INTEGRATED FRAMEWORK FOR THE ASSESSMENT OF SHALLOW GROUNDWATER QUALITY IN SEMIARID BASIN

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ABSTRACT

Groundwater is the water that is found below the earth's surface. It can be divided into two categories which are shallow and deep groundwater. Shallow groundwater (SGW) quality is threatened by both natural processes and human activities. Thus, understanding groundwater quality requires an integrated approach. This study aimed to assess SGW quality using an integrated framework which combines geochemical modelling, and statistical and seasonal analyses. Theoretically, SGW is not impacted by seasonal and geological variability. Thus, the SGW is suitable for drinking and irrigation uses. The semiarid Sokoto Basin in Northern Nigeria was selected as the study area. Due to its geological and climatic characteristics, the basin was divided into three sub-basins, i.e., Birnin kebbi, Sokoto and Gusau which are located in three different states in Northern Nigeria. Ninety SGW samples were selected and analysed in different seasons. Physical parameters were analysed in situ while the chemical parameters were analysed in the laboratory. Geochemical modelling and statistical analysis were applied in the hydrochemical evolution of groundwater. The study also used drinking and irrigation water quality indices to measure its suitability for drinking uses. The findings showed that SGW quality was controlled by rock weathering. However, seasonality and geological variation have impacted SGW quality through significant variation ($p \leq 0{,}001$) in Temperature, Electrical Conductivity (EC), Dissolved Oxygen (DO), Total Dissolved Solids (TDS), Bicarbonate (HCO_3^-), Chloride (Cl^-), Ammonium (NH_3) and Phosphate (PO_4^{3-}). It was found that SGW quality is not suitable for drinking purposes in some locations. Water Quality Index (WQI) was 90.09, 122.52 and 51.76 in Birnin kebbi, Sokoto and Gusau during the dry season. WQI was 119.18, 148.69 and 69.79 in Birnin kebbi, Sokoto and Gusau during the wet season. Based on mean WQI SGW is unsuitable for drinking. Heavy Metal Pollution Index (HPI) during the dry season was 47.32, 133.75 and 189.73 in Birnin kebbi Sokoto and Gusau. HPI was 55.25, 122.29 and 113.75 in Birnin kebbi, Sokoto and Gusau during the wet season. HPI values above 38 indicate high pollution. Irrigation water quality was significantly impacted by seasonal and geological differences. SGW is threatened by high Magnesium Adsorption Ratio (MAR), and low Sodium Adsorption Ratio (SAR). Mean MAR was above 50 in which high magnesium destroyed soil structure and reduced crop yields. Meanwhile, a low SAR of 0.97 inferred the plant osmotic pressure. Statistically, this study inferred that seasonal and geological variability significantly influenced SGW quality in the semiarid Sokoto Basin. Hence this study has established a framework for assessing groundwater quality in semiarid environments.

