Assessment of Groundwater Potential Zones Using Remote Sensing, Geographic Information System and Multi-Influencing Factor Techniques: A Case Study of Juba City

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Abstract—This study focused on the assessment of groundwater potential zones of Juba city using remote sensing, GIS and multi influencing factor (MIF) techniques. It is a city that mainly depends on the White Nile for water which is supplied by water tankers for drinking and other domestic use, however, the areas far from the Nile face problem of water since the price of the water supplied by water tankers depend on the distance from the Nile hence there is need to assess groundwater potentiality to address the problem. To achieve this objective, thematic layers for the study area such as rainfall, slope, land cover and land use, soil type, drainage density, digital elevation model, geology, geomorphology were generated from various data sources and later transformed into raster using ArcGIS. Regarding the weights and ranks assignment to these parameters, the MIF technique was used, whereby the weight assigned to each parameter was computed statistically to avoid bias and to generate the groundwater potential zones correctly. The generated groundwater potential zones map consists of four classes, in which 0.6% (1km^2) of the area falls under very poor groundwater potential zone, 41% (69km^2) falls under poor groundwater potential zone, 52.4 % (88km^2) falls under good groundwater potential zone and 6.0%(10km^2) falls under very good groundwater potential zone. The model was validated by the superimposition of 7 Failed and 125 operating borehole locations on the generated map to check whether the failed and operating borehole locations fall in poor and good groundwater potential zones respectively, it was found that 85.7% (6 boreholes) of the failed borehole locations fall in poor groundwater potential zone and 88.8% (111 boreholes) fall in good groundwater potential zone which shows the robustness of the method and usefulness of the study. The current study would fill the gap and provide a necessary database for future project planning to ensure sustainable utilization of groundwater resources by planners, policymakers and local authorities

Index Terms— Remote Sensing, Geographic Information System(GIS), Multi-Influencing Factor(MIF) Technique, Groundwater potential Zones, Juba City

1. INTRODUCTION

A very good number of the populations in the developing countries do not have access to acceptable water supplies. The arranging procedure that is used for creating water ventures is normally lacking and results in failed water projects[1], Africa at large and Juba city, in particular, are not exceptional. Juba city mainly depends on the White Nile for water that is supplied by water tankers for drinking and other domestic use, however, due to the expansion of the residential areas as well as an increase in population, there is a rise in water issues in the city, therefore, it is worth mentioning that the price of water supplied by water tankers depends on the distance from the White Nile hence the farther the area, the higher the price of the water, areas far from the White Nile face severe issues of water leaving the residents with no options rather than depending on the available hand pump boreholes, however, almost half of them are not functioning either due to mechanical problems or drilled in poor groundwater potential zones[2]. This calls for a robust and cheap method of assessing groundwater potential zones to address those problems, in which remote sensing and geographic information system prove to be the best answer due to their numerous advantages such as availability of spatial, spectral and temporal data covering large and inaccessible areas and also good for study areas that have limited ground data compared to other methods which are costly, time-consuming and require skilled manpower.

The term 'groundwater potential' can be characterized as the chance of groundwater event occurring in a region. In South Sudan, there is little information about the distribution of groundwater or the rates of water extraction and the impacts of human activities such as; potential over obstruction and pollution of groundwater[3], in which Juba city, in particular, is not exceptional. When using remote sensing and GIS for assessing or delineating groundwater potential zones, there is always a debate on which groundwater influencing factors to consider and how many to consider, for example, soil, slope, rainfall, lithology, drainage, lineaments, land use /land cover[5], geomorphology, lithology, drainage density, slope and lineament[6], geology, rainfall, geomorphology, soil, drainage density, lineament density, land use, slope and drainage proximity[7], rainfall, lithology, drainage density, lineament density, and slope[8], geology, soil, land use, slope, lineament and drainage[9], altitude, slope aspect, slope angle, curvature, distance from rivers, fault distance, fault density, lithology and Land use / land cover[10], geology, geomorphology, drainage, drainage density, lineament, lineament density, slope, soil type, soil texture, soil depth and land use/ land cover[11], lithology, soil cover, land use, normalized difference vegetation index (NDVI), elevation, slope angle, aspect, planform curvature, profile curvature, curvature, stream power index (SPI), stream transport index (STI), topographic wetness index (TWI), mean annual rainfall, distance from river network and distance from the road network[12], as shown above by many researchers, one can conclude that the groundwater influencing factors and the number to consider when assessing groundwater potential zones using remote sensing and GIS are area specific and oriented. However, based on the nature of the terrain of the area, the selection of the influencing factors can be based on whether the area is a mountainous or alluvial plain/ depositional basin. For mountainous areas, rainfall, geology, drainage pattern, geological structures, drainage density, land use/ land cover (LULC), geomorphology, slope, lineaments, soil, topographic wetness index (TWI) as the factors responsible for influencing the occurrence of groundwater while for the alluvial plain/ depositional basins, land cover/ land use, soil map, water table, specific yield, distribution of aquifer materials, distribution of ponds and water bodies and different aquifer characteristics in which thickness of aquifer material, well yield, hydraulic conductivity, water table as being the decisive parameters and also in case of scarcity of all required data, yield and aquifer thickness can be used[13]. The debate does not end there, but also another key point of argument is the method for calculating the weights for the thematic layers, there are several methods used for the calculation of the weights, each having its advantages and disadvantages, for example, multi- influencing factor (MIF) in this method, interrelationships between

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groundwater influencing factors play an important role in delineating the groundwater potential zone. Each relationship is weighted according to its influencing strength i.e. the more influencing the factor is, the higher the assigned weight [5], other methods such as analytic hierarchy process (AHP) [14], The frequency ratio model (FR), the DRASTIC method [15][16], the weights-of-evidence method [17][10]. Therefore, one can conclude that the choice of a method for calculation of weights depends on the interest of the researcher. In this study, the weights were assigned using MIF method because of its simplicity in application.

