

# Groundwater Recharge Zone Mapping Using GIS-based Analytical Hierarchy Process and Multi-Criteria Evaluation: Case Study of Greater Banjul Area

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**Abstract** Remote sensing (RS) and Geographic Information System (GIS) play a crucial role in understanding groundwater potential recharge in semi-arid areas. In this present study, groundwater recharge zone map is delineated for the shallow aquifer in the Greater Banjul Area (GBA) using GIS, RS and Multi-Criteria Evaluation (MCE) technique utilizing seven criteria (geology, land-use/cover, slope, drainage density, soil texture, groundwater fluctuation and aquifer transmissivity). Analytical Hierarchical Process (AHP) is used as MCE technique to normalize the weights of the various criterion. Each class of the different themes was assigned suitable score and normalized using a Fuzzy membership algorithm. Thematic layers were integrated using Weighted Linear Combination (WLC) in a GIS platform to generate groundwater recharge zone maps. The recharge map thus obtained was divided into four classes (poor, moderate, good, and very good) based on their influence to groundwater recharge. Results indicates that about 10.5 % of the total study area falls under 'poor' and 'moderate' zone and cover the estuarian portion of GBA, 40% of the total area falls under 'very good' zone which is a good indication for future artificial recharge planning and potential drilling of boreholes.

**Keywords:** groundwater recharge zone, multi-criteria evaluation, greater Banjul area

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## 1. Introduction

Groundwater is the largest available freshwater resource in the world, especially in semi-arid areas characterized by climate variability and change which has significant impact on water availability. This is more problematic in reverse estuary areas characterized by inflow marine waters towards Rivers and lowlands/floodplains of the river, making coastal aquifer vulnerable to marine/seawater intrusion. The western part of Gambia is facing this situation and water shortage due to increasing water demand for population need, industrial activities and irrigation particularly in coastal areas constitutes a big challenge. In the Greater Banjul Area (GBA), the future of shallow groundwater system (beneath the city) which constitutes the only source of potable water have become an important issue with respect to appropriate water resource planning with regard to climate change impact.

Earlier studies revealed that groundwater is successfully replenished through artificial recharge in various parts of the world [1,2]. The practice of artificial recharge through the construction of suitable structures increases the groundwater level for proper water resource management [3,4]. Artificial recharge of groundwater does not only maintain the underground water quality but also dilutes the pollutants and prevents saltwater intrusion [5].

Recently, many scientists have used Multi-Criteria Evaluation (MCE) techniques to delineate the artificial recharge zones for augmenting the groundwater potential of a region [6,7]. Many researchers made efforts to explore the suitable sites for artificial groundwater recharge by using integrated remote sensing and Geographical information system (GIS) analysis [8,9,10,11,12] and various geospatial parameters. Modern techniques like remote sensing and GIS provide diverse data source over large area and facilitate fast and reliable results comparing to conventional method [2]. Geographical information systems are capable of managing large amount of spatially related information, providing the ability to execute Weighted Linear

Combination (WLC) technique based on per pixel calculation method by integrating multiple thematic layers for site suitability mapping [13].

Thematic layers used for delineating groundwater potential recharge zones vary from one study to other, and their selection is quite random. The assignment of weights to different thematic layers and their classes are solely based on personal decisions. However, [7,14] have recently successfully used MCE technique taking into accounting the weights for groundwater potential mapping studies. Analytical Hierarchical Process (AHP) proposed by [15] is a widely used MCE technique for taking decision for resources mapping and their management [16] and has been accepted worldwide as a very efficient tool for dealing with complex decision-making problems.

The main objective of the present study is to delineate Groundwater Recharge Zones (GWRZ) in the GBA with integrated use of remote sensing, GIS and MCDM techniques.

## 2. Study Area

The study area referred to as the Greater Banjul Areas (GBA) is located at the Southwestern part of the Gambia between latitude 13° 00" - 13° 30" N and longitude 16° 50" and 17° 20" W (Figure 1).

It covers two municipalities: Banjul City Council (BCC) and the Kanifing Municipal Council (KMC), and four administrative districts of Kombo North, Kombo West, Kombo Central and Kombo East. It is limited to the north by the River Gambia, the East by Bullock Bolong, the south by Cassamance, and the south-west by the Atlantic Ocean. It covers an area of 1001.7 km<sup>2</sup>, which is about 9% of the total land area of the country.

GBA has a Sudano-Sahelian climate type, which is characterized by 2 distinct seasons: a short rainy season from June to October (about 1200 mm/year) and a long dry season extending from November to May. The highest rainfall is recorded in August with monthly mean of about 366 mm. More than 70% of the annual rainfall occur from July to September. Annual average temperatures in the study area is around 27°C. In the dry season, mean daytime temperatures could rise as high as 36°C (between March and June). The monthly mean relative humidity peaks during the wet reason with values as high as 90%. Evapotranspiration is lowest during the rainy season (August-September) and reaches its maximum during the dry season when temperatures are high. Evapotranspiration is estimated at 1412 mm per year with a maximum of about 190 mm in May.