ABSTRAK

Air bawah tanah ialah air yang terdapat di bawah permukaan bumi. Ia boleh dibahagikan kepada dua kategori iaitu air bawah tanah cetek dan dalam. Kualiti air tanah cetek (SGW) terancam oleh kedua-dua proses semula jadi dan aktiviti manusia. Justeru, memahami kualiti air bawah tanah memerlukan pendekatan bersepadu. Kajian ini bertujuan untuk menilai kualiti SGW menggunakan rangka kerja bersepadu yang menggabungkan pemodelan geokimia, dan analisis statistik dan bermusim. Secara teorinya, SGW tidak dipengaruhi oleh kebolehubahan bermusim dan geologi. Oleh itu, SGW sesuai untuk kegunaan minuman dan pengairan. Lembangan Sokoto separa kering di Nigeria Utara telah dipilih sebagai kawasan kajian. Oleh kerana ciri geologi dan iklimnya, lembangan itu dibahagikan kepada tiga sub-lembangan, iaitu, Birnin kebbi, Sokoto dan Gusau yang terletak di tiga negeri berbeza di Nigeria Utara. Sembilan puluh sampel SGW telah dipilih dan dianalisis dalam musim yang berbeza. Parameter fizikal dianalisis secara in situ manakala parameter kimia dianalisis di makmal. Pemodelan geokimia dan analisis statistik digunakan dalam evolusi hidrokimia air bawah tanah. Kajian ini juga menggunakan indeks kualiti air minuman dan pengairan untuk mengukur kesesuaiannya untuk kegunaan minuman. Dapatan kajian menunjukkan kualiti SGW dikawal oleh luluhawa batuan. Walau bagaimanapun, variasi bermusim dan geologi telah memberi kesan kepada kualiti SGW melalui variasi ketara ($p \leq 0,001$) dalam Suhu, Kekonduksian Elektrik (EC), Oksigen Terlarut (DO), Jumlah Pepejal Terlarut (TDS), Bikarbonat (HCO3-), Klorida (Cl-), Ammonium (NH_3) dan Fosfat (PO_4^{3-}). Didapati kualiti SGW tidak sesuai untuk tujuan minuman di beberapa lokasi. Indeks Kualiti Air (WQI) ialah 90.09, 122.52 dan 51.76 di Birnin kebbi, Sokoto dan Gusau semasa musim kemarau. WQI ialah 119.18, 148.69 dan 69.79 di Birnin kebbi, Sokoto dan Gusau semasa musim hujan. Berdasarkan min WQI SGW tidak sesuai untuk diminum. Indeks Pencemaran Logam Berat (HPI) pada musim kemarau ialah 47.32, 133.75 dan 189.73 di Birnin kebbi Sokoto dan Gusau. HPI ialah 55.25, 122.29 dan 113.75 di Birnin kebbi, Sokoto dan Gusau semasa musim hujan. Nilai HPI melebihi 38 menunjukkan pencemaran yang tinggi. Kualiti air pengairan terjejas dengan ketara oleh perbezaan musim dan geologi. SGW diancam oleh Nisbah Penjerapan Magnesium (MAR) yang tinggi dan Nisbah Penjerapan Natrium (SAR) yang rendah. Purata MAR adalah melebihi 50 di mana magnesium yang tinggi memusnahkan struktur tanah dan mengurangkan hasil tanaman. Sementara itu, SAR rendah 0.97 membuat kesimpulan tekanan osmotik tumbuhan. Secara statistik, kajian ini membuat kesimpulan bahawa kebolehubahan bermusim dan geologi secara signifikan mempengaruhi kualiti SGW di Lembangan Sokoto yang separa kering. Oleh itu kajian ini telah mewujudkan rangka kerja untuk menilai kualiti air bawah tanah dalam persekitaran separa kering.

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LIST OF ABBREVIATIONS

BRK	-	Birnin kebbi
Ca^{2+}	-	Calcium
Cl^{-}	-	Chloride
CO_3^{2-}	-	Carbonate
Cu^{2+}	-	Copper
DO	-	Dissolved Oxygen
EC	-	Electrical Conductivity
GUS	-	Gusau
GW	-	Groundwater
HCO_3^{-}	-	Bicarbonate
HPI	-	Heavy metal pollution index
K^{+}	-	Potassium
KI	-	Kelly's index;
km	-	Kilometre
Km^2	-	Kilometre square
MAR	-	Magnesium adsorption ratio
Mg^{2+}	-	Magnesium
Na%	-	Sodium percent
Na^{+}	-	Sodium
NH_3^{-}	-	Ammonium
NO_3^{-}	-	Nitrate
NSDWQ	-	Nigerian Standard for Drinking Water Quality
P	-	Precipitation
p/ETP	-	Potential Evapotranspiration
pH	-	Redox Potential
PI	-	Permeability index
PI	-	Permeability index;
PO_4^{3-}	-	Phosphate
PS	-	Potential salinity
RSC	-	Residual sodium carbonate

RSC	-	Residual sodium carbonate
SAR	-	Sodium adsorption ratio
SAR	-	Sodium adsorption ratio
SI	-	Saturation index
SO_4^{3-}	-	Sulfate
SOK	-	Sokoto
SW	-	Surface water
TDS	-	Total Dissolved Solids
Temp.	-	Temperature
TH	-	Total Hardness
WHO	-	World Health Organization
WQI	-	Water quality index
Zn^{2+}	-	Zinc

LIST OF SYMBOLS

≥	-	Greater or equal to
≤	-	Less than or equals to
±	-	Plus/minus
∑	-	Sum
~	-	about
@	-	at
Wi	-	Relative weight
q_i	-	Quality rating
C_i	-	Individual Water Samples
S_i	-	WHO standard
K	-	Proportionality content
Q_i	-	Sub index of ith parameter
i^{th}	-	Standard reference value of parameter
V_i	-	Is the monitored value of the of ith parameter

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BAB 1

INTRODUCTION

1.1 Introduction

The problem of shallow groundwater pollution in semiarid environments has increased globally during the last decades. This problem highly affects the shallow groundwater quality due to environmental change, mainly in the form of seasonal droughts, land use change. Although the semiarid environments are drained by large rivers, such as the River Niger, they suffer from water scarcity and cross-border water resources management challenges (Adaawen *et al.*, 2019; Amini *et al.*, 2021).

Likewise, the increase in water demand has led to shallow groundwater quality degradation, especially in heavily irrigated. Therefore, quantification of basin-scale hydrochemical process and shallow groundwater quality can help to delineate different shallow groundwater zones and improve our understanding of which parts of the basin have suitable water for drinking and irrigation uses (Kiewiet *et al.*, 2019).