2. Materials and methods

2.1 Study Area

The study area covers Juba city the capital city of South Sudan that became a capital city after the signing of the comprehensive peace agreement between South Sudan and Sudan in 2009. It lies on latitude 4° 51' 50.68'' and 4° 53' 00.33'' N, Longitude 31° 28' 15.96'' and 31° 37' 51.97'' E, approximately covering an area of 168 km^2. Administratively, it covers the main payams (a subdivision of a city) of Juba county viz. Munuki Payam, Kator Payam, Juba Payam and some Neighbouring payams. The city is situated on the western bank of the White Nile in an alluvial plain that slopes in the South West to North-East towards the White Nile (Barhr-el-Jebel) in the East. According to the 5th Sudan population and housing census that took place in April/May 2008 stated that the population of juba county was 372,413, which later was rejected by the government of South Sudan, since then, there hasn't been population census, most of the population figures are being estimated by non-governmental organizations[2] The study area is situated in beautiful landforms, from the high ground such as mountain (Jebel) Kujur in South-West part of the study area; ranging from an altitude of 643 - 733 metres above mean sea level to plains in the North East along banks of White Nile (Bahr-al-Jebel) ranging from an altitude of 451 – 481 metres above mean sea level. It is predominantly dominated by sandy loam soil and loam soil and covered by quaternary, Precambrian geology [18] [19] and the drainage pattern is dendritic with streams such as Khor Rumula, Khor William etc. flow in different directions concerning their origin and finally draining into the White Nile. Most of these streams are seasonal streams where water flow can be seen in the rainy season and during the dry season they dry up. Its climate is classified as tropical climate with two seasons; Rainy season and Dry season. The rainy season starts from April to October with an average annual rainfall of 941mm and the dry season starts from November with little amount of rainfall and intensifies from December to March. The average annual temperature of Juba is 27.5° c with the lowest precipitation in January amounting to an average of 4mm and in August, the precipitation reaches its peak with an average of 147 mm. March is the hottest month of the year with an average temperature of 29.9° c and August is the coldest month of the year with an average temperature of 25.5° c. Fig1shows locale of the study area

