Multi-criteria analysis of different land-use activities on groundwater resources in Maiduguri, Borno State

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Abstract

Land use and their related anthropogenic activities are likely to continue to impact shallow groundwater quality at different scales. Multi-criteria analysis (MCA) is a framework for evaluating decision options against multiple criteria. This study employed the Simple Multi-Attribute Rating Technique (SMART) methodology in ranking the different land-use activities based on their adverse effects on groundwater quality. In this respect, the strategic stakeholders engaged in this study were allowed to prioritise these activities based on the magnitude of their negative effect on the groundwater resources of the study area. The stakeholders' ranking shows that the residential area is the principal activity (44.7%) that has an impact on groundwater resources in Maiduguri. This is followed by agricultural land and forested areas with negative impacts in the range of 9% and 2.18%, respectively. Geographic Information System data was obtained from secondary data sources to show the impact of different land uses in the study area This study will be helpful to policymakers and decision-makers in adopting mitigation strategies that will provide solutions to the negative effects of groundwater contamination in Borno State.

Keywords: Multi-criteria Analysis, Land use activities, Negative Impact, Groundwater Resource

INTRODUCTION

Groundwater is a vital resource to domestic, industrial, and agricultural water supply in Maiduguri and Nigeria. Globally, it was estimated that about 2 billion people depend on groundwater for drinking water (Gleeson et al., 2012). Also, about 43% of global irrigation and a large share of global industrial activity depend on groundwater (World Bank, 2020). Furthermore, rapid population growth and uncontrolled urbanisation aggravate the increasing magnitude and distribution of above-ground human activities which potentially affect the quality and quantity of underlying groundwater resources (Giordano and Villholth, 2007; Siebert et al., 2010).

Problems attributed to anthropogenic contamination of groundwater by different land-use activities have been documented by Datta (2005), Schwartz and Ibaraki (2011). Also, Zaporozec (1994) contend that Multi-Criteria Assessment (MCA) of different land-use types and their anthropogenic Impact is an essential component of implementing a sustainability

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framework for managing water resources. Similarly, Schmoll et al. (2006) outlined and documented different land use activities that harm both surface and groundwater resources. In sub-Saharan Africa, a particular study (USEPA, 2002) has investigated the impact of various land-use types on groundwater systems.

Multi-Criteria Analysis (MCA) is defined as a decision-making tool developed to solve complex multi-dimensional problems, considering the qualitative and quantitative objectives of the situation in the decision-making process (Gebre et al., 2021). It is a scientific discipline that emphasizes combining planning in developing systematic models to prioritize finite management alternatives with conflicting criteria and trade-offs (Martin et al., 2006).

MCA provides an effective tool for land use and natural resources management by adding auditing, structure, transparency, and rigour to the decision-making process (Brentan et al., 2021). Recently, a variety of methods for addressing the MCA problem has increased. Current research papers identified multitudes of MCA techniques for ranking (Wu, 2022; Hagos et al., 2023). In this regard, there are two major MCA problem formulation types (CIFOR, 2008; Huang et al., 2021).

Firstly, the relative implication of land use activities is described through MCA through weights. Criteria weights are considered quantifiable outcomes of stakeholder choices. Second, mathematical procedures are used to aggregate and rank the management alternatives based on comparing the trade-offs in each alternative and by incorporating measures of uncertainty to simulate the imprecision of those consequences (Sibert et al., 2010). The MCA methodology is flexible and can be modified to suit different objectives. Based on their analysis, Fontana et al. (2013) argued that the MCA methodology is the most suitable for case studies; this is because it can easily be tailored to suit local conditions.

The analytical methodology adopted herein employs the Simple Multi-Attribute Rating Technique (SMART) (Velasquez et al., 2013). This methodology does not involve mathematical intricacies, it is relatively easy and quick to implement. The method has been widely judged to be robust and suitable for fast decision-making purposes (Buede, 2013).

