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Application of Geographic Information Systems in Groundwater Prospecting: A Case Study of Garissa County, Kenya

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Abstract

Groundwater prospecting in Kenya has been haphazard and expensive due to lack of information on the appropriate areas for hydrogeological exploration and drilling of boreholes. Drilling in areas without prior knowledge about their groundwater potential has been leading to the drilling of numerous dry boreholes. In this study, we explored the use of Geographic Information System as a pre-analysis tool to identify zones with groundwater potential for Garissa Country. Factors that contributed to groundwater occurrence were identified as landcover, soil type and rock formation. The groundwater potential zones were generated by analysing thematic data of the three factors and integrating the musing Weighted Index Overlay Analysis (WIOA) method. The groundwater potential zones were validated by comparing the predicted potentials with actual yields of existing boreholes drilled within those areas. Results indicate that, whereas the model correctly predicted areas with low or no groundwater potential, it performed sparingly well when predicting areas with good groundwater potential. The study conclusively identified areas where groundwater prospecting should not be attempted and other alternative methods of surface water provision should be explored.

Keywords

Groundwater, Geographic Information Systems, Weighted Index Overlay

1. Introduction

Kenya is classified as a water scarce country, characterized by high spatial and temporal variability in rainfall leading to extreme droughts and floods. Kenya's renewable fresh water supply is estimated at 647 m^3 per capita, almost half the United Nations' recommended bench mark of 1000 m^3 per capita. This compares dismally with its neighbours namely Uganda with 2940 m^3 and Tanzania with 2696 m^3 per capita respectively [1]. Kenya's fresh water supply is reducing due to declining rainfall, increase in population, and degradation of existing water catchment/conservation forest cover, and is projected to drop to 245 m^3 per capita by the year 2025 [1]. Among the economically underdeveloped areas of the country, northern Kenya is the most vulnerable since water, arable land and pasture are scarce resources [2]. Famine and drought are common in this region and coupled with underdeveloped water supply facilities, water sources are a major cause of conflict between local communities [2] [3].

Northern Eastern Kenya covers the largest part of the country but has the greatest scarcity of water. This problem is as a result of many factors. Traditionally, water security has been achieved by harvesting surface water through construction of river flow obstruction/storage structures such as dams and water pans [4]. However Northern Kenya lacks suitable embankment materials and sites for construction of dams. Construction of dams would require transportation of suitable embankment materials from borrow sites in far regions which is an expensive exercise due to the bulky nature of these materials. High temperatures and poor vegetation cover that characterise the region lead to high evaporation and siltation rates respectively greatly reducing the lifespans and storage capacities of the water pans.

Groundwater source provides a viable alternative to surface water harvesting, and has proven useful in dry areas [5] [6]. However, groundwater resources in Kenya are underdeveloped with only 0.18 billion cubic meters extracted annually from a total estimated yield of 1.08 billion cubic meters [7]. Therefore there is need to identify and map potential groundwater harvesting zones in the Northern region as well as in other Arid and Semi-Arid Land (ASAL) areas in Kenya.

Garissa Country experiences water supply problems when surface water sources dry up during dry seasons. All the hinterland rivers are seasonal (**Figure 1**) and only River Tana flowing along the southern border offers perennial water source to the nearby communities and towns.

For many years, ground water harvesting has been tried in various parts of the country by the national government and non-govern mental organizations as an alternative water source. However, the exploration has been haphazard due to lack of information regarding groundwater potential areas. Overtime, drilling has relied on hydrogeological estimates and data from nearby boreholes, if any, which has led to the drilling of many dry or low yielding boreholes. Drilling of dry boreholes is a waste of time and precious resources. This negatively affects the livelihoods of the local community. Therefore there is an urgent need to utilize efficient pre-exploration methods to enhance use of all valuable resources.

In recent years the use of Geographic Information Systems (GIS) and Remote Sensing (RS) has made it easier to define the distribution of different groundwater

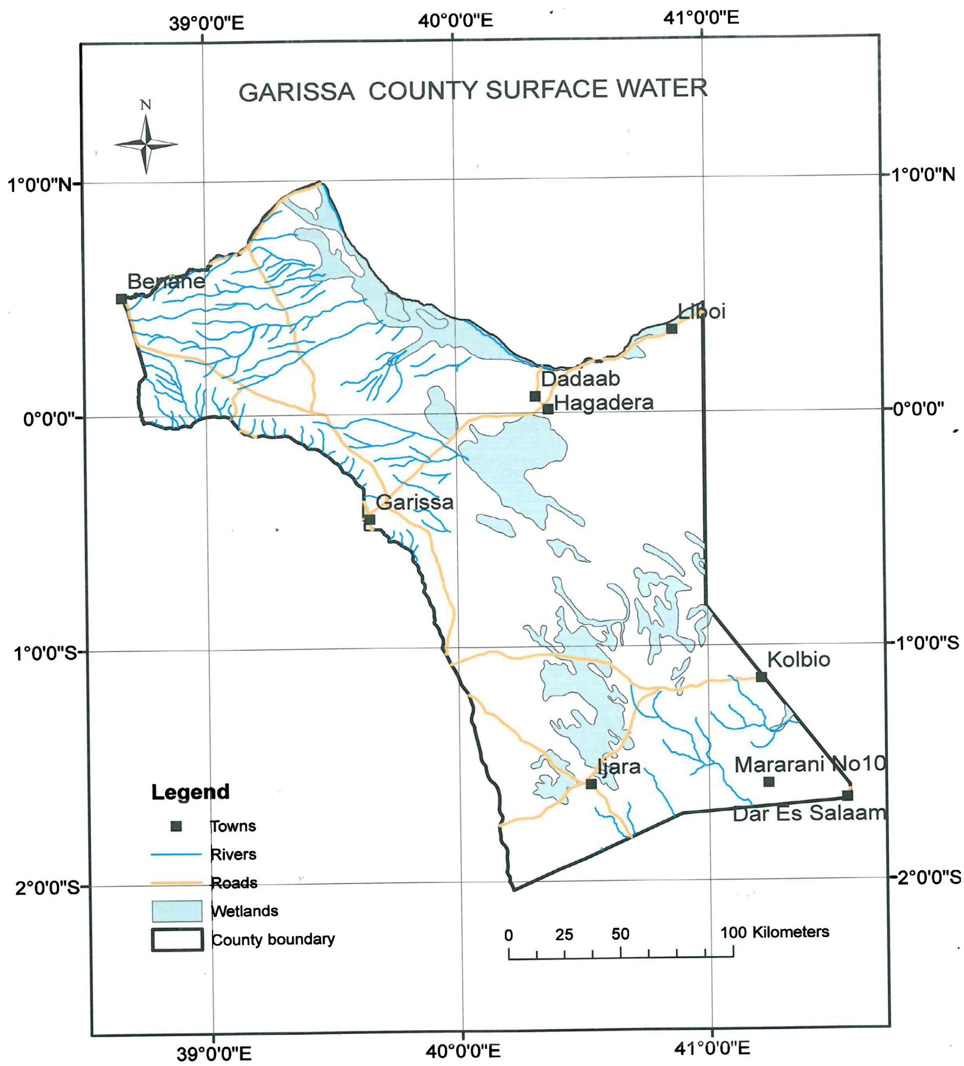

Figure 1. Distribution of surface water in Garissa Country.

prospective zones. When used in the preliminary stages of a survey, GIS and RS help in delineating potential groundwater harvesting sites based on the geo morphology, hydrogeology, vegetation, and other associated features of a region. The sites identified are then ear marked for detailed exploration work, drastically reducing the costs associated with groundwater exploration. GIS and RS techniques are used in this study to deter mine groundwater sources in Garissa Country.

The overall objective of the study was to develop a groundwater potential zones map for Garissa Country, using Weighted Index Overlay Analysis (WIOA) modelling, for selection of areas suitable for drilling of boreholes.

The specific objectives of the study were:

1) To identify factors that influence occurrence of groundwater in an area;

2) To establish suitable locations for exploration of groundwater for Garissa Country;

3) To test the validity of the generated groundwater potential map.