The study area is densely populated with 926,120 inhabitants which accounts for about 49% of the country's total population (National census, 2013). A great number of the economically active population in the study area particularly the eastern part is involved in agricultural activities, which include cultivation of cash crops (groundnuts, mangoes and cashew nuts); food crops (cassava, potatoes, and rice) and horticulture (vegetable gardening). Outside the rainy season, all agricultural and domestic water needs are mainly supplied from the Shallow Sandy Continental Terminal (CT) aquifer exploited through dug wells which varies from a depth of 5 - 25 m and boreholes drilled at a depth of 35-100 m.

Other major economic activities in which communities along the coastal line and tributaries of the study area engaged themselves in are fishing and oysters harvesting. However, most of the arable agricultural lands are converted to settlements due to the increasing population and this is partly due to immigration from rural areas to the GBA for job seeking.

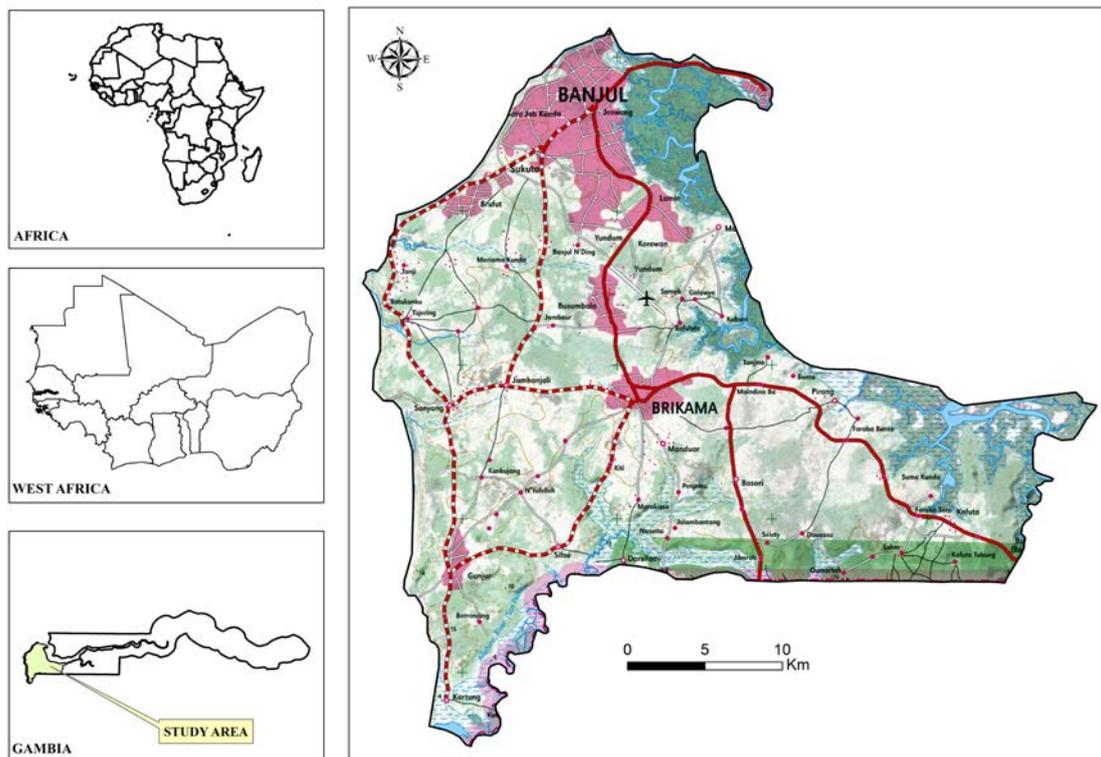


Figure 1. Study area

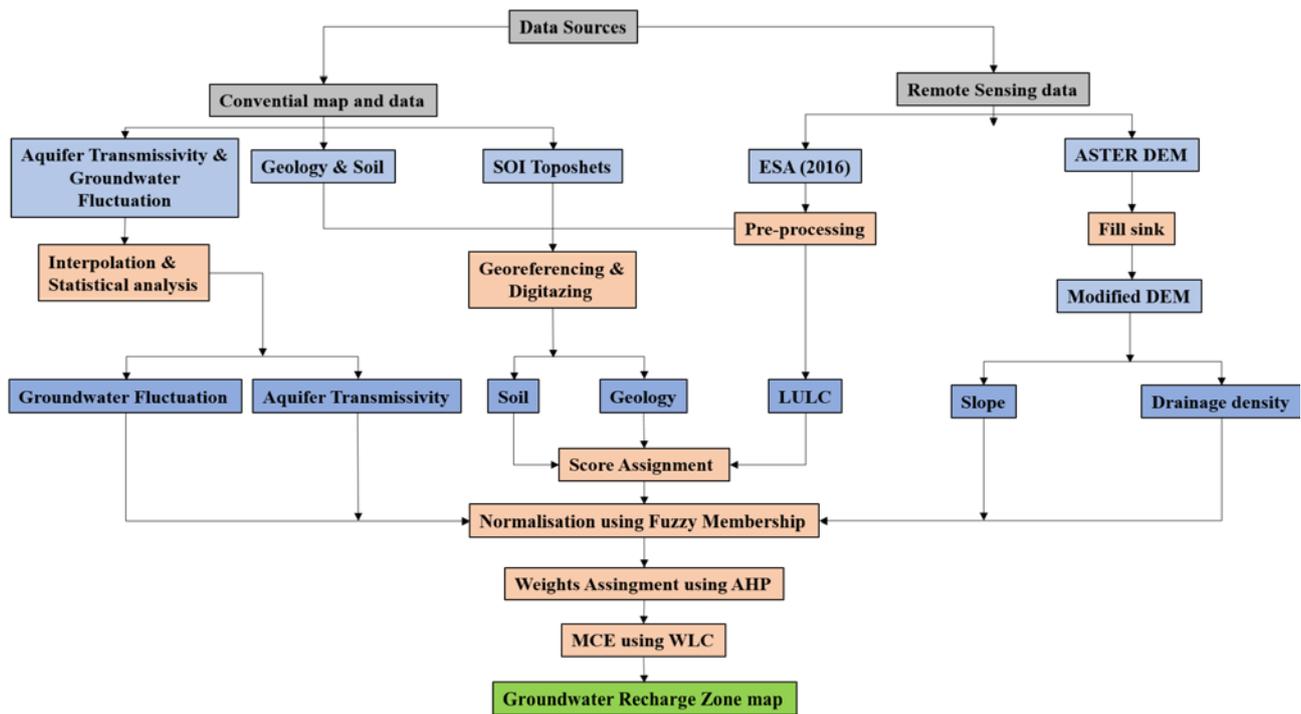


Figure 2. Flow chart of methodology

### 3. Methodology

#### 3.1. Data Collection and Processing

In the present study, integrated GIS and MCE were used for the delineation of groundwater recharge zones (GWRZ) by considering a multiparametric data set comprising seven criteria known as factors. These include geology, land use/land cover, soil texture, aquifer transmissivity, drainage density, slope and groundwater fluctuation. The flow chart of the methodology used in this study is outlined in Figure 2.

All data sets used to prepare the thematic layers are derived from various data sources such as remote sensing data, topographical maps, district resource map, field surveys and other collateral data. All data sources have been converted and geographically referenced to UTM-WGS 84 projection and coordinate system by applying the ground control points (GCPs) obtained from GPS field survey.