In Borno State and Nigeria as a whole, urbanisation and agricultural activities are the mainland-use activities affecting the underlying groundwater system (Chilton, 1999; Wakida & Lerner, 2005; Eni *et al.*, 2011; Bakari, 2016). Over the past three decades, intense human activities have resulted in significant urban landscape changes with a major impact on groundwater quality (Bakari, 2014; Bilgilioglu, et al., 2022). Enormous pressure from the increasing population due to the influx of internally displaced people to the Maiduguri metropolis has led to increased changes and patterns in land-use activities. Also, other points and non-point sources of pollution across the city are likely to exert significant pressure on the hydrogeological system on a temporal and spatial scale (Foster et al., 1998; Bakari, 2016). Therefore, this paper aims to implement the MCA methodology and evaluate the impact of the different land-use activities (agricultural land, residential area, and forested area) on the underlying groundwater resources in Maiduguri, Nigeria. The outcome of this paper will offer solutions to mitigate the negative impacts of the different land-use activities in Borno State and Nationally.

STUDY AREA DESCRIPTION
The study area corresponds to 11° 50′ N 13° 09′ E. Maiduguri Metropolis is the capital of Borno State in North-eastern, Nigeria It is in a vast sedimentary Basin, the Chad Basin (Borno Basin) the topography attains an elevation of about 300 metres above sea level (Bakari, 2016).

Two groups of rivers drain the Borno region; one is bound towards the south draining to the Benue system while the other is towards Lake Chad (World Bank, 2010). The study area is drained by seasonally ephemeral Yedzaram and Ngadda Rivers into Lake Chad.

Figure 1 Map of Nigeria showing the study area (Bakari, 2016)

Maiduguri enjoys the warm tropical climatic condition of Western Africa. There are three different seasons in the study area: a long hot dry season (March to May). This is followed by a rainy season from June to September with a daily minimum temperature of 24°C and a maximum of 34°C with a relative humidity of 40 to 65% and annual rainfall from 560 to 600 mm (Bakari, 2014a).

Lastly, the Harmattan or cold season runs from November to January when temperatures fall to about 19 to 21 degrees Celsius. The vegetation of the study area is mainly Sahel and Sudan of the Sudan vegetation type, which is characteristically dominated by Trees, and shrubs, and various grass species.

According to the provisional figures from the 2006 census, the study area (Borno State) has a total population of 4,596,589; and males outnumber females by 58,033 (NPC, 2006). The average population ranges between 50-70 people per square kilometre (NPC, 2006).

Geology and Hydrogeology of the Study Area
According to Furon (1960) and Obaje (2009), the Chad Basin was a tectonic cross point between a NE to SW trending "Tibesti-Cameroon Trough" and the NW to SE trending "Air-Chad Trough" in which over 3600 m of sediments have been deposited. The crystalline basement complex outcrops in the eastern, south-eastern, south-western, and northern rims of the basin; its configuration beneath the sediments near the lake has the semblance of a horst and graben zone (Oteze and Fayose, 1988). The stratigraphy of the Chad Basin (Bornu sub-Basin) shows a depositional sequence from top to bottom which includes the younger Quaternary sediments, PlioPleistocene Chad Formation, Turonian-Maastrichtian Fika shale, the late Cretaceous Gongila formation and the Albian Bima Formation (Maduabuchi et al., 2006). The Bima sandstone is the major aquifer in the study area. Its thickness ranges from 300 to 2000 m and its depths are between 2700 and 4600 m (Obaje, 2009). A pioneer investigation carried out by Barber and Jones (1960) revealed that the Chad Formation reaches a thickness of at least 548 m at Maiduguri; in the central part of the basin, the thickness may reach 600 to 700 m and it is the major source of groundwater supply (Offodile, 1992).