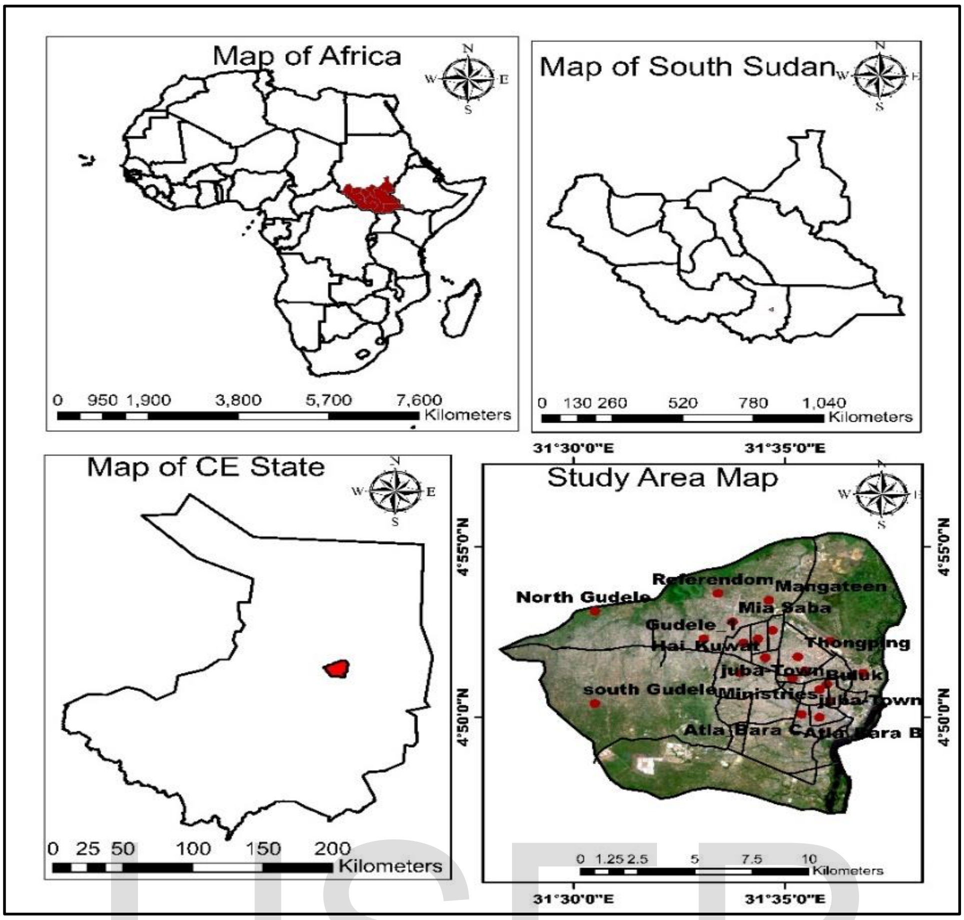

Fig1

2.2 Methodology

The methodology of the study is as, in figure3.2A, the base map for the study area was digitized from Google Earth and all the other thematic maps were subset according to the base map boundary. The input data consists of two categories viz., remote sensing data and conventional maps. From the remote sensing data, a digital elevation model (SRTM DEM) of a 30-metre resolution was downloaded from USGS whereby slope, elevation, geomorphology maps were generated from it, drainage network was digitized from Google Earth in which drainage density was prepared from it in ArcGIS 10.2. land use/ land cover was generated from Landsat-8 (OLI/TIR C1 level1 data dated 5th/8/2018 path 172 and row 57) downloaded from USGS site. The conventional maps were downloaded from reliable sites. Finally, soil type, rainfall, lithology and geology were prepared in ArcGIS. All the thematic maps were then projected to WGS-1984 UTM zone 36N and later converted to raster and weights were assigned using MIF technique for the generation of groundwater potential map. The final groundwater potential map was generated in ArcGIS 10.2 using weighted overlay analysis (WOA) function in spatial analyst tool in ArcGIS 10.2. Failed and operating borehole locations in the study area were acquired and superimposition on the generated groundwater potential zones map was done. The general schematic methodology flow chart is as shown in fig2.2A. To generate the weights, MIF method was used. In this method, interrelationships between groundwater influencing factors play an important role in delineating the groundwater potential zone. Each relationship is weighted according to its influencing strength i.e. the more influencing the factor is, the higher the assigned weight. A factor with a higher weight value shows a larger impact and a factor with a lower weight shows a smaller impact on the groundwater potential zones. The impacts/effects can be divided into two i.e. major impact and minor impact. Therefore, the major impact is assigned a weightage of 1.0 and a minor impact is assigned a weightage of 0.5. The representative weight of a factor of the potential zone will be the sum of all weights from each factor. Integration of these components with their weights is calculated through a weighted overlay analysis in ArcGIS. The cumulative weight of both major and minor effects are then considered for calculation of the relative rates and the rates are further used for calculating the score of each influencing factor. The proposed score for each influencing factor is calculated by using the formula below;

$$\left[\frac{(M+N)}{\sum(M+N)}\right] \times 100 \qquad \text{Equation (1)}$$

Where: **M**=major effect **N**= minor effect.

Fig2.2B shows multi-influencing factor method flow chart.