The geological setting and the soil characteristics were obtained from the Department of Geology published in 1988 and the National Environment Agency of the Gambia, respectively. Furthermore, the aquifer transmissivity layer was obtained from pumping test data of the borehole reports obtained from the Water Division of NAWEC, Serekunda and a drilling company (Kawsu Conta). Groundwater fluctuation data were calculated using groundwater depth level collected during this present study. This fluctuation rate is the seasonal variation of water depth level measured at 118 wells during the pre-monsoon and post-monsoon of 2018. A kriging interpolation was then used in order to transform discrete data into gridded layer and to demarcate the variation of the aquifer transmissivity and the groundwater fluctuation. The thematic layer of Land-use/cover was obtained from

the European Space Agency S2 prototype which cover the entire GBA with a spatial resolution of 20m. For the drainage density layer, the drainage network and watersheds were extracted using an ASTER DEM (20m) and the topographic map of the study area. The spatial characteristics of drainage density are then computed from the drainage network using 'line density tool' of spatial analyst module in ArcGIS 10.7 software. The slope map was obtained using the same ASTER DEM data and the Slope module in Terrset software.

#### 3.2. Criterion Score

After the compilation of the thematic layer, each class of the individual such as geology, land-use/cover and soil texture were assigned suitable score according to their relative importance in groundwater recharge. This is to transform the qualitative factors into quantitative continuous scale. The transformation was achieved based on the categories such as: poor (weight = 1-2); moderate (weight = 2-4); good (weight = 4-6); very good (weight = 6-8); and excellent (weight = 8-9). However, because of the different scales upon which criteria are measured, it is necessary that factors be normalized before combination, such that all factors maps are positively correlated with suitability. Therefore, in this study, all factors were assumed to be fuzzy sets [17] and then were normalized using the Fuzzy module of TerrSet software. The fuzzy membership function, shape and type of each layer were specified and control point values were based on minimum and maximum data values. The result is a continuous scale ranging from 0.0 to 1.0.