Except for a belt of alluvial deposits around the edge of the basin, the formation is of lacustrine origin and consists of thick beds of clay intercalated with irregular beds of sand, silt, and sandy clay (Miller et al., 1968). Barber and Jones (1960) divided the Chad Formation into three water-bearing zones designated upper, middle, and lower aquifers (Miller et al., 1968; Odada et al., 2006; Adelana, 2006). The upper aquifer is Quaternary alluvial fans and deltaic sediments of Lake Margin origin (Akujieze et al., 2003; Maduabuchi et al., 2006). The reservoir in this system is composed of interbedded sands, clays, silts, and discontinuous sandy clay lenses which give aquifer characteristics ranging from unconfined, through semi-confined to confined types (Maduabuchi et al., 2006). It extends from the surface to an average depth of 60 m but locally to 180 m. The transmissivity of this aquifer system ranges from 0.6 to 8.3 m2 /day and the aquifer yield in Maiduguri is between 2.5 to 30 l/s (Akujieze et al., 2003). This aquifer is mainly used for domestic water supply (hand-dug wells and shallow wells), vegetable growing and livestock watering (Maduabuchi, 2006). In Maiduguri, the principal sources of contamination of groundwater are mainly anthropogenic activities such as Agricultural activities, municipal solid waste, and pit latrines.

METHODOLOGY

Stakeholder Analysis
This paper adopted the analytical multi-criteria methodology outlined in Buede (2013; Wu et al., 2023). A stakeholder analysis was carried out to identify the key stakeholders that ranked the different land use activities in the case study area. The stakeholders were engaged via semi-structured questionnaires and face-to-face interviews. The researcher interviewed the stakeholders in a one-on-one format in their various offices and with an exceptional few in their homes. This method is robust and transferable to different case studies. The procedure consists of five different but complementary steps:

I. Establishing the principal statement.
II. classifying the criteria to be used.
III. Identifying and assigning stakeholders to rank and rate the selected MCA criteria.
IV. weighing and Scoring of each criterion.
V. Adding the weights and scores for each criterion to derive aggregated benefits.

The above-mentioned steps adopted in this study are enumerated below.

Step 1- Establishing the Principal Statement
As stated earlier, the MCA analysis of this study shows that agricultural land, residential and forests are the major activities in the study area. The MCA analysis presented herein takes into consideration environmental attributes such as decision-making.

Step 2- Classifying the attributes to be used
The criteria identified in this study are classified under environmental criteria (Table 1); i.e., based on the negative impact of the different land-use activities (Figure 2).
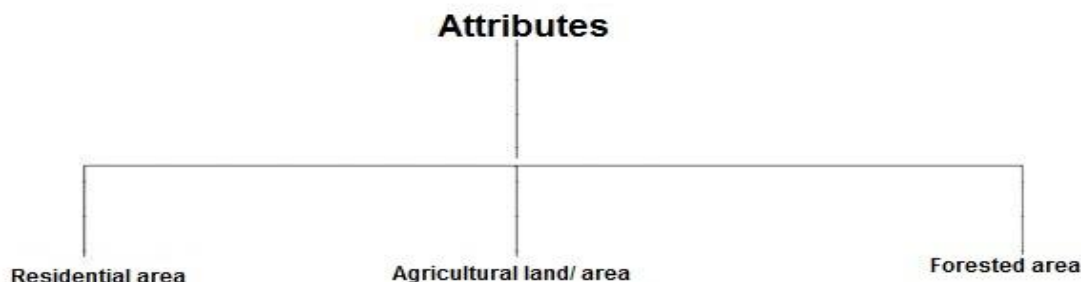

Figure 2 Attribute tree chart. Representation of the different land-use activities as the criterion (After Goodwin and Wright 2001)

Step 3- Identifying stakeholders and data collection.
The result of the MCA is profoundly dependent on input from experts and stakeholders as carried out in the stakeholder analysis. However, a limited number of strategic stakeholders were engaged in the study due to time constraints. The respondents are professionals, mostly senior staff members from water, health, and environment ministries. The respondents were asked to rank the different land-use activities based on their negative impact relative to the principal statement.

Principle Statement: *Anthropogenic activities have the potential of impacting underlying groundwater resources negatively.*

Table 1 Criteria attributes to decision making.