The quality of shallow groundwater is primarily influenced by natural geological and environmental factors and human activities such as urbanisation, industrialisation, mining and agriculture (Duvva *et al.*, 2021; Gautam *et al.*, 2022). In global semiarid environments, shallow groundwater quality is primarily controlled by seasonal rainfall, which recharges shallow aquifers or infiltration from valleys and floodplain wetlands. For instance, spatio-temporal analysis of shallow groundwater in semiarid Cebala-Borji-Touil, Tunisia, revealed that lead (Pb) concentration varied significantly with seasonality.

Likewise, in Beijing, China, the seasonal replenishment of shallow aquifers from precipitation or irrigation play a significant role in the seasonal variation of shallow groundwater hydrochemistry (Wang *et al.*, 2018). Therefore, evaluation of seasonality's impact on shallow aquifers' hydrochemistry is vital for groundwater resource management in semiarid environments. Apart from the impact of seasonality, the quality of shallow groundwater is also affected by the geology of the environment. The hydrochemical composition of shallow groundwater is primarily related to regional geology (Li *et al.*, 2018).

Thus, understanding the correlation between shallow groundwater quality and regional geology is vital for sustainable water quality management. For example, correlational analysis of hexavalent chromium to hydrochemistry of groundwater zones revealed a geogenic formation of manganese, iron(+2) and Cr(VI) (Charoula *et al.*, 2021). Despite the dominant control on hydrochemistry of shallow groundwater by geology and environment, increasing evidence shows groundwater hydrochemical changes due to human activities (Li *et al.*, 2019; Sunkari *et al.*, 2021).

Conversely, irrigation return flow in semiarid basins is one of the significant factors impacting the quality of shallow groundwater (Mustafa Al Kuisi and Ahmad Abdel-Fattah, 2010). In addition, shallow groundwater is threatened by heavy metals pollution in industrialised areas in global semiarid environments (Dong *et al.*, 2022; Mthembu *et al.*, 2022). For instance, in the industrialised area of Shagamu, Nigeria, shallow aquifers are unsuitable for drinking due to heavy metals pollution (Zacchaeus *et al.*, 2020). Assessment of geochemical variations of heavy metals (fluoride and Uranium) in semiarid region of southwest Punjab, India revealed that groundwater quality is controlled by silicate weathering and evaporation.

According to the above, it is possible to have varied shallow groundwater quality due to variations in environment, geology and human activities. Therefore, understanding shallow groundwater's hydrochemical controls have presented a thought-provoking topic that requires an integrated framework assessment due to the complexity of natural and human processes that influence groundwater quality.

Consequently, an integrated assessment framework that combines seasonal, geochemical and statistical analyses and water quality indices (WQIs) is required to analyse shallow groundwater quality in semiarid environments including the Sokoto basin. It is a potentially promising tool for solving complex hydrogeochemical problems. Furthermore, previous studies have demonstrated the significance of shallow groundwater quality evaluation using an integrated framework to understanding a complex shallow groundwater system in a semiarid basin (Keesari *et al.*, 2021; Srivastava *et al.*, 2012; Teng *et al.*, 2019).

It is against this background that this study aimed to determine the seasonal and geochemical processes regulating the hydrochemistry of shallow groundwater and explore the suitability of shallow groundwater for drinking and irrigation uses in the Sokoto basin, Northern Nigeria, using an integrated framework that combined seasonal analysis, geochemical modelling, water quality indices and multivariate statistical analysis.

1.2 Problem Statement

Despite the robustness of the integrated approaches to groundwater quality assessments, groundwater quality studies tend to be silent concerning the incorporation of impacts of seasonal and geological factors on groundwater quality in global semiarid environments. Accordingly, the question of water quality is largely ignored especially in semiarid areas where groundwater is the only reliable source of drinking water, due to impression that groundwater is naturally suitable for drinking and other uses.

According to UNWater (2021), about 73% of the Sub-Saharan Africa's population used unsafely managed drinking water in 2017 based on UNICEF/WHO (2019) estimates. The annual global demand for water for all uses is currently 4,600 km^3 and is projected to increase by 20%-30% by 2050. By 2025, the demand for water by agriculture will increase by 60% with most increases happening in Africa and Asia.

Global water demand cannot exceed water availability and this is clearly evident in developing countries including Nigeria. The global water demand, water resources and water quality depends on multiple geopolitical factors that are hard to predict. The declines in water quantity and quality only partially investigated, thus, may be harder to control (Boretti and Rosa, 2019). Currently, about half of global population (47% or 3.6 billion) live in regions that suffer at least 1 month of water scarcity each year.