2. Methodology

2.1. The Study Area

Garissa Country is comprised of the former Garissa and Ijara districts. The Country covers an area of about 34,952 km^2 and has a population of more than 623,060 [8]. It borders Wajir Country in the North along Habasweni swamp and Lamu Country in the East. In the South, Tana River runs from west to east and for ms its boundary with Tana River Country. On the western side it borders Mt. Kenya game reserve and Isiolo Country. It lies in between latitudes 2˚01'30"S & 0˚59'36"N and longitudes 38˚40'20"E & 41˚34'40"E (**Figure 2**).

Among the counties in the Northern region, Garissa Country was chosen as a priority for this case study because of three main reasons. First, it is one of the economic gateways to the region. Second, Garissa has been characterised by insecurity for many years which curtailed water infrastructure develop ment for long. Third, Garissa Country is projected to have a significant increase in population and economic development due to the proposed Lamu Port South Sudan Ethiopia Transport (LaPSSET) corridor infrastructure development which will pass through the country (**Figure 3**).

2.2. Data Collection

2.2.1. Existing Boreholes Data

The Ministry of Water and Irrigation drilled boreholes nationally at a high rate

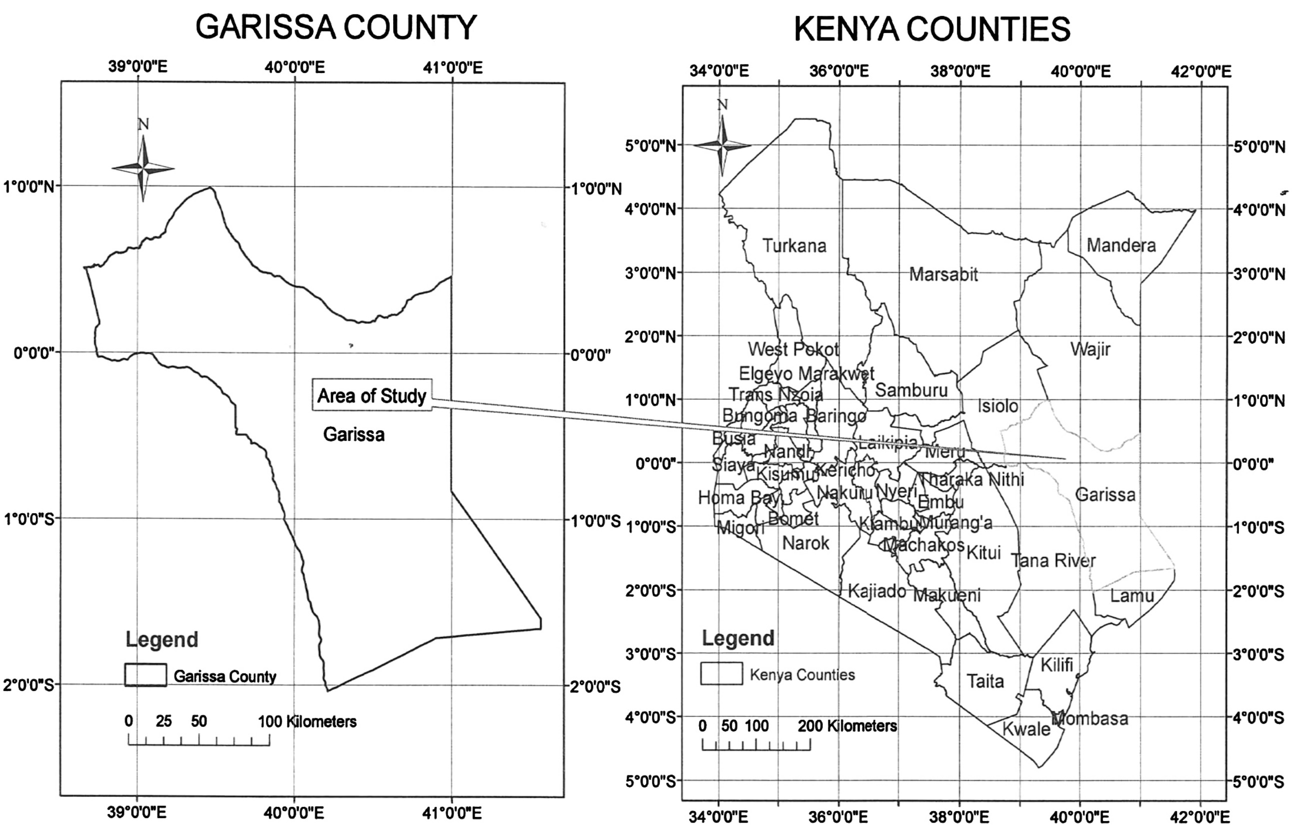

Figure 2. Location of Garissa Country.

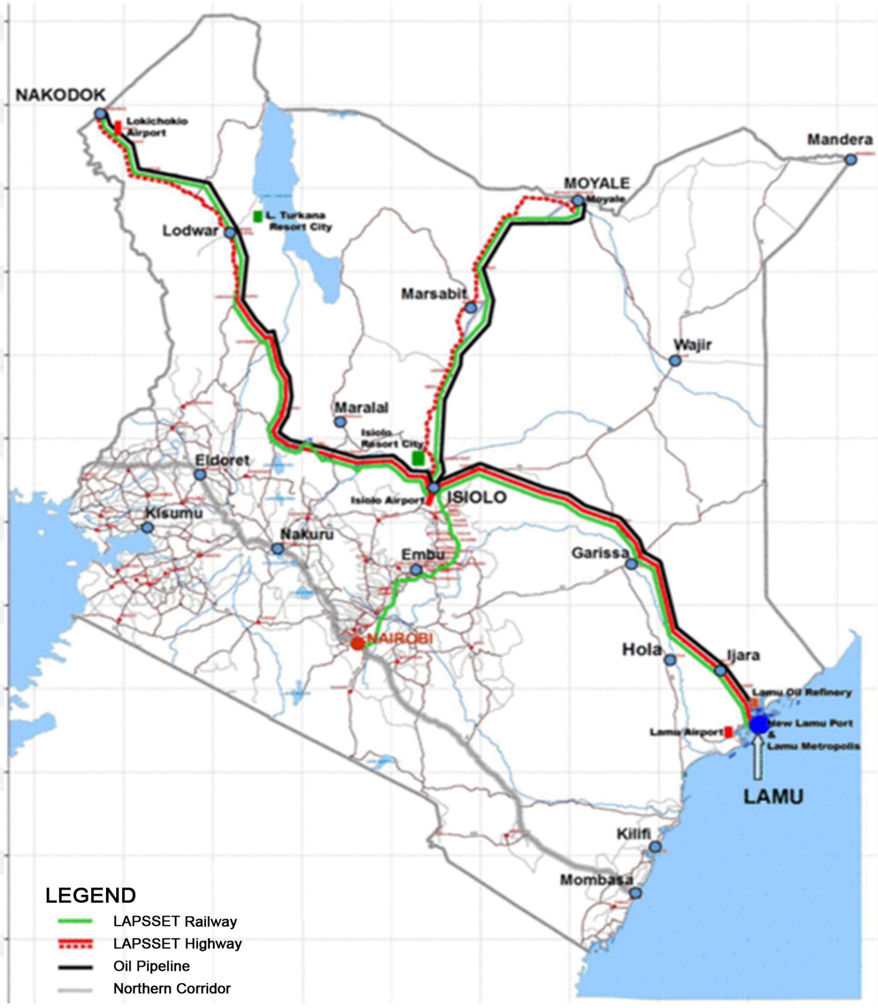

Figure 3. Map showing the scope of the Kenya LAPPSET Project within Kenya. Source: https://en.wikipedia.org/wiki/Lamu_Port_and_Lamu-Southern_Sudan-Ethiopia_Transport_Corridor 2013.

from 2005 to 2010 [9]. The Northern Water Service Board (NWSB) received the greatest number of projects, therefore making the region a priority study area. The NWSB region boreholes data was extracted from boreholes drilling records obtained from National Water Conservation and Pipeline Corporation (NWCPC) for boreholes drilled during the six years development period. The boreholes raw data was screened to re move unreferenced sites to obtain complete data records. Many boreholes records were incomplete and out of 218 boreholes drilled, only 111 borehole sites were georeferenced (Table 1).