Criteria
1. Human activities from residential areas increase chloride concentration in groundwater.
2. Contaminated groundwater is a result of agricultural activities.
3. Forested areas are significant sources of anthropogenic contamination.

Step 4- Ranking and Rating
According to Caylor et al. (2021), to arrive at a preferred option with maximum aggregate benefits, respondents were required to rank and rate each criterion (Caylor et al., 2012). The ranking methodology involves assigning each criterion a rank that reflects its perceived degree of importance close to the decision being made by the respondent (CIFOR, 2008). The

essential criterion being number 5 and the weakly necessary standard being number 1, the rating scoring is like ranking, except that the rating involves assigning corresponding 'grades' between 0 and 100 to each ranked criterion (CIFOR, 2008 and Caylor et al., 2021) (Table 2).

Table 2 Ranking and Rating scores for criterion (After CIFOR, 2008)

Ranking	Rating/grades
Most important = 5	80-100
More important = 4	60-79
Moderately important = 3	40-59
Less important = 2	20-39
Weakly important = 1	0-19

Hence, respondents were required to rank the criterion in order of importance on a scale of 5 to 1 and assign grades from 0 to 100 to each ranked measure (CIFOR, 2008). According to stakeholders' responses, rankings and ratings of criteria are presented in Tables 4, 5. Table 6 summarises the appraisal of the score for the criteria. And Table 7 summarises the rationalised criteria scores.

Stage 5- Assigning normalized scores to criteria.
The distribution of major land use activities was outlined in Table 3. The percentage aggregate impact of the different land use activities is presented in Table 4.

GIS Data Generation
Geographic Information System classification data according to Xu and Zhang (2023). This method develops spectral signatures of known categories, such as urban and forest, and then the software assigns each pixel in the image to the cover type to which its signature is most comparable. Supervised classification is used for quantitative analyses and land use map development (Hamdy et al., 2022). The supervised classification method outlined by Rwanga et al. (2022) was also utilized to classify the different land use activities such as residential areas, agricultural areas and forested areas respectively (Table 3) . The GIS software assigns each pixel in the image to the cover type to which its signature is most comparable.

Results
Table 3 Distribution of the major land-use activities

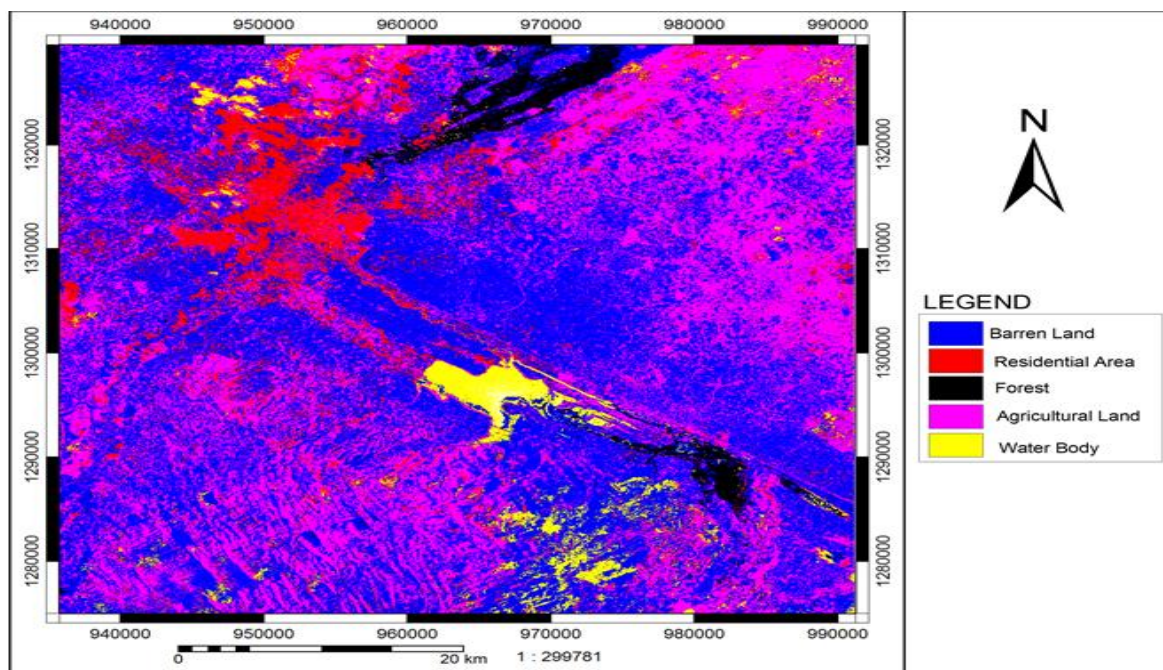| Land use	Percentage of the area covered
Residential area	9%
Agricultural area	44.7%
Forested area	2.18%