#### 3.3. Criterion Weights Assignment

A wide variety of techniques exist for the development of weights. However, breaking down the information into

simple pairwise comparisons in which only two criteria need to be considered at a time can greatly facilitate the weighting process, and will likely produce a more robust set of criteria weights. This decision-making process known as the Analytical Hierarchy Process (AHP) developed by [15] incorporates the evaluations of all decision-makers into a final decision, without having to elicit their utility functions on subjective and objective criteria, by pairwise comparisons of the alternatives. Moreover, a pairwise comparison method has the added advantages of providing an organized structure for group discussions, where group members can use their experience, values, and knowledge to breakdown a problem into a hierarchy and then solve by AHP steps. It also incorporates systematic checks on the consistency of judgments known as consistence ratio (CR) developed by [15] which indicates the probability that the matrix ratings were randomly generated.

In this present study, weighting assignment to different criteria is based on previous literature and weights suggested by various experts after discussion, subsequently normalized on the basis of Saaty’s scale. Geology was taken as the principal factors for delineation of potential GWRZ. Consideration of geology as principal factors was based on the infiltration of water which in turns depends on facies unit, thickness of formation, grain size, type and degree of cementation, and the extent of the weathering. The other factors such as land use/cover, slope, drainage, aquifer properties (transmissivity and groundwater fluctuation), and soil were the factors incorporated in characteristic expressions of geological units as evidenced by [14].

The following steps was carried out to apply the AHP procedure and compute the CR [7]:

1. The normalized pair wise comparison matrix A is built as:

$$A = \begin{bmatrix} a_{11}' & a_{12}' & \dots & a_{n1}' \\ a_{21}' & a_{22}' & \dots & a_{n2}' \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1}' & a_{n2}' & \dots & a_{nn}' \end{bmatrix}, \tag{1}$$

$$a_{ij}' = \frac{a_{ij}}{\sum_1^n a_{ij}} \text{ for } i, j = 1, 2, \dots, n$$

The values assigned to  $a_{ij}$  according to Saaty scale which is provided on a 9-continuous scale is given in Table 1.

**Table 1. Saaty’s scale of preferences in the pair-wise comparison process [15]**

1/9	1/7	1/5	1/3	1	3	5	7	9
extremely less important	very strongly less important	strongly less important	moderately less important	equally	Moderately more important	strongly more important	very strongly more important	extremely more important
less important					more important			

2. The eigenvalue and the eigenvector are calculated as:

$$W = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \text{ and } w_i = \frac{\sum_1^n a_{ij}'}{n}$$

$$\text{for } i = 1, 2, \dots, n \ \& \ W' = AW = \begin{bmatrix} w_1' \\ w_2' \\ \vdots \\ w_3' \end{bmatrix} \tag{2}$$

$$\& \lambda_{\max} = \frac{1}{n} \left( \frac{w_1'}{w_1} + \frac{w_2'}{w_2} + \dots + \frac{w_n'}{w_n} \right)$$

Where,

W: Eigenvector;

$W_i$ : Eigenvalue of criterion;

$\lambda_{\max}$ : Average eigenvalue of the pair wise comparison matrix.

3. Consistency index (CI) and consistency ratio (CR) proposed by [15] to verify the consistency of the comparison matrix are defined as follows:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{3}$$

$$CR = \frac{CI}{RI} \tag{4}$$

Where n is the number of themes or classes and RI the Ratio Index. This latter represents the consistency index of a randomly generated pairwise comparison matrix. The CR is acceptable if  $CR \leq 0.1$ . Otherwise, the re-evaluation of the comparison matrix is solicited to avoid inconsistency.

### 3.4. Delineation of Potential Groundwater Zone

To demarcate the potential GWRZ, the weighted linear combination (WLC) aggregation method as proposed by [10] was used. This method multiplies each standardized factor map (i.e., each raster cell within each map) by its factor weight and then sums the results. Since the set of factor weights for an evaluation must sum to one, the resulting suitability map will have the same range of values as the standardized factor maps that were used. The WLC were computed using the MCE module of Terrset software, expressed as follows:

$$WLC = \sum_{i=1}^{i=n} (w_i \times x_i) \tag{5}$$

Where WLC refers to weighed index value (raster map of the suitability rate of GWP);  $w_i$  the weight of factors i;  $x_i$  the criterion score of factors i