Garissa Country Boreholes

From the regional data the country data was arrived at by carrying out a comparison of the data for the seven counties. The comparison was based on the number of boreholes drilled and the number of boreholes with GPS coordinates. Garissa Country was found to have the largest number of boreholes with complete data records. The georeferenced country data was further filtered to re move repeated, erroneous and inconsistent records to obtain the data records that constituted the study validation data (Table 2).

Table 1. Boreholes with GPS coordinates.

S/No.	Country	No. of boreholes	Boreholes with GPS coordinates
1	Laikipia	26	8
2	Isiolo	24	22
3	Samburu	19	8
4	Marsabit	48	12
5	Mandera	26	18
6	Wajir	30	16
	Garissa	**45**	**37**
	TOTAL	**218**	**111**

Source NWCPC borehole drilling records.

Table 2. Garissa Country study validation data.

S/No.	Borehole Name	*X*	*Y*	Depth m	Yield m 3/h
1	Ashadin	39.0916	0.1592	200	0
2	Skanska	39.3067	0.9147	134	0
3	Bulla Iftin	39.1125	−0.0653	85	0
4	Dujis	39.4114	0.2483	220	0
5	Gurufa	39.4658	0.8011	220	7
6	Abdi Samet I	39.6558	−0.0055	204	3
7	Katama II	39.6558	−0.0055	198	18
8	Dadaab II	40.0092	0.1878	135	3
9	Majengo III	40.1189	−1.6755	53	15
10	Sareto II	40.1356	−0.0244	156	14
11	Kotile	40.1461	−1.9514	50	10
12	Sitie	40.1708	−0.3425	82	0
13	El-Humon	40.2075	0.0828	170	8
14	Lebisigaley II	40.285	0.1672	178	20
15	Mathagasi	40.4261	0.1586	204	17
16	Shimbre	40.5525	−0.3417	177	2
17	Sangailucwp	40.745	−1.4188	170	0
18	Damanjare	40.7883	0.1039	180	10
19	Hagarbul II	40.8375	−0.2494	210	0
20	Lago	40.865	0.2042	227	15
21	Hulugho	41.0283	−1.2083	200	0

2.2.2. Groundwater Factors Data

For this study the factors that were found to play a substantial role in influencing the occurrence of ground water in Garissa Country were landcover (vegetation), soils and lithology (rock formation). Rainfall, slope (topography) and drainage though important, were found not to play a significant role since their spatial layers are linear as compared to the others which are polygons. The groundwater factors data was obtained from ILRI website [4].

Landcover Data

Landcover (vegetation) data for the study area was acquired from the Japan International Co-Operation Agency National Water Master Plan landcover data. This data is available on the International Livestock Research Institute (ILRI) GIS portal (http://www.ilri.org/gis). The data was classified into five categories; Woodland, Dense bushes, Sparse bushes, Grassland, and Swamps (**Figure 4**).

Soils Data

Data on the soils type in the study area was downloaded from the International Livestock Research Institute (ILRI) GIS portal (http://www.ilri.org/gis). The data was initially generated from a study done by the Kenya Soil Survey (KSS) in 1982, and thereafter revised in 1997. The soil data was classified into 4 types; Clay, Very Clay, Loamy and Sandy Soils (**Figure 5**).

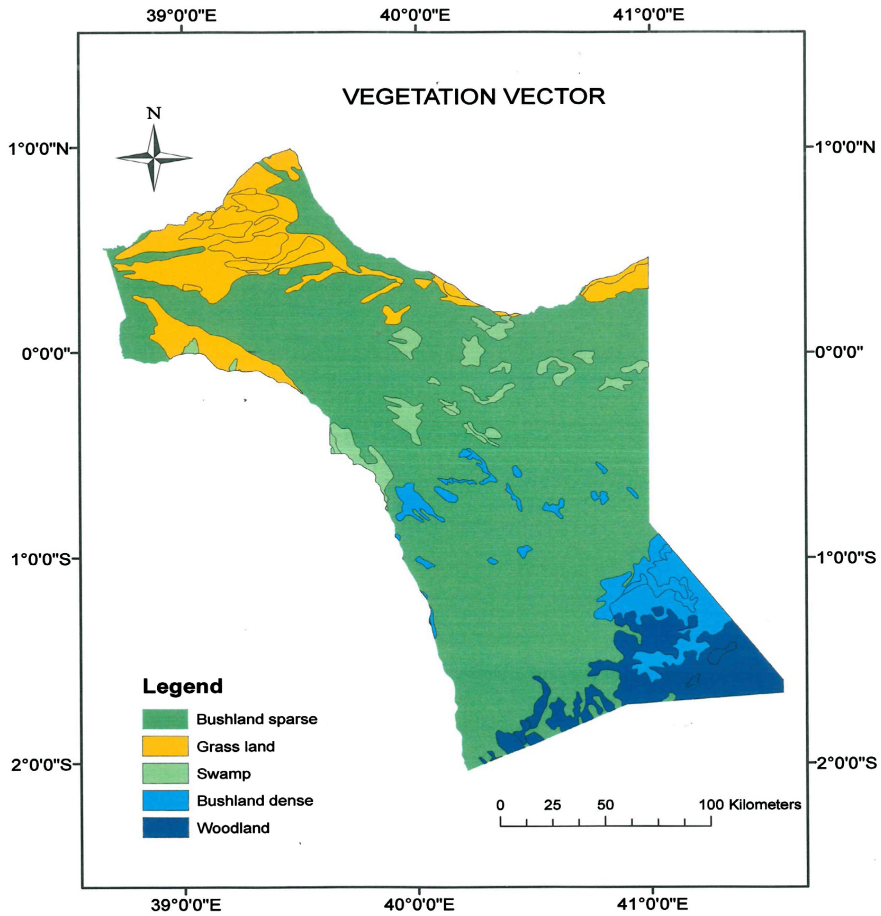

Figure 4. Landcover types in Garissa Country.

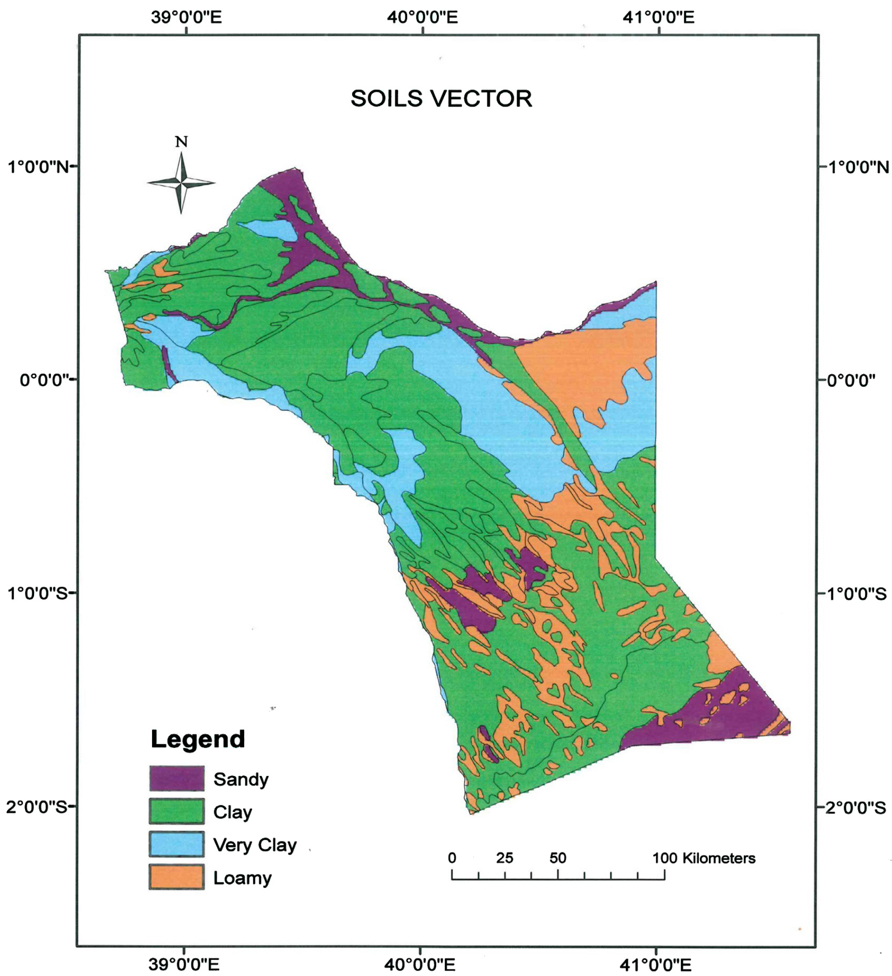

Figure 5. Soils Textural classes in Garissa Country.