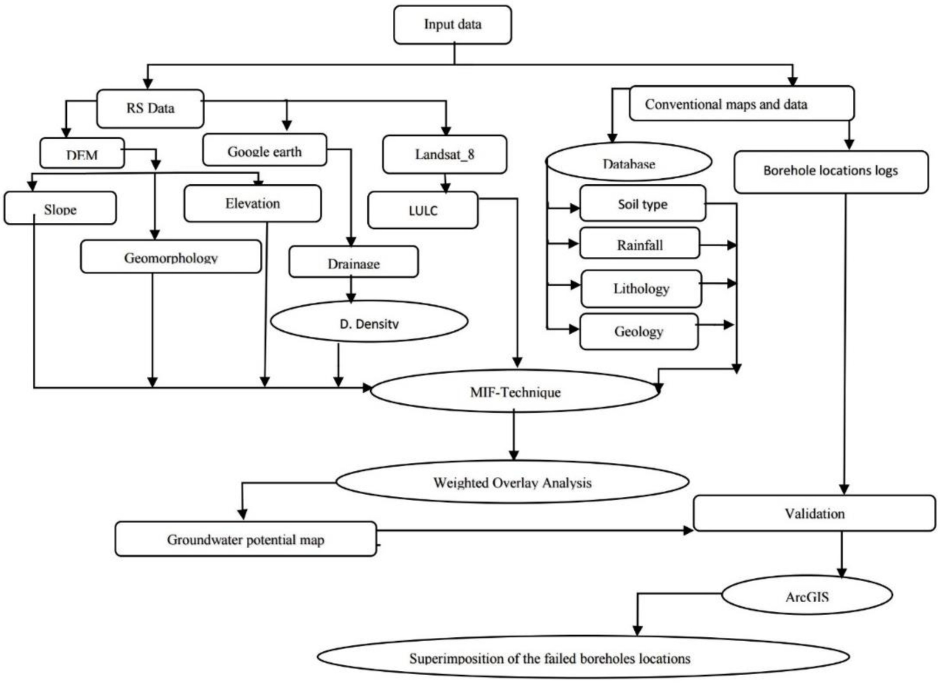

Fig2A

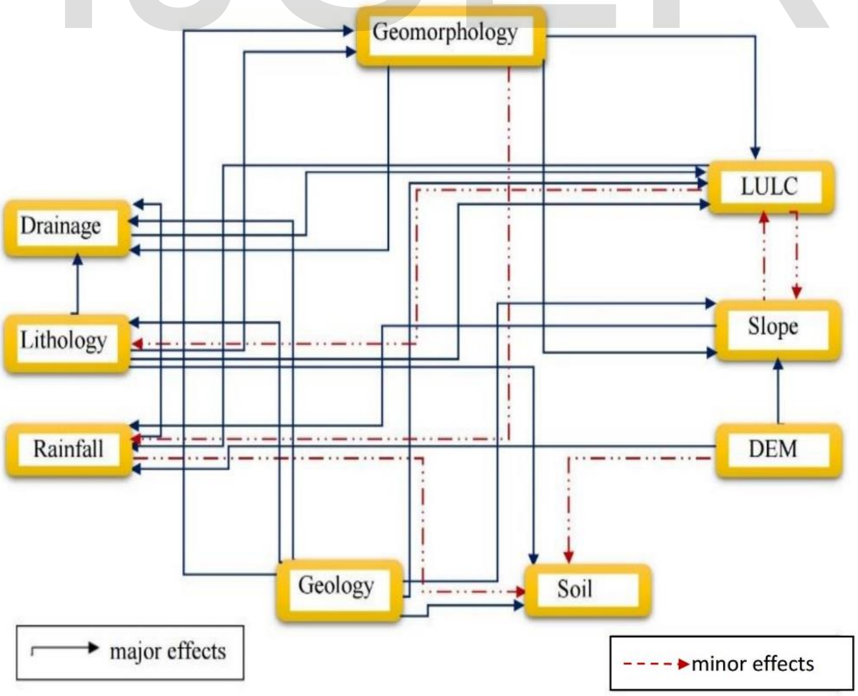

Fig2B

3.Results and discussions

Elevation map: A digital elevation model of a 30-metre resolution was downloaded from https://earthexplorer.usgs.gov. and processed in ArcGIS 10.2. The elevation of the study area varies from 451 to 733 metres above mean sea level (AMSL) with 51.8 % of the area falling under low land areas (451 to 481metres above mean sea level) and 0.6% falls under highland (642 to 733 metres above mean sea level) as shown in Fig3A. In terms of groundwater potential, areas of high elevation such as mountains and hills with steep slopes are considered to be of low groundwater potential due to the tendency of more runoff than infiltration facilitated by the high slopes whereas areas of low elevation are considered to be of good groundwater potential due to their ability to increase the residence time of surface water that in turn facilitates high infiltration. The study area elevation map was then reclassified into five classes in terms of groundwater potentiality as; 451-481m (AMSL) as being very good, 482-513m (AMSL) as good, 514-566 m (AMSL) as being moderate, 567-642 m (AMSL) as poor and 643-733 m (AMSL) as being very poor as shown in Fig 3B.

Slope map: a slope is a very crucial parameter for occurrence and recharging conditions of groundwater. Therefore, the slope map of the study area was prepared from processed DEM using spatial Analyst tool in ArcGIS 10.2. The study area slope varies from 0-44.5 degrees in which 79.89% of the area falls under slope that ranges from 0-5.0 degrees and 0.65% falls under >20.6 degrees as shown in Fig3C below. In terms of groundwater potentiality, the areas where the slope is low are capable of holding the rainwater and allow percolation into the ground which in turn recharges the groundwater hence are considered as good groundwater potential zones and the reverse is true for areas of high slopes. Therefore, the slope of the study area was later reclassified into five classes based on groundwater potentiality viz., 0-2.27 degrees as very good, 2.27-5.06 degrees as being good, 5.06-10.48 degrees as moderate, 10.48-20.60 degrees as being poor and 20.60-44.52 degrees as being very poor as shown in Fig3D below.

Drainage density map: drainage density is an indirect measure of porosity and permeability of a terrain. It also indicates the closeness of spacing of channels which provides a quantitative analysis of average length of stream channels stretching the entire part of the study area. The streams of the study area were digitised from Google Earth in keyhole makeup language (kml) format and later converted from kml to polyline layer in ArcGIS in which drainage density map was later on generated from it using line density of spatial analyst tool in ArcGIS. The drainage density of the study area ranges from 0 - 2.68 km/km2 in which 34 km2 of the area falls under 0-0.5km/km2 and 10km2 falls under 2.1-2.68km/km2 as shown in Fig3E. For groundwater potentiality, low drainage density shows high groundwater potentiality while high drainage density shows low groundwater potentiality. Therefore, the drainage density map was reclassified into five classes based on groundwater potentiality viz., 0-0.5km/km2 as being very good, 0.5-1.0 km/km2 as good, 1.0-1.6 km/km2 as being moderate, 1.6-2.1 km/km2 as poor and 2.1-2.7km/km2 as being very poor as shown in Fig3F below.

Rainfall Map: Groundwater recharge mainly comes from rainfall which is the main parameter that influences groundwater potentiality and viability. Therefore, precipitation dissemination alongside the inclination legitimately influences the percolation rate and runoff water. The rainfall data was downloaded from Climate Research Unit (www.cru.uea.ac.uk/data) in "Netcdf format" which was later converted into a useable format and interpolated using kriging in spatial analyst tool in ArcGIS 10.2 to generate the annual rainfall of the study area. The annual rainfall of the Juba city is fairly distributed running from 972 mm to 1012mm, 41.67% of the study area receives annual rainfall ranging from 1003mm to 1012mm and 35.12% receives annual rainfall ranging from 972mm to 989mm as shown in Fig3G. Therefore, areas such as North Gudele and South Gudele receive the highest annual rainfall. For groundwater potentiality, areas with high annual rainfall are considered as good groundwater potential areas and areas with low yearly precipitation are considered as the low groundwater potential areas. The annual rainfall map was later reclassified into four classes based on groundwater potentiality viz., 972-989mm as being moderate, 989-996 mm as good, 996-1003 mm as very good and 1003-1012mm as being excellent as shown in Fig3H below.

Geomorphology map: geomorphology reflects varies landforms and structural features, many of which favour the occurrence of groundwater potential and determines runoff, flooding, groundwater recharge and rainfall to some extent. Geomorphic features like hill, hill slopes, river valley, terraces, piedmont zones (fan and flood plain), river bed and plain area are very important from groundwater potential point of view. The geomorphologic units of the study area were delineated from the DEM downloaded from U.S. Geological survey https://earthexplorer.usgs.gov. and with the help of Google Earth. The study area was classified into seven categories based on groundwater potentiality viz., waterbody, valley fill, alluvial plain, highland, buried pediment medium, buried pediment shallow and Pedi plain. 35.71% of the study area falls under Pedi plain, 25.6% buried pediment medium,17.26% buried pediment shallow, 1.79% highland,10.71% alluvial plain, 1.19% Valley fill and 7.73% water body as shown in fig4I.