## 4. Results and Discussion

### 4.1. Geology

The study area is covered by the Tertiary sequence of Miocene-Pliocene formations known as the Continental Terminal (CT) overlain by the Quaternary sequence (Holocene and Pleistocene). The CT formations cover the whole country but are mostly found in the Eastern and Central part of Gambia and they composed of low hilly platforms and cliffs along the banks of the tributaries of River Gambia. It is composed of brown ferruginous quartz sandstone & sand-bearing ferruginous rock with ferruginous kaolinitic quartz greywacke. The lowlands and river floodplains are made of the Quaternary formations. These comprise the Pleistocene formation of earth-yellow clayey fine-grained sandy clay distributed on terraces of the two sides of the River Gambia and its tributaries and the red sub-sandy, sandy mild clay and gravelly mild clay formation distributed throughout the study area. The Holocene marine fluvial deposits are found on the estuary of the River Gambia and its tributaries. They comprised of medium-fine quartz sand, locally ilmenite-bearing quartz sand; and grey symmict sand, silt, clay and salt, containing cockle shells. The spatial distribution of the geological facies and their suitable score to groundwater recharge by fuzzy membership is presented in the Figure 4. The ferruginous quartz sandstone formation has been given higher preference because of their high porosity and availability of water content. In contrast, clayey silts formations have lower suitability score.

### 4.2. Land Use/Land Cover

The Climate Change Initiative (CCI) S2 prototype land-use/cover of European Space Agency [18] with its high resolution of 20m was used in this study. The LULC map is classified into 7 classes (Figure 4), as Tree cover (40.8%), Shrubs and grassland (11.0%), Cropland (30.5%), Wetlands (1.7%), Open water (3.2), Bare area (0.3) and Urban area (12.4). More than 80% of the total area is covered by vegetation (Tree, shrubs and grassland and crops). It is known that LULC affects the surface runoff, evapotranspiration and groundwater recharge. Water body, cropland and wetlands are excellent groundwater recharge hotspots, while built up area and tree cover or forest are considered to be less significant because of high runoff and evapotranspiration respectively. Therefore, highest weightage is given to water body, wetland and cropland, and lowest for the urban area and Tree cover as shown in Figure 5b.

### 4.3. Slope

The slope of the study area generated from the ASTER DEM varies from 0.0 to 22.7 %. However, most of the area in GBA lies between 0 to 2% (Figure 5a). Lowlands are able to retain more precipitation and facilitate recharge compared to elevated areas with higher slopes having high runoff and low infiltration rates. On this basis, a decreasing membership function shape were used to fuzzy the slope, in order to give the highest score to the lowest slope as shown in Figure 6b.

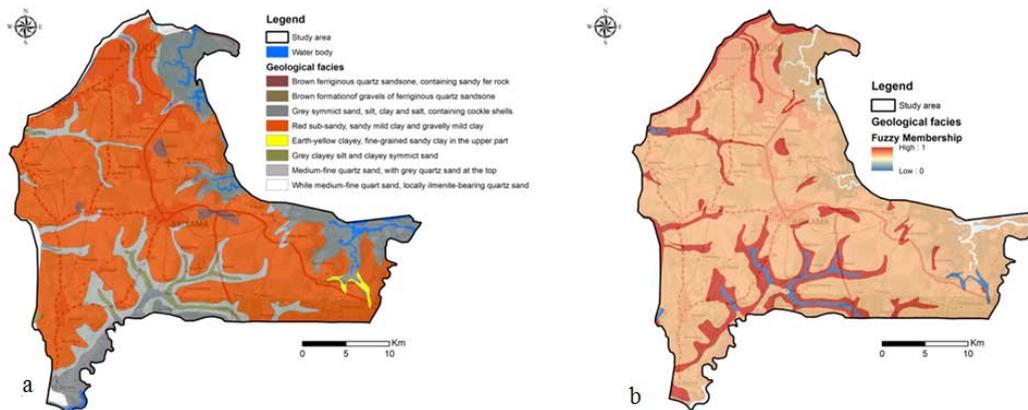


Figure 3. Geology [a: thematic layer, b: Fuzzy Normalization]

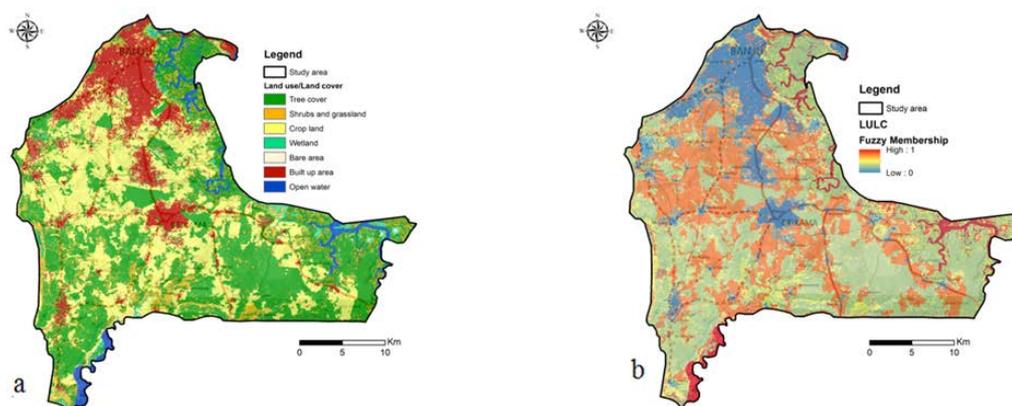


Figure 4. LULC [a: thematic layer, b: Fuzzy Normalization]