Lithology Data

Data on the rock structure found beneath the surface of the study area was downloaded from the ILRI GIS portal (http://www.ilri.org/gis). The data was initially generated from a study done by the Kenya Soil Survey (KSS) in 1982. The data was classified into the following groups: Igneous, Metamorphic, Sedimentary and Unconsolidated rocks (Figure 6).

2.3. Data Analysis

2.3.1. Existing Boreholes

The data in Table 1 was used to generate a map layer showing the locations and yields of existing boreholes (Figure 7).

2.3.2. Groundwater Factors

Conversion to Raster

To make the Factors layers integration possible the factors data was converted from vector for mat to raster for mat using ArcGIS10.1 Arc Toolbox (conversion tools—to raster and feature to raster). The thematic factors raster layers are shown in Figure 8, Figure 9 and Figure 10.

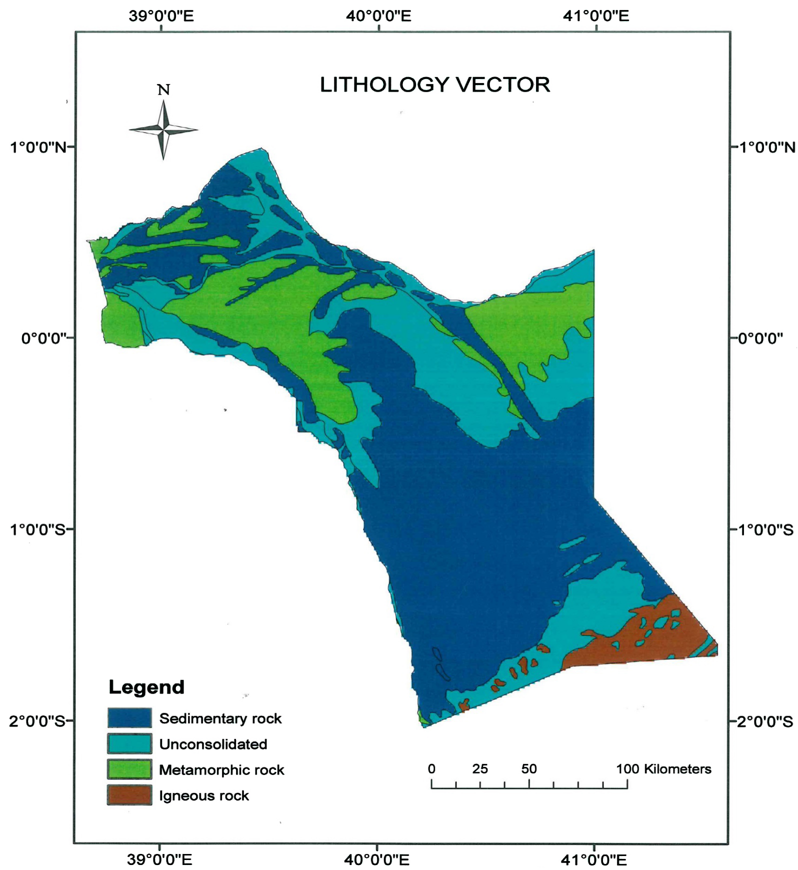

Figure 6. Underlying rock formation in Garissa Country.

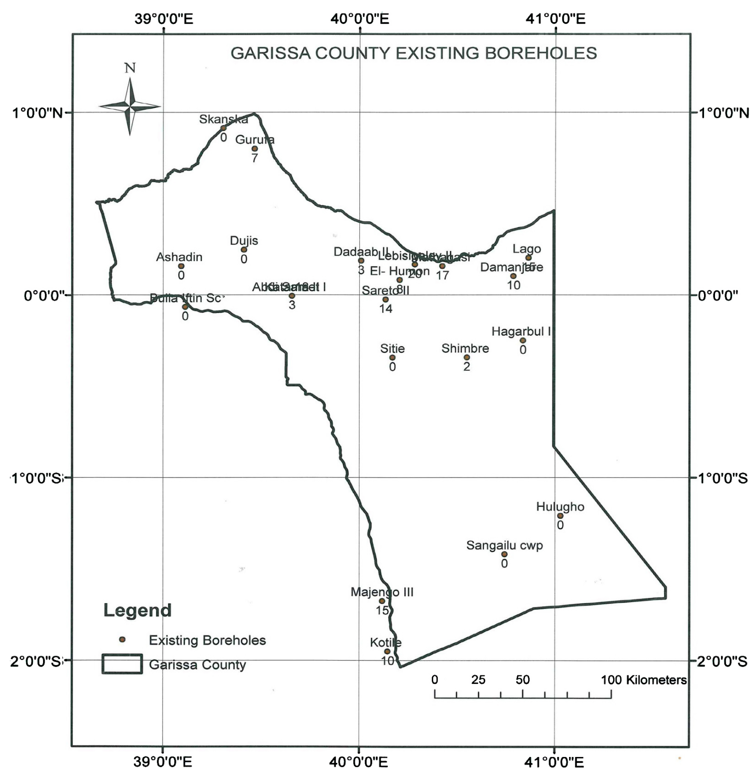

Figure 7. Map showing location of existing boreholes and their yields.

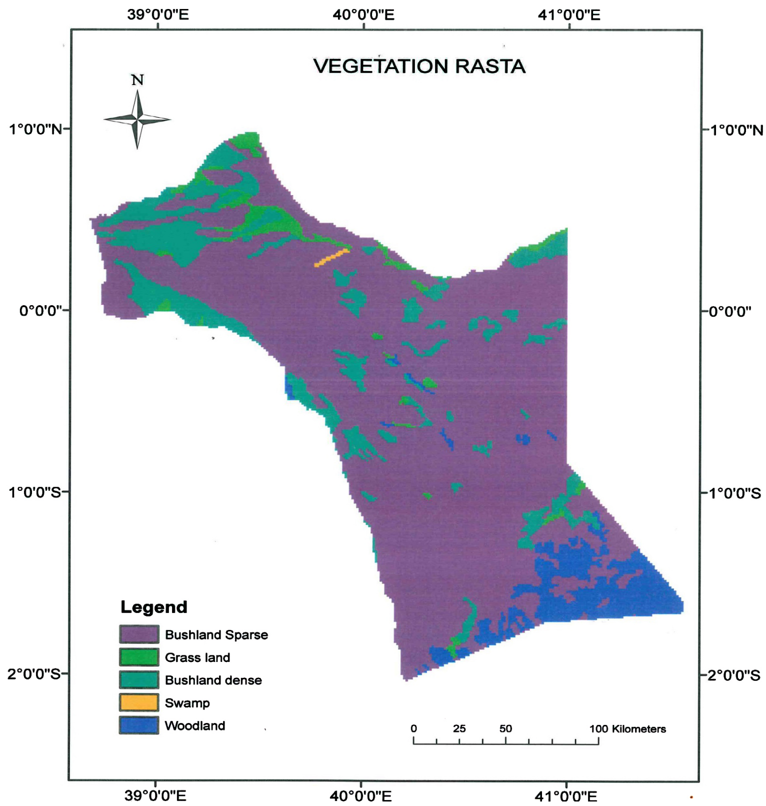

Figure 8. Garissa Country landcover raster.