Lithology Map: The lithology map was downloaded from http://opendata.rcmrd.org/datasets/africa-surface-lithology as African surficial lithology dataset which is a map of parent materials - a mix of bedrock and unconsolidated surficial materials classes consisting of nineteen surficial lithology classes that were delineated in Africa based on geology, soil and landform developed as a primary input dataset for an African ecological footprint mapping project undertaken by united states geological survey and the nature conservancy(*Africa surface lithology*, n.d.). The lithology map of the study area was then generated from it in ArcGIS 10.2 whereby 87.74% (147.4 km²) of the study area consists of meta igneous lithology, 10.73% consists of alluvium and the rest is covered by water as shown in Fig4J below.

Geology map: The infiltration-runoff relationship is controlled prevalently by porousness, which thusly is an element of rock type and cracking of the bedrocks or bed surface hence geology is a very important parameter in the perspective of groundwater potential mapping. The geology map was downloaded from the website https://catalog.data.gov/dataset/surficial-geology-of-africa (scale 1:500,000) that shows geology provinces of Africa meant to provide the geological information (Ahlbrandt, 1997). The geology map of the study area was generated from it in ArcGIS. in which 74.78 km² of the study area falls in quaternary (undivided) and 93.78 km² falls under Precambrian (undivided) as shown in Fig4K.

Soil map: Soil texture plays a significant part in the measure of percolating water into the soil. Therefore, infiltration rate relies upon the soil texture and related hydraulic characteristic of the soil. The soil map was downloaded from the FAO soil website (http://www.fao.org/geonetwork/srv/en/metadata) and the study area map was generated from it in ArcGIS 10.2. Therefore, the study area has two types of soil texture namely; loam soil and sandy loam soil. 0.05 km² of the study area falls under loam soil while 167.95 km² falls under sandy loam soil and in terms of groundwater potential perspective, sandy loam soil areas are considered as excellent areas for groundwater while areas of loam soil are considered as good as shown in fig4L.

Land use/Land cover map: Landsat 8 data was downloaded from https://earthexplorer.usgs.gov and supervised classification in ArcGIS 10.2 was used to classify the study area into seven categories namely; water body, settlement, Artificial forest (plantation), grassland, agriculture, wetland and bare land as shown in fig4M below.