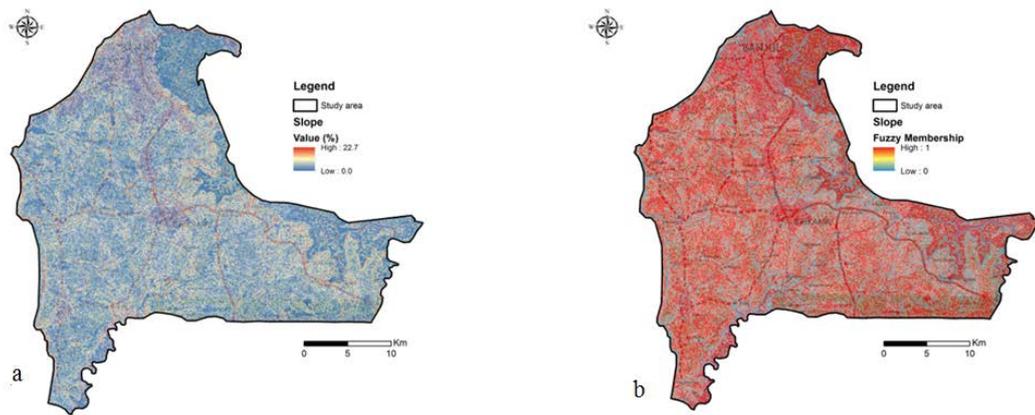


Figure 5. Slope [a: thematic layer, b: Fuzzy Normalization]

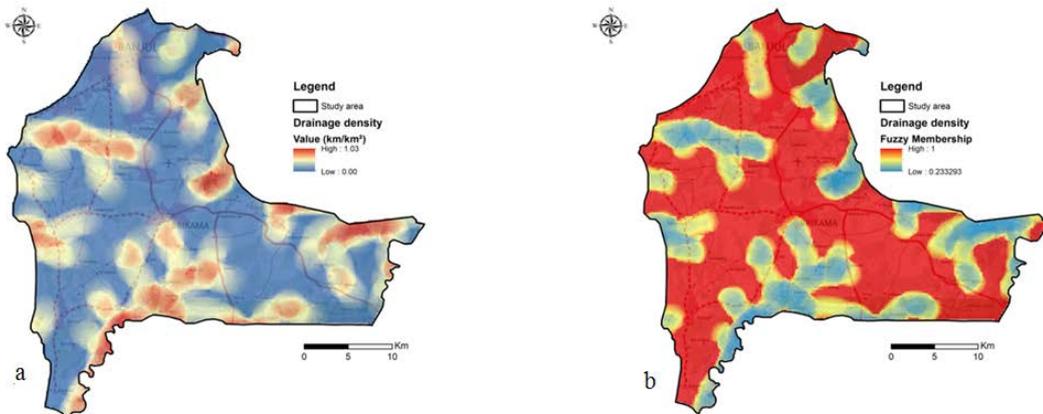


Figure 6. Drainage density [a: thematic layer, b: Fuzzy Normalization]

#### 4.4. Drainage

Drainage density, expressed in terms of stream length per unit area ( $\text{km}/\text{km}^2$ ), is an expression to indicate the closeness of spacing of stream. It is considered to be an inverse function of permeability and thus indirectly indicates the suitability of groundwater recharge in an area. The drainage density layer of the study area is prepared using line density tool in ArcGIS software, and were fuzzy using the decreasing membership function shape because high drainage density is expected to generate more runoff and thus less infiltration (Figure 7).

#### 4.5. Groundwater Fluctuation

Depth to water table measured during pre-monsoon and post-monsoon 2018 has been used to calculate the seasonal groundwater fluctuation which is an important indicator for groundwater recharge. The layer was prepared by kriging interpolation on a set of 118 water points (Figure 7a). The higher fluctuation values (2m) are observed in the northern part at Banjul and in the West and South at Sanyang and Basori localities. In the central and south-western as well as south-eastern part of the study area, the fluctuation rate is low and reaches negative values (1.7m). These areas are considered to be the discharge site of the study area due to high evapotranspiration and/or high abstraction rate. On this basis, a linear fuzzy membership function shape was applied for layer weightage as shown in Figure 7b.

#### 4.6. Transmissivity

The aquifer transmissivity is defined as the groundwater discharge through unit width of aquifer for the fully saturated depth under a unit hydraulic gradient. Its layer was prepared from pumping test data applying a kriging interpolation. The values vary from 16.4 to 4178.8  $\text{m}^2/\text{day}$  in the study area. The central and south-eastern parts of the study area have high transmissivity values whereas the northern part falls under the lowest transmissivity zone. As the suitability of groundwater recharge is correlated to the transmissivity value, linear fuzzy membership function shape was applied for layer weightage as shown in Figure 9b.