Figure 3 Spatial distribution of the different land-use activities in the study area

Table 4 Ranking and Ratings of criteria by stakeholders

	Stakeholder 1		Stakeholder 2		Stakeholder 3		Stakeholder 4	
Criteria	Ranking	Rating	Ranking	Rating	Ranking	Rating	Ranking	Rating
Agricultural land impact	4	70	3	50	5	95	4	75
Residential area impact	5	93	5	90	4	65	5	98
Forested area impact	2	31	3	45	3	50	2	30

Continuation of Table 4

	Stakeholder 5		Stakeholder 6		Stakeholder 7		Stakeholder 8		Sum of ranking	Sum of rating
Criteria	Ranking	Rating	Ranking	Rating	Ranking	Rating	Ranking	Rating		
Agricultural land impact	5	90	4	73	4	66	5	94	34	613
Residential area impact	5	95	4	75	5	85	4	79	37	680
Forested area impact	3	47	2	35	3	45	2	33	20	316

Table 5 Normalised criteria Rankings and Ratings

Criteria	Sum of Ranking	Sum of Rating	*Relative Ranking wt	**Relative Rating wt	***Cumulative Mean wt
Agricultural land impact	34	613	37	38	37
Residential area impact	37	680	41	42	41
Forested area impact	20	316	22	20	22
Cumulative	91	1609	100	100	100

*The relative Ranking weighting is the ratio of the sum of each criterion to the cumulative ranking × 100 (CIFOR, 2008)

**The relative Rating weighting is the ratio of the sum of each criterion to the cumulative Rating × 100 (CIFOR, 2008)

***The combined mean weighting is the average of the relative Ranking and Rating weighting (CIFOR, 2008)

Table 6 Appraising the score for the criterion.

	[a] Values	[b] Score	Sum of values
Agricultural land impact	9	1	9
Residential area impact	44.7	1	44.7
Forested area impact	2.18	1	2.18

Table 7 Rationalised criteria scores and derived aggregate impacts

Criteria	ACW	[b]S	[c](CW * S)
Agricultural land impact	37	1	37
Residential area impact	41	1	41
Forested area impact	22	1	22

Based on ranking and ratings of criteria (Table 4) by stakeholders, the sum of ranking for the residential area is 37, while agricultural land has a score of 34. Also, the forested area has a score of 20 as its sum of ranking. The sum of ratings for the three land-use activities is 680 for residential areas, 613 for agricultural land, and 316 for forested areas. The normalized criteria ranking and rating result (Table 5) for the three land-use activities have a cumulative mean of 41, 37 and 22 for residential area, agricultural land, and forested area individually.

Also, appraising score criterion results (Table 6) for residential land, agricultural land and forested area are 44.7, 9 and 2.18, respectively. Furthermore, the rationalized criteria scores and aggregate impact result (Table 7) show that residential area has a score of 41, while agricultural land has a score of 37 and forested area has a score of 22.