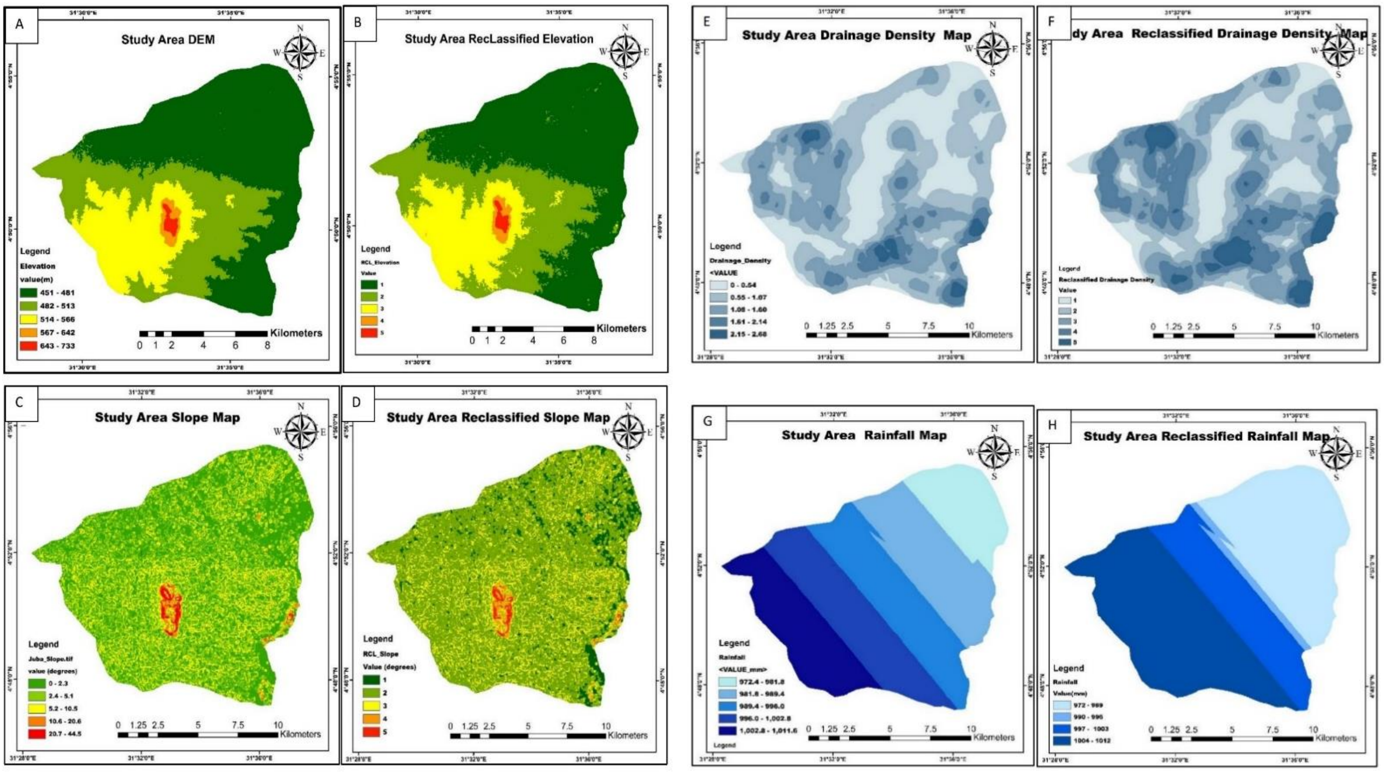

Fig3

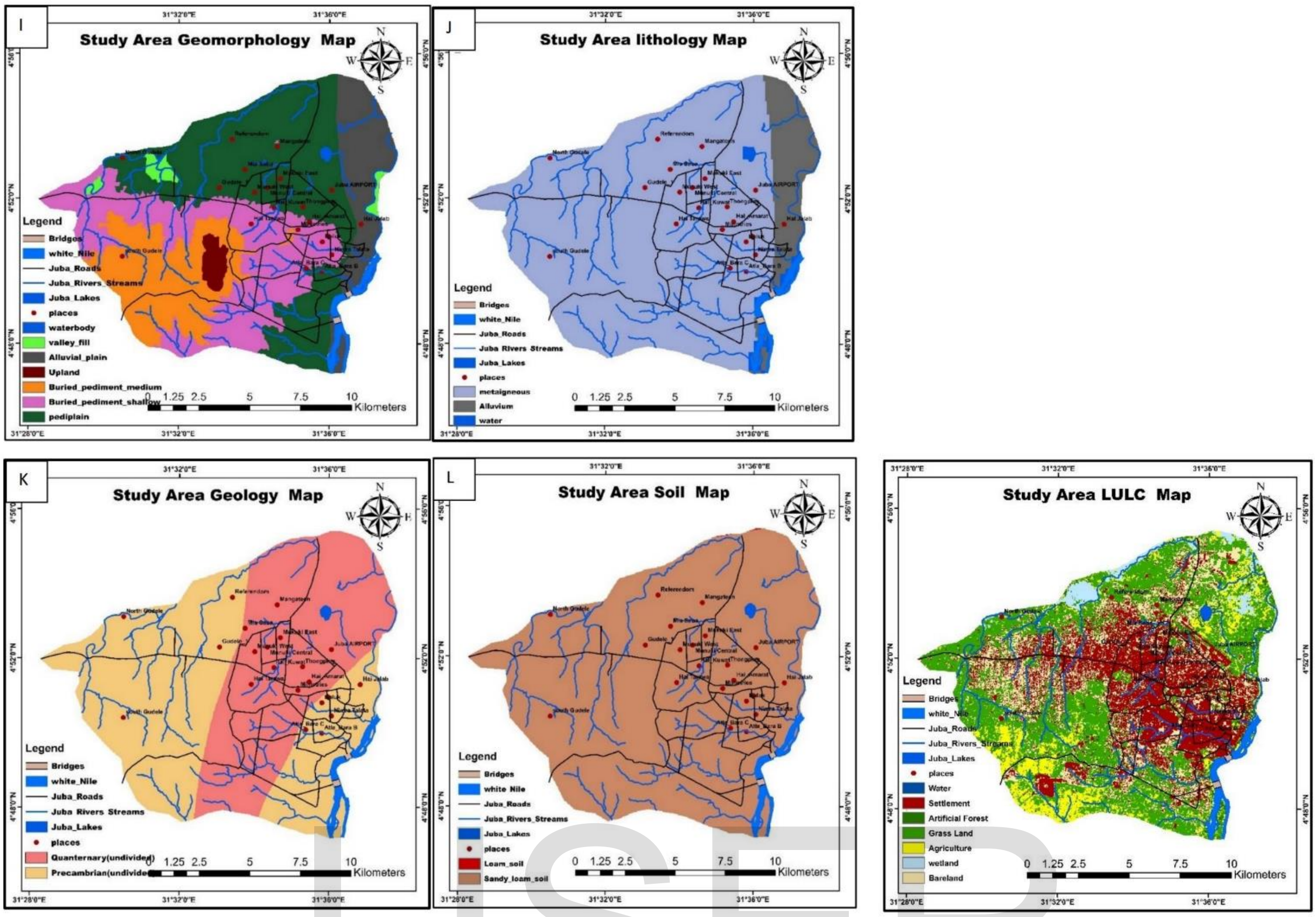

Fig4

Generation of Weights: The weights were assigned using the MIF technique as described with a schematic diagram as shown in Fig2B based on the influencing strength of each factor over others in terms of groundwater potential perspective, the proposed weights were calculated based on the formula (1) and shown in Table 2

Allocation of Ranks: The ranks were from 1 to 5 based on the importance of each unit of the influencing of groundwater parameters. The ranks in terms of importance are; 1,2,3,4,5 i.e. very poor, poor, moderate, good, very good respectively as shown in Table 2

Factor	M	N	(M+N)	Proposed weight
	(M)	(N)		
Geomorphology	3	0.5	3.5	15
LULC	1	1	2	8
slope	1	0.5	1.5	6
Elevation	3	0.5	3.5	15
Soil	1	0	1	4
Geology	6	0	6	25
Rainfall	1	0.5	1.5	6
Lithology	4	0	4	17
Drainage Density	1	0	1	4
Sum			24	100