#### 4.6. Soil

The soil texture of the study area is classified into 5 classes according to CPCS (1976) as Coarse sand represented by coastal dune portions in the north-East and South-West, Ferritic sand distributed throughout the study area (70%), loamy and loamy sand in the stream floodplains, and mudflats throughout the estuarine portions of the study area (Figure 9a). Soil layer has been assigned weights on the basis of infiltration rate. Coarse sand has high infiltration rate, while mudflats (clayey soil) has lower infiltration rates, hence it was given the lowest weights. Then the linear fuzzy shape is applied to normalize the weightage as shown in Figure 9b.

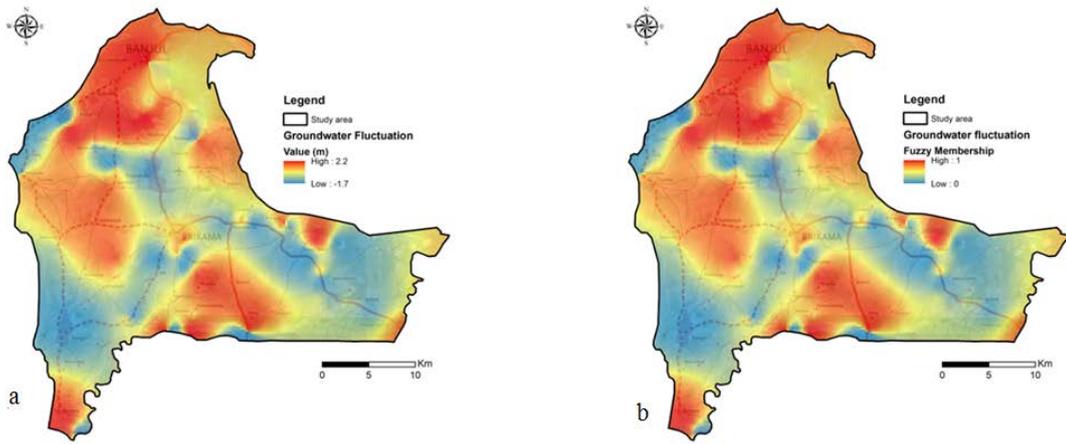


Figure 7. Groundwater fluctuation [a: thematic layer, b: Fuzzy Normalization]

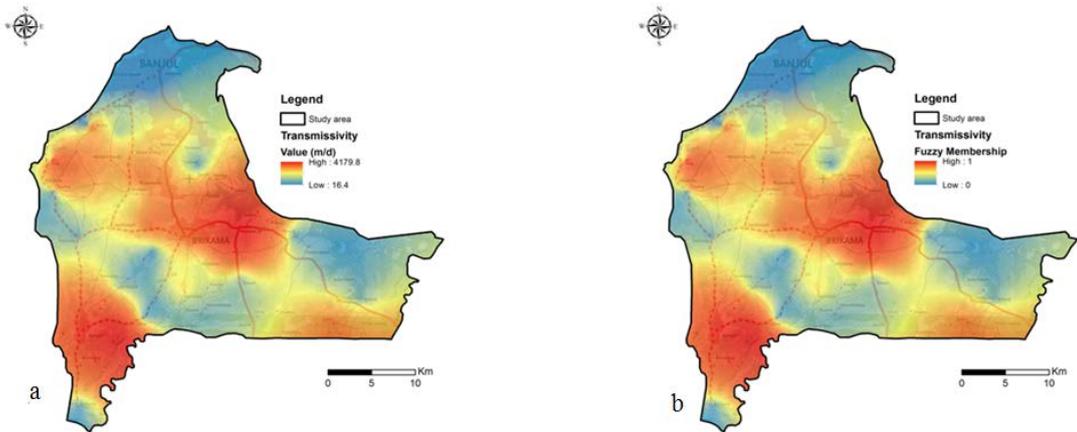


Figure 8. Aquifer transmissivity [a: thematic layer, b: Fuzzy Normalization]