DISCUSSION
Different land use affects the quality of both surface and groundwater resources. The impact of land-use changes on water quality involves the association of land use and water quality indicators (Gebre et al., 2021). The vulnerability of groundwater due to the negative impact of above-ground land-use activities is directly linked to the hydraulic characteristics of an aquifer. (Foster, 2002; Huang et al., 2022). Also, the type of land use activity and the resultant pollutants it generates determines the severity of groundwater contamination.

GIS land cover data is required for policy-making and administrative purposes. With their spatial details, the data are also important for environmental protection and spatial planning in both developing and developed countries (Rwanga et al., 2022). Understanding the Impact of different land use changes is essential to planning urban dynamics in the management of land and anthropogenic activities and providing services in rapidly changing environments in developing countries. This agrees with the situation in Maiduguri (Yang and Lo, 2023).

Based on the criteria scores and weight, the MCA analysis presented in this study shows that residential areas and agricultural land received the most favourable ranking and rating. Thus, it is safe to assume that residential areas are the anthropogenic activity with the greatest negative effect on groundwater resources in Maiduguri. This agrees with the work of Wu et al. (2023). The second land use activity with the highest score is agricultural land, and the forested area has the most negligible impact on the underlying aquifers in Maiduguri. The World Bank (2020) outlines that urban centers in sub-Saharan Africa exert pressure on urban aquifers. Also, urban sanitation lies at the root of many development challenges, as poor sanitation impacts groundwater resources, and it directly affects public health and the environment (Droogers and Loon, 2007; Loon et al., 2007).

Additionally, agricultural land was ranked second to residential areas based on stakeholders' opinions. Dunn et al. (2014) established relationships between the impact of farmland and residential areas on groundwater in eastern Scotland; they identified positive chemical signatures in urban groundwater due to the impact of arable cropping and fertiliser application (Brentan et al., 2021). Many agricultural activities can lead to groundwater pollution. Fertilizers applied to crops on intensively cultivated lands and domestic gardens in residential areas may negatively impact groundwater resources (Chilton, 2000; Bakari, 2014b). Likewise, irrigation of cultivated lands often results in the build-up of salt in surface and groundwater. This salt build-up is largely the result of salt dissolution in weathered soils and leaching to the saturated groundwater zone (Foster et al., 2012; Graham and Polizzotto, 2013). Lastly, the effects of forested areas on groundwater contamination are insignificant in comparison to residential and agricultural land use activities. Similarly, Wilson (2014) and Huang et al (2021) observed that forested areas have a minimal net effect on underlying groundwater resources. Furthermore, Nainar et al. (2017) underlined some rainforest contributions to the preservation of water quality in Malaysia.

Therefore, the sum ranking for the residential area and agricultural land is akin to both land uses. In this respect, the World Bank (2020) report outlines that uncontrolled urbanisation and agricultural activity are the major anthropogenic activities with the greatest effect in this century, providing the foundation and momentum for unsustainable global change.

Therefore, the strategic stakeholders' continuous engagement will be vital for reversing the unsustainable land use management in the study area. Thus, the Borno State Government needs to implement policies that will protect groundwater from the impact of the different land use activities. Equally, through the Ministries of Environment and Water Resources, the State Government should implement policies that will ensure the shift towards sustainable Environmental Management; this has the potential of addressing key global Environmental challenges of the 21st century.

CONCLUSION
This study carried out an MCA of the different land-use activities and evaluated their impacts on groundwater based on stakeholder rankings. Strategic stakeholders were allowed to prioritise these activities based on the magnitude of their negative impact on groundwater. This MCA analysis presented in this study shows that residential areas are the land use with the highest effect. The second land use activity with the highest score is agricultural land, and forested areas have the least rating thereby making it land use with little negative effect on the shallow aquifer of the abovementioned area.

Thus, there is a need to continuously engage all the relevant stakeholders in addressing the negative impacts of above-ground anthropogenic activities, focusing on developing and implementing sustainable strategies. This will ensure the attainment of key goals and objectives related to groundwater quality management in Nigeria. Lastly, groundwater quality protection is vital in achieving socioeconomic prosperity and Improved access to water is key to the United Nations Agenda 2030.

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