Table1

Factor	class	weightage	Rank	Groundwater perspective
Geomorphology	waterbody		1	very poor
	valley fill		4	Good
	Alluvial plain		5	Very Good
	Highland	15	1	Very poor
	Buried pediment (medium)		3	Moderate
	Buried pediment (shallow)		2	Poor
	Pedi plain		4	Good
Land use/ Landcover	water body		1	Very poor
	Settlement		1	Very poor
	Artificial Forest		5	Very Good
	Grassland	9	3	Moderate
	Agriculture		4	Good
	Wetland		2	Poor
	Bare land			
Soil	Loam soil	4	4	Good
	Sandy loam soil		5	Very Good
Slope (degrees)	0 - 2		5	Very Good
	2 - 5		4	Good
	5 - 10	7	3	Moderate
	10 - 21		2	Poor
	21- 45		1	Very poor
Lithology	Meta igneous		3	Moderate
	Alluvium	17	5	Very Good
	Water		1	Very poor
Drainage Density (km/km^2)	0 - 0.54		5	Very Good
	0.54 -1.07		4	Good
	1.07 -1.61	4	3	Moderate
	1.61 - 2.14		2	Poor
	2.14 - 2.68		1	Very poor
Elevation	451 - 481		5	Very Good
	481 - 513		4	Good
	513 - 566	11	3	Moderate
	566 - 642		2	Poor
	642 - 733		1	Very poor
Geology	Quaternary	26	5	Very Good
	Precambrian		3	Moderate
Rainfall (mm)	972 - 989		2	poor
	989 - 996	7	3	moderate
	996 - 1003		4	Good
	1003 - 1012		5	Very Good

Table2

Generation of groundwater potential map: The groundwater potential map of the study area was generated using the following equation:

$$GWPI= GM_wGM_r + LULC_wLULC_r + Sl_wSl_r + El_wEl_r + S_wS_r + G_wG_r + RF_wRF_r + L_wL_r + DD_wDD_r \quad \text{Equation (2)}$$

Where; GWPI=Groundwater potential Index, GM=Geomorphology, LULC=Land use/ land cover, Sl=Slope, El= Elevation, RF= Rainfall, DD=Reclassified Drainage Density, L=Lithology, S=Soil, G= Geology, subscript w and r refer to weight of theme and ranks for the individual feature of the theme. The generated groundwater potential zone map is as shown in Fig5

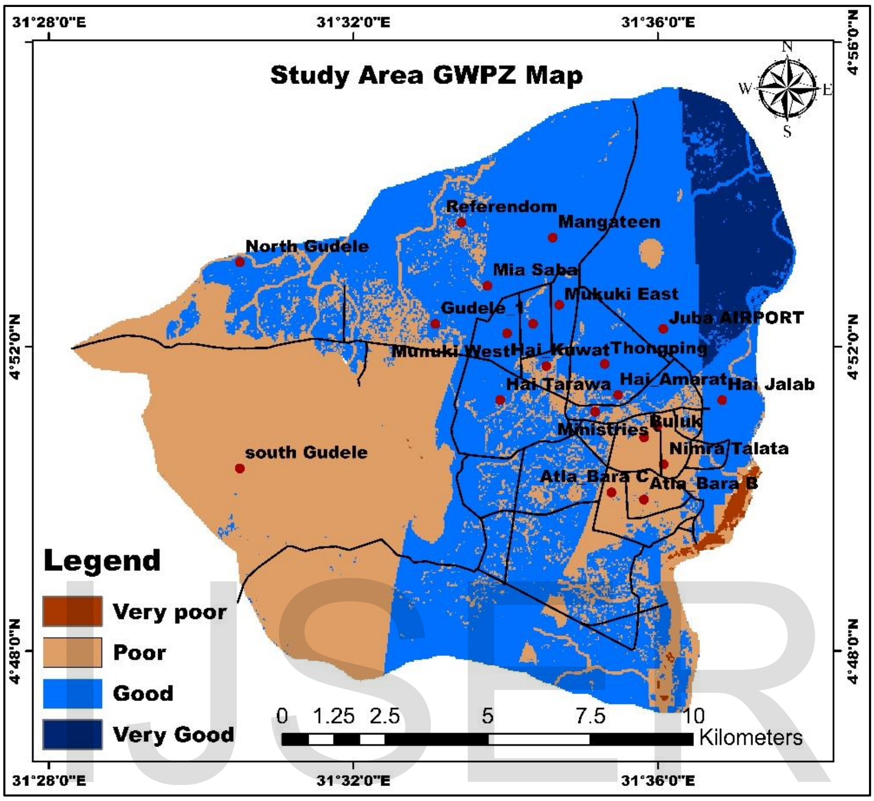

Fig5

Analysis of the generated groundwater potential map: The generated groundwater potential map consists of four classes namely: very poor, poor, good and very good. 0.6% (1km^2) of the area having very poor groundwater potential zone, 41% (69km^2) falls under poor groundwater potential zone, 52.4 % (88km^2) falls under good groundwater potential zone and 6.0%(10km^2) falls under very good groundwater potential zone as summarized in the graphically in Fig6 below.