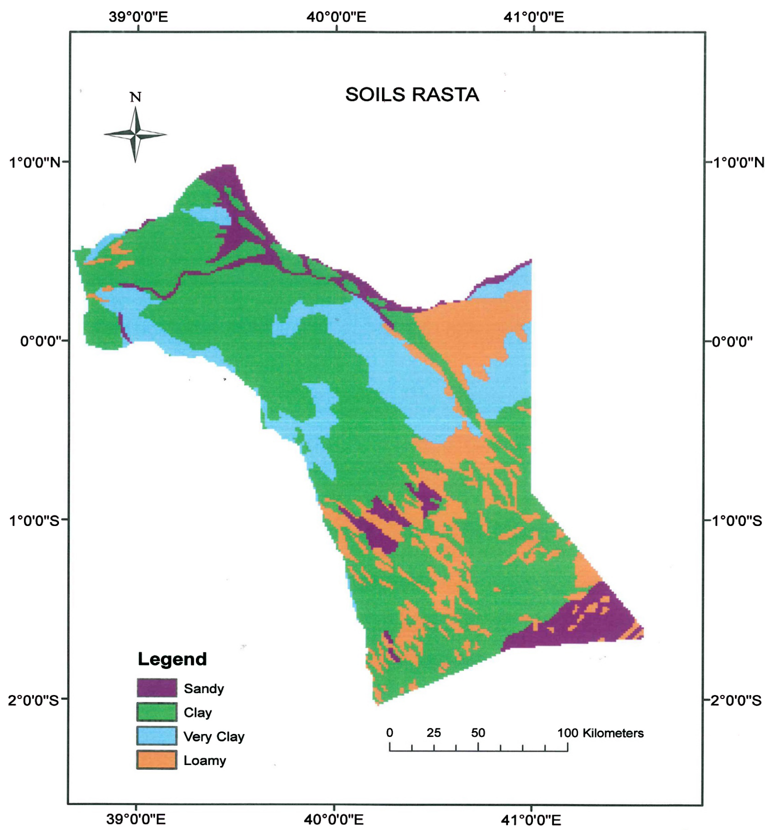

Figure 9. Garissa Country soils textural raster.

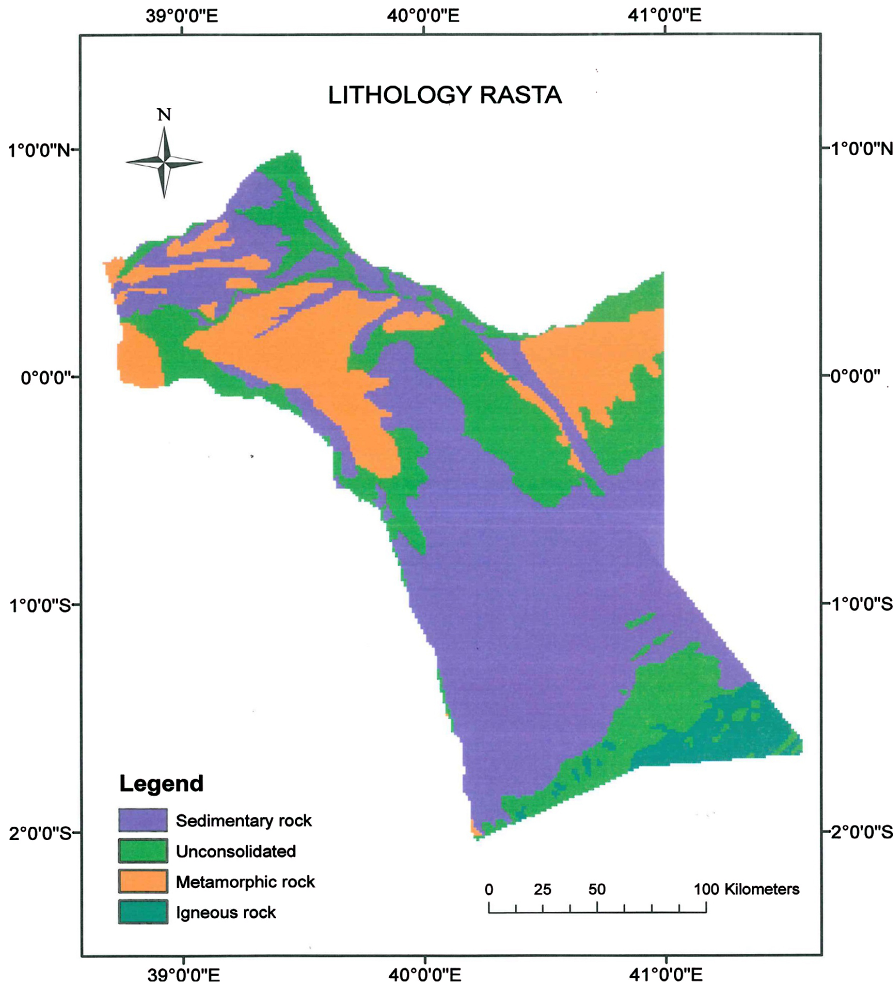

Figure 10. Garissa Country underlying rock formation raster.

Reclassification to One Scale

Integration/addition of factors layers requires them to be re-classified to a common measurement scale. A scale of 1 to 3 was chosen for this analysis. In reclassification, ranks are given to each individual parameter in each factor layer according to its relative influence on groundwater occurrence when compared to the other parameters. Using the scale of 1 to 3 each parameter in each factor layer was assigned a new value; 1-high, 2-medium, and 3-poor groundwater potential influence (Tables 3-5).

The thematic factors raster layers were then reclassified using ArcGIS10.1 Arc Toolbox (Spatial Analyst Tools—Reclass-Reclassify). The re-classed raster layers are shown in Figures 11-13.

2.4. Weighting the Factors

After reclassification, the three thematic (factor) layers were weighted using the Analytical Hierarchy Process (AHP) method. AHP is a logical framework that is used to deter mine the relative input of each factor towards accomplishing a certain output [10]. AHP involved pairwise comparison of the three variables (factors) with respect to each individual variable's relative influence on groundwater potential. The comparison was done on a scale of 1 - 4 as follows; lithology is 2 times as important as soils; soil is 3 times as important as landcover and

Table 3. Vegetation re-classification.

S/No.	Landcover	Old Value	New Value
1	Woodland	2	2
2	Bushland (dense)	3	3
3	Bushland (sparse)	4	1
4	Grassland	5	2
5	Swamp	6	1

Table 4. Soils re-classification.

S/No.	Drainage Description	Clay Description	Texture Description	Old Value	New Value
1	Well	Montmorillonitic	Clayey	1	2
2	Well	Kaolinitic	Clayey	2	2
3	Extremely slow	Interstratified	Clayey	3	3
4	Slow	Kaolinitic	Clayey	4	3
5	Extremely slow	Montmorillonitic	Clayey	5	3
6	Well	Montmorillonitic	Loamy	6	1
7	Well	Kaolinitic	Loamy	7	1
8	Slow	Montmorillonitic	Loamy	8	2
9	Slow	Kaolinitic	Loamy	9	2
10	Very rapid	Montmorillonitic	Sandy	10	1
11	Well	Montmorillonitic	Sandy	11	1
12	Slow	Montmorillonitic	Very clayey	12	3
13	Extremely slow	Kaolinitic	Very clayey	13	3

Table 5. Lithology re-classification.

S/No.	Lithology	Major Class	Old Value	New Value
1	Conglomerate, breccia	Sedimentary	1	2
7	Sandstone, greywacke, arkose	Sedimentary	1	2
2	Eolian unconsolidated	Unconsolidated	2	1
3	Fluvial	Unconsolidated	2	1
5	Lacustrine unconsolidated rock	Unconsolidated	2	1
6	Marine unconsolidated	Unconsolidated	2	1
4	Gneiss, migmatite	Metamorphic	3	3
8	Ultrabasic igneous rock	Igneous rock	4	3