More than half (57%) of global population will live in regions that suffer water shortages for at least 1 month per year by 2050. At least, 14% of Africa's population (160 million) live in areas facing water scarcity, due to un even water resources distribution and inequality in the access to portable and clean water services, including semiarid regions such as the Sokoto basin, Nigeria.

A critical analysis of groundwater quality studies revealed that the Integrated framework for groundwater quality assement applied by many researchers (Mehra *et al.*, 2016; Mohseni *et al.*, 2022; Sarti *et al.*, 2021; Srivastava et al., 2012; Yang *et al.*, 2015) has the full potential to explain groundwater water quality in a semiarid Sokoto basin. However, these studies' frameworks failed to integrate the potential impact of geology and seasonality on groundwater quality. Major reasons was that most of these studies were no conducted in semiarid environments. The few studies that were carried out in semiarid environments are lacking seasonal approach due to time and resource considerations.

Conversely, there is evidence of increasing contamination threats to shallow groundwater caused by changes in mineral phase chemistry due to impact of seasonality, geology or human activities and thus, requires an integrated framework assessment of groundwater quality which employed geochemical modelling, water quality indices, seasonal and statistical analyses (Mehra et al., 2016; Singh *et al.*, 2013).

The complexity of groundwater quality exacerbated changes by contaminant origin and environmental processes has necessitated application of integrated

approach to assess groundwater suitability for drinking and other uses particularly in semiarid areas where rainfall is highly variable and irrigation farming expanding. Thus, understanding shallow aquifer hydro geochemistry is essential for sustainable water quality management in semiarid regions (Hamed *et al.*, 2018; He *et al.*, 2019).

Consequently, new studies on groundwater quality are required to guide informed decisions concerning water quality management. An integrated framework incorporating the impact of geology seasonality on shallow groundwater quality are required. It will provide the basis for understanding shallow groundwater's hydrochemistry and suitability for drinking, and irrigation uses.

For that reason, the evaluation of shallow groundwater in semiarid Sokoto basin is justifiable, as it provides the basis for understanding the impact of geology and seasonality on the hydrochemistry of shallow aquifers which can be used for sustainable water quality management. Therefore, the fundamental research question is "What is the hydrochemical composition of shallow groundwater in the Semiarid Sokoto basin, North-western Nigeria?" This remains the fundamental research question to be interrogated in this study. In answering this question, seasonal sampling/data is required over the Sokoto basin's different geological settings.

1.3 Aim and Objectives

This study aims to establish an integrated framework for evaluating shallow groundwater variability in the semiarid basin. The following specific objectives shall be pursued:

i. To determine the impact of seasonality on the hydrochemistry of shallow groundwater using laboratory and statistical analysis.
ii. To assess the impact of geology on shallow groundwater based on graphical methods, ionic exchange and saturation indices.
iii. To evaluate the suitability of shallow groundwater for drinking and irrigation purposes based on an integrated framework.

1.4 Research Hypothesis

This study tests the following null hypotheses:

i. H_0. The hydrochemistry of shallow groundwater did not vary with the wet and dry seasons;
ii. H_0. The hydrochemistry of shallow groundwater did not vary with the geological setting;
iii. H_0. Shallow groundwater quality is unsuitable for drinking and irrigation uses.

This study will discover the impact of geology and seasonality on shallow groundwater quality under semiarid climatic settings, which could be used to manage water quality within the broader arid and semiarid environments.

1.5 Scope and Limitation of the Study

This study covers only the Sokoto basin. It is also designed to assess:

i. The hydrochemistry of shallow groundwater in the semiarid environment using some defined major elements (pH, EC, TDS, DO, TH, Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, Fe^{3+}, Cu^{2+}, Zn^{2+}, NH_3^{-}, CO_3^{2-}, HCO_3^{-}, Cl^{-}, NO_3^{-}, PO_4^{3-}, and SO_4^{2-}.
ii. The focus is on the impact of geology and seasonality on the hydrochemistry of shallow groundwater.
iii. Also, this study determines the suitability of shallow groundwater for domestic, industrial and irrigation uses.
iv. Lastly, this study shall establish a framework for evaluating groundwater quality in arid and semiarid environments.

1.6 Significance of Research

Seasonal evaluation of shallow groundwater in semiarid environments will facilitate the efforts of researchers to:

i. Develop a framework for assessing water quality in semiarid areas using geochemical modelling, water quality indices and multivariate analysis.
ii. Understand the relationship between seasonality and hydrochemistry of shallow groundwater aquifers.
iii. Identify the impact of geological variability on the hydrochemistry of groundwater.
iv. The findings of this study will serve as a policy guide for effective water quality management.

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