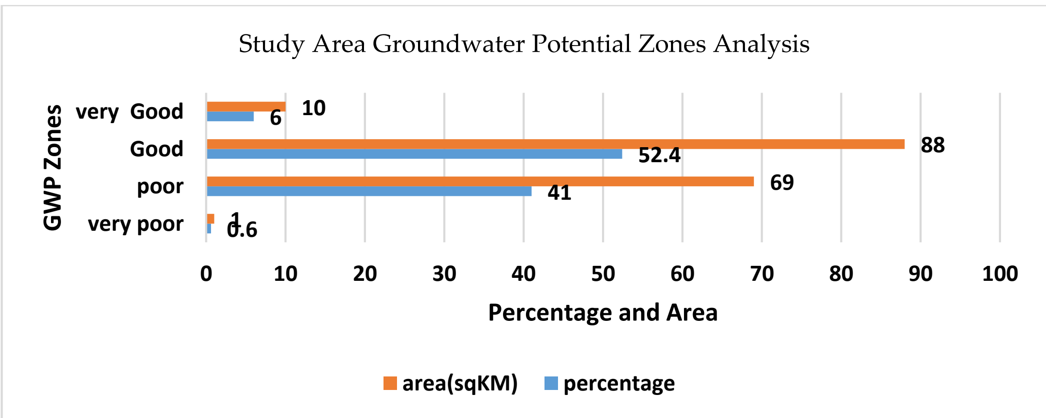

Fig6

Validation of the groundwater potential map: For the current study, 7 Failed and 125 operating borehole locations were superimposed on the generated map to check whether the failed and operating borehole locations fall on poor and good groundwater potential zones respectively, was found that 85.7% (6 boreholes) of the failed borehole locations fall in poor groundwater potential zone and 88.8% (111 boreholes) fall in good groundwater potential zone showing the robustness of the method and usefulness of the study as shown in Fig7 below.

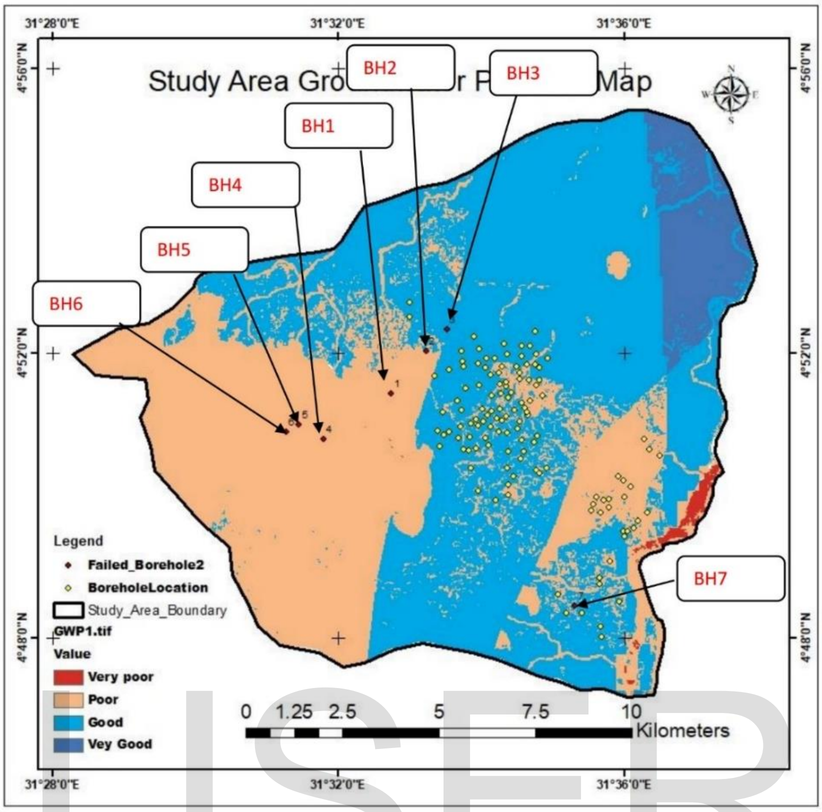

Fig7

4. Conclusion

Based on the objectives of the present study, it can be deduced that remote sensing and GIS are very important tools for the assessment and monitoring of water resources as indicated by the results of the study. Nine groundwater potential influencing factors were used to delineate the groundwater potential zones in which a map was generated consisting of four classes namely; very poor, Poor, good and very good. 0.6% (1km²) of the area having very poor groundwater potential zone, 41% (69km²) falls under poor groundwater potential zone, 52.4 % (88km²) falls under good groundwater potential zone and 6.0%(10km²) falls under very good groundwater potential zone and 7 Failed and 125 operating borehole locations were superimposed on the generated map to validate whether the failed and operating borehole locations fall in poor and good groundwater potential zones respectively and it was found that 85.7% (6 boreholes) of the failed borehole locations fall in poor groundwater potential zone and 88.8% (111 boreholes) fall in good groundwater potential zone which shows the robustness of the method and usefulness of the study. The very good groundwater potential zone falls in alluvium lithology, low elevation with a moderate slope and quaternary (undivided) geology while the poor groundwater potential falls in areas of high elevation, high slopes. Therefore, geology, geomorphology, elevation and slope are the main factors that influence groundwater potential in the study area. The North-East part of the study area that has alluvium lithology has very good groundwater Potential. Areas such as Hai Jalab, Hai Amarat, Thongping, Munuki West, Munuki Central, Munuki East, Mangateen, North Gudele have good groundwater Potential and areas such as South Gudele; Hai Battery, POC, Nimera Talata, Atla_Bara A, Atla Bara C and Buluk have poor Groundwater Potential. In general, about 58.2% of the study area has good groundwater potential and about 41.8% of the area has poor groundwater potentiality, hence, most parts of the study area have good groundwater potential.

The main focus of this project was to assess the groundwater potential zones of Juba city using remote sensing and GIS and MIF Techniques, however, due to lack of ground data, the study mostly used secondary data, therefore the following could be the future scope; the present study was based on logical conditions and reasoning, therefore, the same method can be used with appropriate modifications for other similar studies, the groundwater potential map along with other thematic maps serve as resource information database which can be updated from time to time by adding new information, there is also a need for further studies on the quality of the groundwater of the study area, the same method can be used with ground data for a similar study for the same study area to compare the results, there is a need in future to validate the generated groundwater potential map using groundwater table data since the present study was only validated using the failed and operating borehole locations.

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