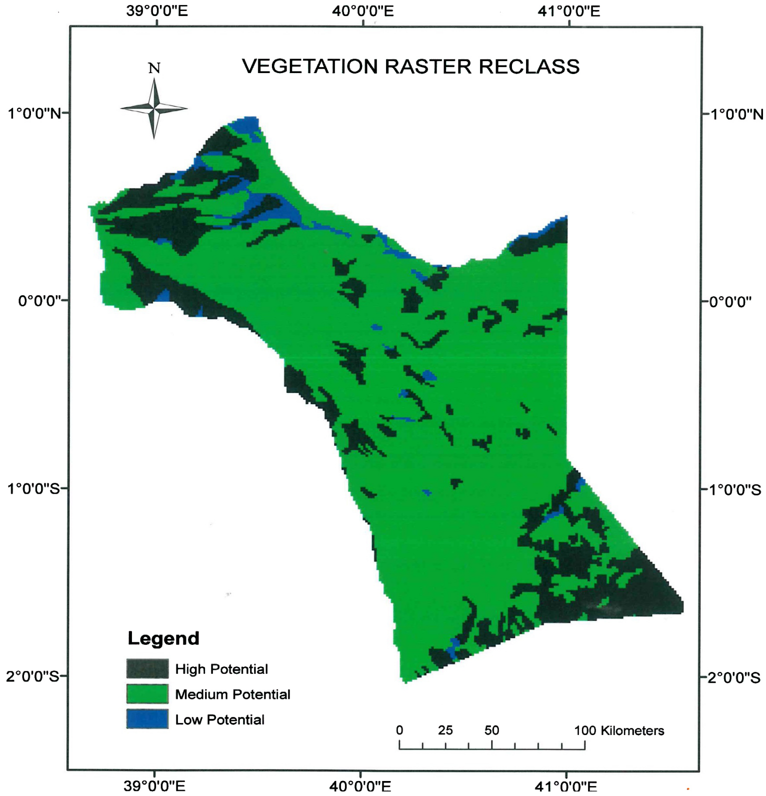

Figure 11. Garissa Country vegetation raster re-classed.

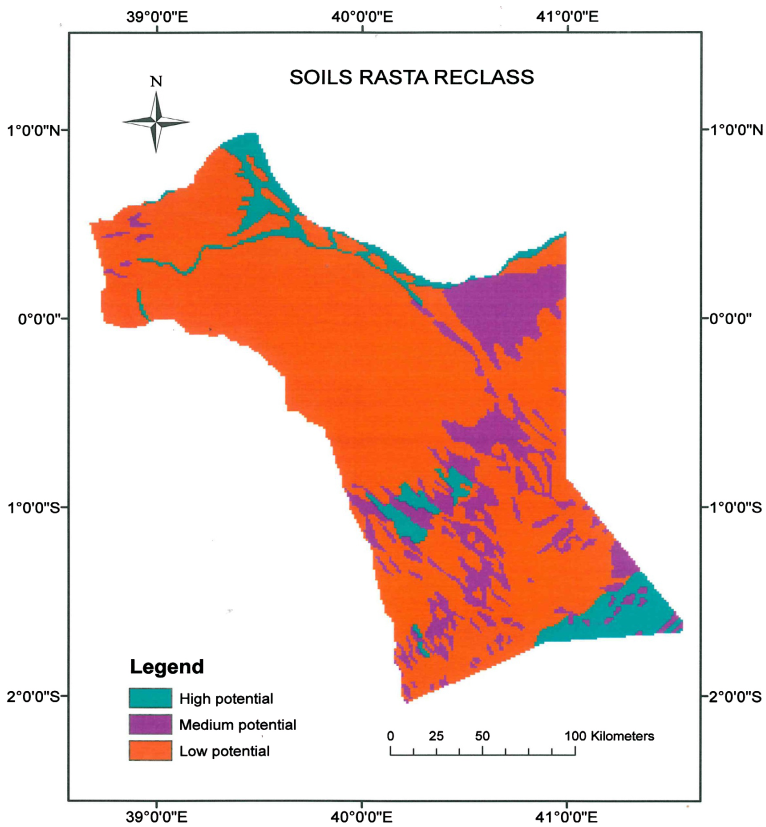

Figure 12. Garissa Country soils raster re-classed.

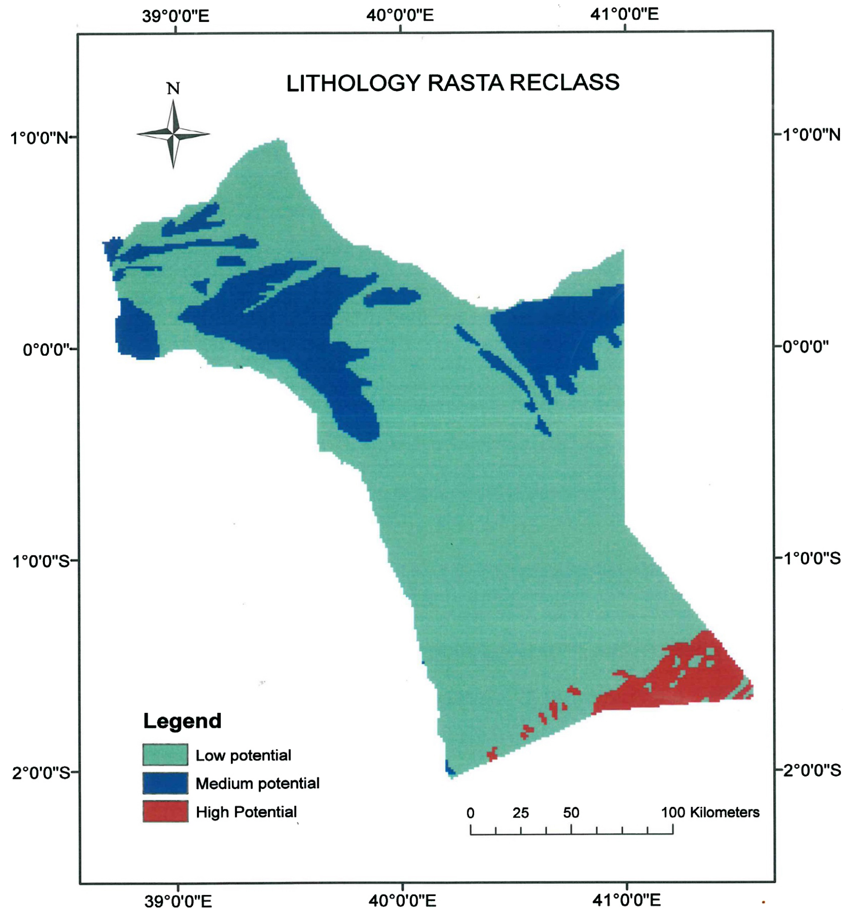

Figure 13. Garissa Country rock formation raster re-classed.

Table 6. Pairwise comparison between factors.

	Soils	Lithology	Landcover
Soils	1/1	1/2	3/1
Lithology	2/1	1/1	4/1
Landcover	1/3	1/4	1/1

Table 7. Weights (indexes) of the factors.

S/No.	Thematic layer	Thematic weight
1	Soils	0.32
2	Lithology	0.56
3	Vegetation	0.12

lithology is 4 times as important as landcover. The comparison was expressed as a ratio and tabulated (Table 6).

The pairwise comparison generated a matrix that was manipulated to produce its Eigen vector. The computation stopped when the difference of Eigen vectors in two consecutive calculations was smaller than 0.001 a prescribed value. The Eigen vector gives the factors weights (Table 7).

3. Results and Discussion

3.1. Results

3.1.1. Integration of the Factors Layers

After weighting, the three Factors (Vegetation, Soils and Lithology) were integrated (added) using ArcGIS10.1 Arc Toolbox (Spatial Analyst Tools-Overlay—Weighted Overlay) to produce the final output (Results) which is the Groundwater potential zones. The Output produced two classes of groundwater potential zones namely; medium and low yield zones (Figure 14).

3.1.2. Validation of the Results

Overlay with Existing Borehole Yields

This was done by overlaying the groundwater potential zones layer (Figure 14) with the existing boreholes layer (Figure 7) and evaluating the predicted ground water potentials against the actual borehole yields. The overlay produced the validation map shown in Figure 15.