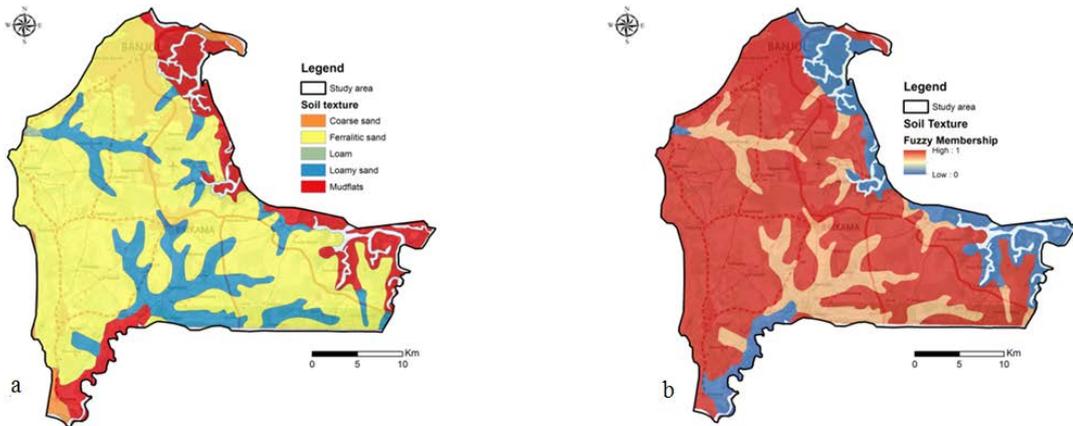


Figure 9. Soil [a: thematic layer, b: Fuzzy Normalization]

Table 2. Pairwise comparison matrix for criterion weightage by AHP

Criterion	GG	LULC	Slope	GWF	DD	AT	Soil	Weightage
Geology	1	3	3	5	5	7	7	<b>0.372</b>
LULC	1/3	1	4	4	5	5	7	<b>0.24</b>
Slope	1/3	1/3	1	3	4	5	7	<b>0.169</b>
Groundwater Fluctuation	1/5	1/3	1/3	1	1	3	5	<b>0.084</b>
Drainage Density	1/5	1/5	1/4	1	1	3	3	<b>0.051</b>
Aquifer Transmissivity	1/7	1/5	1/5	1/3	3	1	3	<b>0.059</b>
Soil	1/7	1/7	1/7	1/5	1/3	1/3	1	<b>0.025</b>

#### 4.7. Delineation of Groundwater Recharge Zone

The GWRZ of the study area were obtained by WLC of Geology, LULC, slope, groundwater fluctuation, drainage density, aquifer transmissivity and soil layer using the MCE module of Terrset software. AHP have been used to calculate suitable weights of the 7 criterions using a pairwise comparison matrix illustrated in Table 2. The consistency ratio of the matrix is 0.09, therefore the matrix was not randomly generated and is acceptable.

The GWRZ map (Figure 10) shows that the least suitable zone is located in the estuarine portion of the study area, while the suitable recharge falls in some parts of center, the Nord-west and south-east regions due to the distribution of quartz sandstone and fine quartz sand, crop land, high fluctuation and transmissivity values with high infiltration capacity. This indicates that geology, land use/land cover, aquifer transmissivity, groundwater fluctuation and soil texture play a vital role in groundwater recharge. Moreover, drainage density and slope are less favourable to the infiltration capacity of the groundwater system as evidenced with their occurrence in low suitable zones. Only 0.5% of the total study area falls under poor suitable zone (index < 0.25), 10 % falls under moderate suitable zone (index= 0.25-0.50), 49.5% falls under good suitable zone (index= 0.50-0.75) and 40% under very good (index= 0.75-1). Therefore, the study area has a great potential of infiltration. Finally, the cumulative effect of multi-influenced factors weighted by WLC through GIS modelling revealed the mapping of the GWRZ in the Great Banjul Area. It thus clearly indicates that, the results are consistent with the results based upon the seven factors, which influence the groundwater recharge.

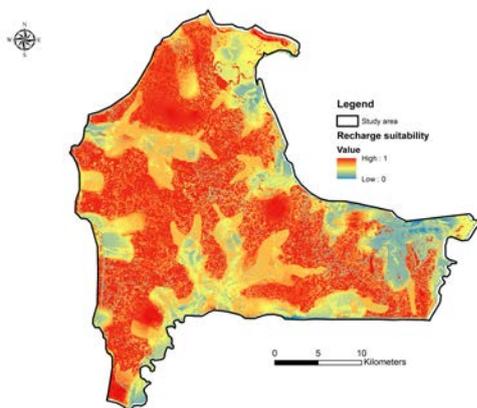


Figure 10. Groundwater potential zone map

### 5. Conclusion

In this study, GWPZ map of the Greater Banjul Area are delineating using GIS and MCDM techniques. It was found that the combination of the 7 factors is helpful to understand the behaviour of groundwater in the study area. The delineated map was classified into four zone, viz., 'poor', 'moderate', 'good', 'very good'. Results indicates that about 10.5 % of the total study area falls under 'poor'

and 'moderate' zone which indicates the least groundwater recharge occurrence. These areas are found in the estuarine portion of the study area, and is as a result of geological formation and soil texture composed of more clayey facies and high drainage density. 40% of the total area falls under 'very good' zone which is a good indication for future artificial recharge planning and potential drilling of boreholes. This method can be widely applied as a valuable tool for solving groundwater problems of semi-arid area with inherent limitations of data scarcity and multi-criteria evaluations.

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