT and PQMT principles use the natural electric field as the field source, based on the electrical differences in the underground rock ore (groundwater), to study the electric field. Thus, as their principles and methodologies are different, data produced from the ADMT Groundwater Detector cannot be interpreted similarly to that from the VES.

7.6 Article 6

A group researchers examined the aquifer's protective capacity and corrosivity level in the University of Abuja's main campus using VES Resistivity method (Ojo et al., 2015). According to the results' executive summary, the overburden units' longitudinal conductance ranged from 0.03802 to 1.58441 mhos. The findings showed that the research area's VES 1, 7, 9, 10, 11 and 12 had comparatively high topsoil resistivity values that are Virtually Non-Corrosive (PNC), while VES 2, 3, 4 and 5 and VES 6 and 8 had moderate corrosivity and mildly corrosivity, respectively. Four distinct aquifer protective capacity zones—poor (VES 11 and 12), weak (VES 3, 6 and 8), moderate (VES 1, 2, 5, 7, 9 and 10) and good (VES 4)—were identified based on longitudinal conductance values. Also, it concluded that the research area's VES 3, 6, 8, 11, and 12 may be vulnerable to surface contamination, whereas VES 1, 2, 4, 5, 7, and 10 may not be due to variations in aquifer protective capacity (APC). The analysis identified areas that are particularly vulnerable to groundwater pollution from surface pollutants and subsurface soils that corrode due underground utility pipes.

7.6.1 Discussion

It was noted from the results that there was no categorization of the APC rating in percentages (%). A framework that accurately categorized the APC of each transversal would have made it simpler to understand and aided in making decisions. Studies conducted by illustrate instances of APCs that are effectively presented (Bayode et al., 2020; Onyenweife et al., 2020; Aina et al., 2019).

8. Conclusion

There have been attempts to point out some issues with aquifer vulnerability assessments. Publicly available sources were used to gather the articles for review, which were then systematically analyzed using basic geophysical and biogeochemical principles. The review's findings were examined, and recommendations for how to enhance the analysis and interpretation of the findings were made. The findings confirmed the need to explicitly describe the materials used for data collecting in order to avoid ambiguities, as was shown in a study that used an Ohmega Resistivity meter without mentioning the type of electrode it was made of. The result was indicated by large Self-Potential (SP) measurements of 200 mV attributed to high fluid flow. According to analysis, copper stakes must have been used to produce such high SP values, as opposed to appropriate non-polarizable electrodes of Cu/CuSO4 porous pots, which only produced SP values of roughly 10 mV. Another study made clear the importance of considering how seasonal and geographic variation affect water parameters while gathering samples. Before using a specific geophysical methodology, it is important to evaluate its efficacy in mapping and defining the infiltration of leachate into the Earth's subsurface. This is because the VES technique only provides average resistivity values, which hides some characteristics. On the other hand, 2-D imaging has been demonstrated to offer a more in-depth perspective of the subsurface behavior of pollutants. The research determined that the interpretation of data obtained by the ADMT Groundwater Detector as belonging to VES was incorrect. This is so that ADMT's guiding principles may be distinguished from VES. A paper that failed to use fundamental statistical techniques to present an Aquifer Protection Capacity (APC) value in percentages (%) was also examined. Each transversal would have been efficiently categorized in this way for simple understanding. Future research are advised to take some of the noted flaws into account in order to enhance data processing and interpretation.

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