Classification of Existing Borehole Yields

After the thematic data was integrated (added) the output (groundwater

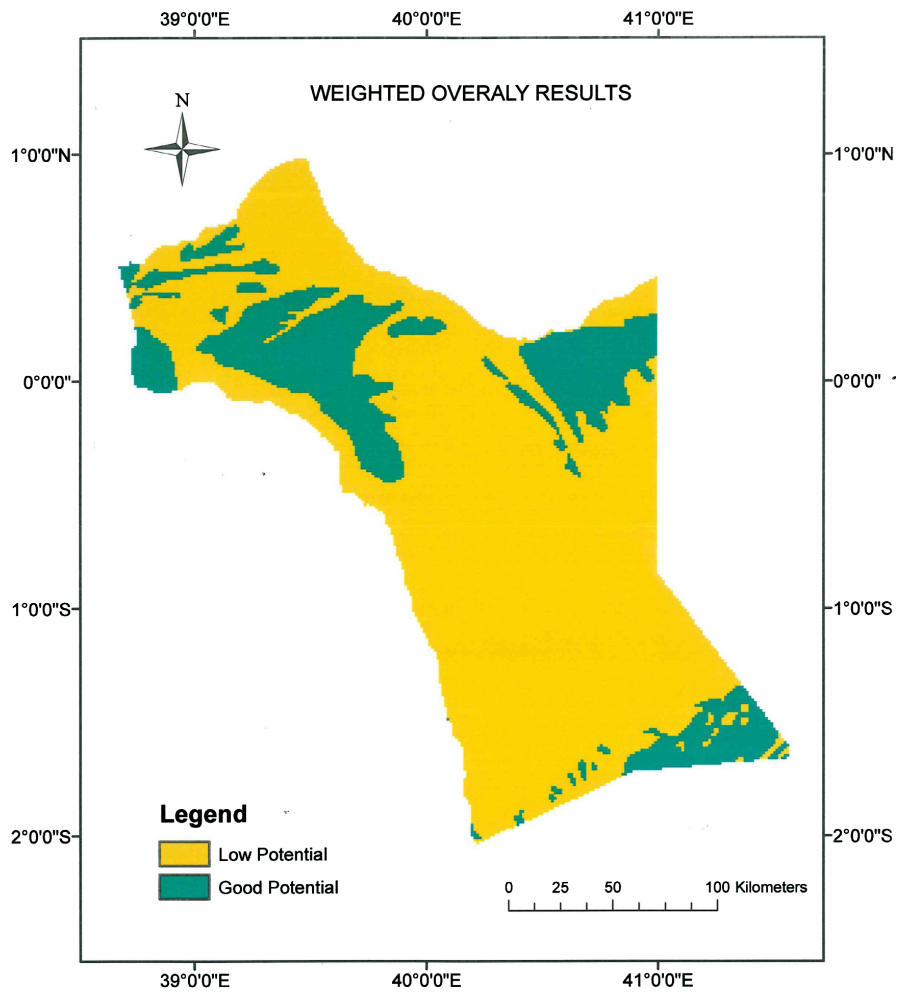

Figure 14. Garissa Country groundwater potential zones.

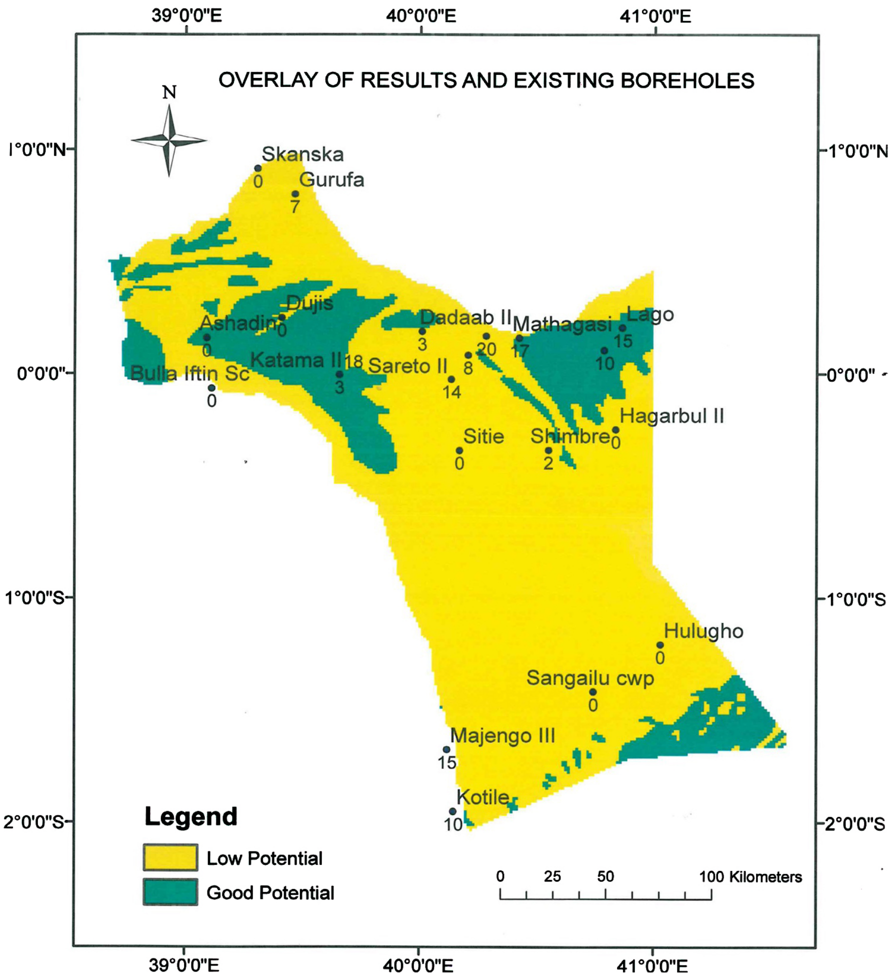

Figure 15. Overlaid groundwater potential zones with existing boreholes.

Table 8. Classified and ranked borehole yields.

S/No.	Yield m^3/hr	Rank	Class	No. B/holes	Percentage
1	0 - 7	2	Low	12	57.1
2	8 - 20	1	Good	9	42.9
	Total			21	

potential zones map) produced two classes of groundwater potential zones namely low and medium. In this regard the existing boreholes yields were classified into two classes; 0 - 7 low and 8 - 20 good in order to enable graphical and statistical analysis (Table 8).

Ranking of Borehole Yields

To enable evaluation of the predicted groundwater potential zones against the yield values of the existing boreholes, the existing boreholes classes were ranked on a scale of 1 to 2. Good yield boreholes were ranked 1, and low yield boreholes were ranked 2 as shown in Table 8.

Ranking of Groundwater Potential Zones

The groundwater potential zones were ranked on a scale of 1 and 2. Good potential was ranked 1 and low potential 2 as indicated in Table 9.

Validation Process

The names and yields of all the existing boreholes were tabulated. For each borehole its rank (1 or 2) Table 9 was noted and indicted as Actual Rank and its corresponding class Good or Low) noted and indicated as Actual Potential from Table 9.

From the validation map (groundwater potential zones and existing boreholes overlay) (Figure 15), the potential zone (Low or Good) in which each borehole was located was noted and indicated as predicted potential and the zone rank (1 or 2) from Table 10 noted an indicated as predicted rank.

Table 9. Ranking of groundwater potential zones.

S/No.	Groundwater Potential Zone	Rank
1	Low	2
2	Good	1

Table 10. The model's predicted potential and boreholes actual yields.

S/No	Name of borehole	Yield M^3/hr	Actual Rank	Actual Potential	Predicted Potential	Predicted Rank
1	Ashadin	0	1	Low	Low	1
2	Skanska	0	1	Low	Low	1
3	Bulla Iftin	2	1	Low	Low	1
4	Dujis	3	1	Low	Low	1
5	Gurufa	0	2	Low	Good	1
6	Abdi Samet I	0	2	Low	Good	1
7	Katama II	14	1	Good	Low	2
8	Dadaab II	17	2	Good	Good	2
9	Majengo III	3	2	Low	Low	2
10	Sareto II	18	1	Good	Good	1
11	Kotile	7	2	Low	Low	2
12	Sitie	10	1	Good	Good	1
13	El-Humon	0.72	1	Low	Low	1
14	Lebisigaley II	0	1	Low	Low	1
15	Mathagasi	0	1	Low	Low	1
16	Shimbre	0	1	Low	Low	1
17	Sangailucwp	8	1	Good	Low	2
18	Damanjare	0	1	Low	Low	1
19	Hagarbul II	20	1	Good	Low	2
20	Lago	15	2	Good	Good	2
21	Hulugho	0	1	Low	Low	1

The comprehensive data on the model and boreholes Yields, Actual and Predicted ranks/potentials were tabulated as shown in Table 10.

Graphical Comparison

The comparison between the predicted and actual potentials was demonstrated graphically by plotting the predicted rank alongside the actual rank (Figure 16).

Statistical Comparison

It can be observed from the graphical comparison that one can't make a quick conclusion of the validation. In this regard it was necessary to exude the validation statistically. The actual and predicted potential scores were expressed inter ms of low and good, and analysed (Table 11).

Groundwater Potential Zones Map

From the above analysis the predicted groundwater potential zones (model results) were validly confirmed to for the Groundwater Potential Map for Garissa Country (Figure 17).

3.2. Discussion

3.2.1. Groundwater Potential and Existing Data

In this study, Weighted Index Overly Analysis and Analytical Hierarchal Process (AHP) were used to produce a Predicted Groundwater Potential Map of Garissa Country using variables known to influence groundwater in an area. A comparison of the predicted values with actual values from boreholes drilled in the area indicated that out of the 21 boreholes sampled, the model correctly predicted the potential of 16 boreholes (76.1%). The model wrongly predicted the potential of 5 boreholes (23.8%). Interestingly, out of the 14 sites with low

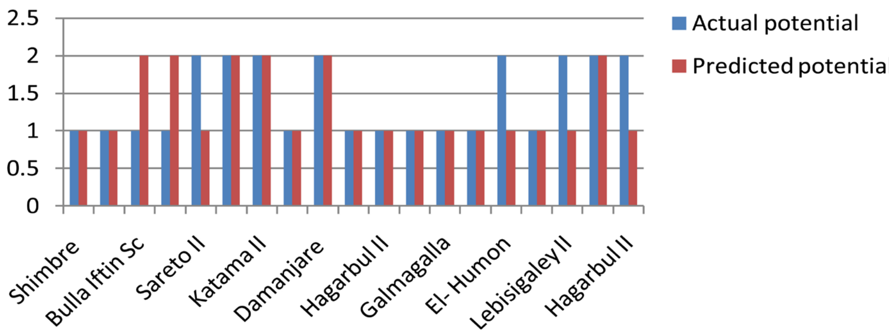

Figure 16. Predicted potential plotted against the actual potential.

Table 11. Predicted vs actual potential analysis.

S/No.	Yield M^3/hr		GW Potential			
	Class	Score	Correct	Wrong	Total	%
1	0 - 7	Low	12	2	14	85.7
2	>8	Good	4	3	7	57.1
	Total		16	5	21	76.1

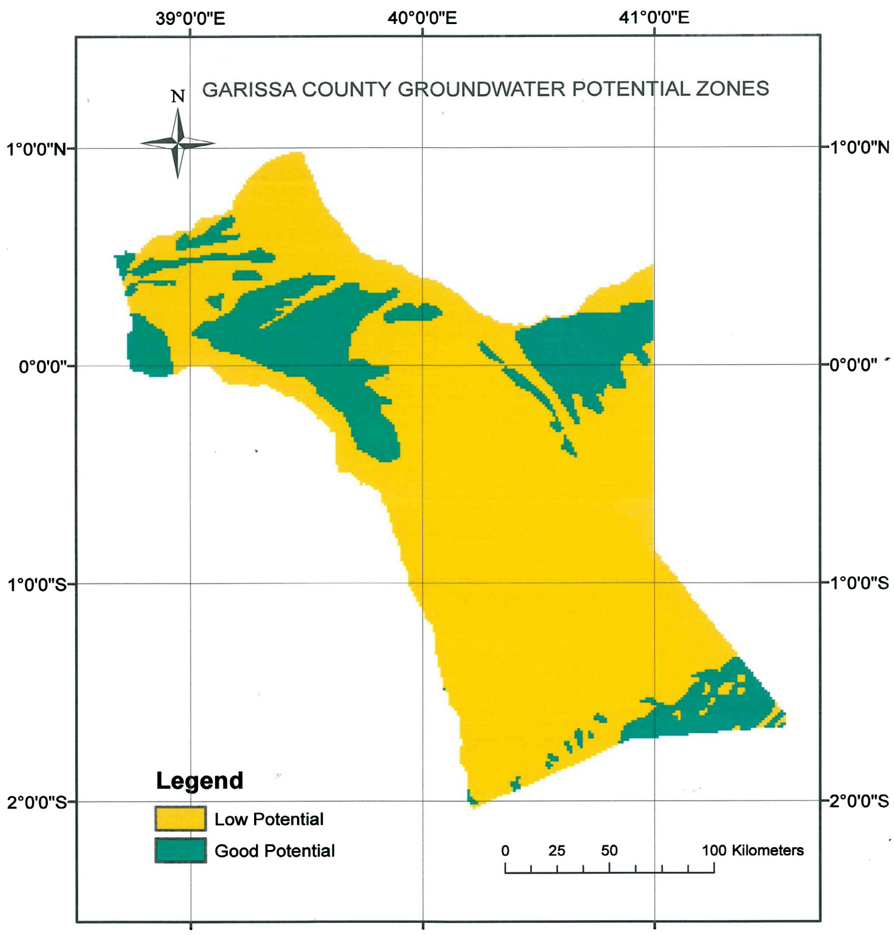

Figure 17. Groundwater potential map for Garissa Country.

Table 12. Overall borehole yields comparison.

S/No.	Yield M^3/hr	Boreholes	Percentage
1	0 - 1	10	47.7
2	2 - 7	4	19.0
3	8 - 14	3	14.3
4	15 - 20	4	19.0
	Total	**21**	**100**

potential for groundwater, the model correctly predicted 12 sites (85.7%) and out of the 7 good sites the model correctly predicted 4 sites (57.1%). This result indicated that the model showed good results when predicting areas with poor potential for groundwater (Table 12).

Existing Data

Existing data of drilled boreholes indicates that majority of boreholes in Garissa yielded no water (47.7%), with only 19% of the boreholes drilled yielding high volumes of water. About 33% of the boreholes yielded low volumes (Table 12).

Table 13. Factors relative contribution to groundwater.

S/No.	Factor	% Contribution
1	Lithology	56
2	Soils	32
3	Landcover	12

Groundwater Factors

The analysis indicated that lithology of the area had the biggest influence on groundwater potential, accounting for 56% of the generated groundwater potential. Soils had the second largest influence on groundwater potential accounting for 32% of the potential and vegetation accounted for only 12% of the groundwater occurrence (Table 13).

Despite the lithology in the country showing great potential for groundwater, overall, the influence of the other factors contribute to the poor groundwater potential experienced in Garissa.

3.2.2. Past Studies and Limitations

Numerous studies have been carried out to map groundwater potential in many regions where consistent supply of surface water is not guaranteed. Water resources managers have taken advantage of the ability to quickly create GIS models, making GIS the "go to" tool when looking at problems dealing with water management, and in particular groundwater exploration.

Few studies corroborate the findings of their model with actual data on the ground, mainly because such data is difficult to obtain or has not been generated. Where possible it is recommended that GIS modelling results are validated with ground data.

4. Conclusions and Recommendations

4.1. Conclusions

- It is established that provided the model is used as a pre-analysis tool. The result of the model can give useful information to planners in that whereas the map generated here does not accurately indicate sites where drilling is to be done, it accurately predicts areas where the groundwater potential is poor and drilling of boreholes should be avoided.
- The model and actual borehole yields showed similar results when overlaid. About 57% of the borehole yields confirmed that the model correctly predicted the zones with good groundwater potential and 86% of boreholes confirmed zones with poor potential and an overall accuracy of 76%.
- The model clearly delineates areas with poor ground water potential where drilling of boreholes will not be used as a method of water supply and other methods of water provision should be explored thus saving time and other resources.

4.2. Recommendations

- Prospecting for groundwater in areas predicted to have good potential require caution since groundwater is not uniformly distributed underneath. Exploration for suitable sites will require use of other available supplementary information such as yields and depths of existing boreholes to evaluate the suitability of a site before borehole drilling work commences.
- The output can be improved by improving the quantity and quality of the study validation data by carrying out field visits to confirm the GPS coordinates and yield values of the all the 37 mapped sites. Therefore a complete mapping of all the existing boreholes will ensure the use of the model in a more conclusive pre-analysis excise.
- The user of the model need to be aware that the actual results may differ from expected results since the whole process is approximation to the end and not a definite conclusion of the outcome.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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