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Groundwater Potential Mapping using Remote Sensing and GIS in Rift Valley Lakes Basin, Weito Sub Basin, Ethiopia

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Abstract-Conventional groundwater exploration methods, though they deliver higher quality results of varied scale, tend to be time consuming and expensive endeavors. The use of remotely sensed data and geographic information systems opens up the possibility to harness information of vast spatial and temporal scale, analyze, and manage it efficiently. In this paper, remotely sensed data along with geologic maps and discrete rainfall data are used to develop groundwater potential map for Weito watershed in the rift valley lake basin(RVLB) in Ethiopia. Thematic layers of rainfall, land use, slope, soil, lithology, drainage, lineament and geomorphology were developed. PCI Geomatica software is used for land use classification and lineament extraction from Landsat 8 OLI/TIRS multispectral images. ArcGIS 10.0 and its extensions are used to develop slope and geomorphologic maps from SRTM 30m DEM and digitize existing geologic maps. Soil data from ISRIC's soilgrids database at 250m resolution for the top 200cm is used to develop soil map for the watershed. Weights are assigned to the layers using analytical hierarchy process (AHP) and overlay analysis in ArchGis used to develop the groundwater potential map. The results show 1, 15 and 23 per cent of the watershed classified as excellent, very good or good respectively, while the remaining 60 per cent of the land area is either poor or very poor groundwater potential.

Index Terms- AHP, DEM, GIS, Groundwater, Landsat 8, Map, Overlay, Remote Sensing, SRTM, Watershed

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1 Introduction

THE importance of groundwater for the socio-economic improvement of developing countries like Ethiopia cannot be over-emphasized. The ever-increasing population, rapid economic development and climate change are some of factors increasing the strain on surface water sources and shifting priorities to groundwater resources. These challenges can only be mitigated through effective utilization of all available resources in efficient and sustainable manner.

Ground water is contained in underground rocks, which contain and transmit water in economical rate generally referred to as aquifers. The amount and distribution of groundwater is a function of the amount of open space and the special extent of these rocks. The behavior of these rocks in turn is function of their formation and geological processes that shaped their status.

Conventional groundwater exploration require hydro-geologic investigation to study the lithology, stratigraphy and structural aspects of a region using geologic methods to understand the factors that regulate the amount, circulation and quality of groundwater, [1].These studies deliver results of various type and quality based on the scale of the study.

In recent years, relatively cheap availability of remotely sensed data of higher spatial and spectral resolution and increasing availability image processing algorithms and GIS technology has enabled better efficiency in groundwater resource potential exploration.

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In this paper groundwater potential map for Weito watershed, the southernmost sub-basin of the rift valley lakes basin in Ethiopia is developed using Landsat 8 OLI/TIRS images, shuttle radar topographic mission (SRTM) digital elevation model (DEM) and other data sources using overlay analysis.

2 Background

2.1 Groundwater availability and Utilization in Ethiopia

Rechargeable ground water potential of Ethiopia is controversial and there is no consensus so far as to the estimated exploitable groundwater potential, [16]. It varies from WAPCOS [17] estimate of around 2.5 BCM to preliminary national estimates of Ayenew et al [2] at 185 BCM. WAPCOS [17] reported an estimate for groundwater potential of rift valley lakes basin using methods such as base flow separation, subsurface drainage and replenishable recharge as 2217 MCM/year, 1280 MCM/year, 889 MCM/year respectively. Halcrow and GIRD [9] put forward an estimate of the groundwater in the basin at 1080 MCM/year. This estimate is based on rainfall recharge coefficient method. The coefficients are weighted based on hydro-geologic formations presumed in each Woreda (administrative units) in the basin. The groundwater potential of Weito sub-basin is not separately reported and it is not possible to estimate from their work due to the nonalignment of hydrologic and administrative boundaries.

Although these estimates are course, with a low degree of confidence, they indicate availability of

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significant resource, which can and should be utilized in socio-economic development of the region. Currently groundwater is the main source for domestic waters supply. Irrigation and industrial water demand are addressed from surface water sources in the basin.

2.2 Description of the study Area

Weito watershed is the southernmost watershed of rift valley lakes basin, one of the twelve river basins in Ethiopia. The sub basin is located between longitude 36.6^0 to 38.1^0 E and latitude 4.9^0 to 6.3^0 N with a total area 13,988.55 square kilometers. Elevation ranges between 3400 m a.s.l in Gamo highlands to 490 m a.s.l in the Chew Bahir area, Fig.1.

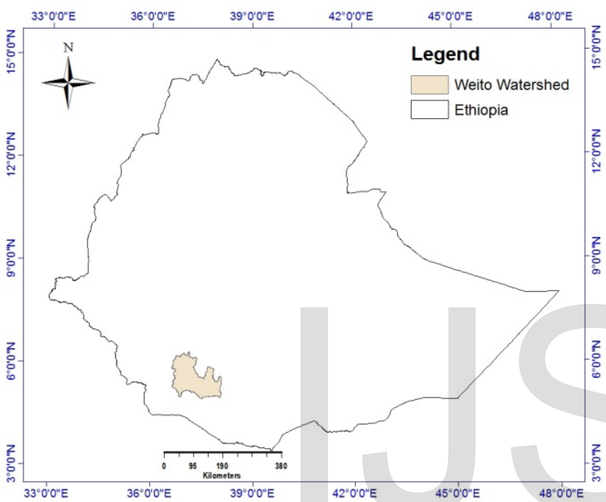

Fig.1. Location map of Weito Watershed

The sub basin receives a mean annual rainfall 869.44 mm (24 stations in and around the watershed National Meteorological Agency).However, the rainfall has large spatial variation 2000 mm in the northwest highlands to 305 mm southern low lands and follows a bi-modal temporal pattern. The mean annual temperature ranges 22^{0}C and 24^{0}C (National Meteorological Agency). The watershed dominated by semi-arid tropical climate.

Weito watershed is drained by to major river systems, namely Weito river which flows north-south and Segen river which flows east-west with a confluence at Chew Bahir wetland, Fig.2. According to Harclow and GIRD [9] rift valley lakes basin (RVLB) master plan study reports the two river systems drain 506 Mm^3 per year in to the Chew Bahir and surrounding Wetland.

The sub basin is a subject of large-scale irrigation development through private and public investment in recent years. As a result, the existing surface water sources are under increasing pressure. Development of groundwater sources will help alleviate some of the strain caused by competition for water.

3 Groundwater Exploration using Remote sensing and GIS

The Ethiopian aquifers are perceived as the most complex, compartmentalized, and relatively low storage aquifers, [16].This is attributed to the multifaceted geological history. Henceforth, the conventional groundwater exploration methods will be expensive and time consuming.

Remote sensing methods compile spectral information about a region of interest from which geological, ecological, environmental and hydrologic information can be extracted. Geographic information system application facilitates integration of these spatial data in efficient manner to facilitate decision-making.

A brief review of the hydrologic cycle illustrates the replenishable groundwater potential of a particular area is a result of recharge from precipitation and/or subsurface and groundwater flow. Groundwater basin boundaries rarely align precisely with surface water basin boundaries. Hence, the probability of groundwater flow from adjacent land area into the watershed is considerable.

Water from direct precipitation will infiltrate into the soil. The type of soil i.e. the hydraulic conductivity affects infiltration; the land use/ land cover condition, the slope and other variables also influence the magnitude of infiltration. Some of the infiltrated water will travel horizontally as subsurface flow while the other will percolate into the groundwater to recharge the underground reservoir.

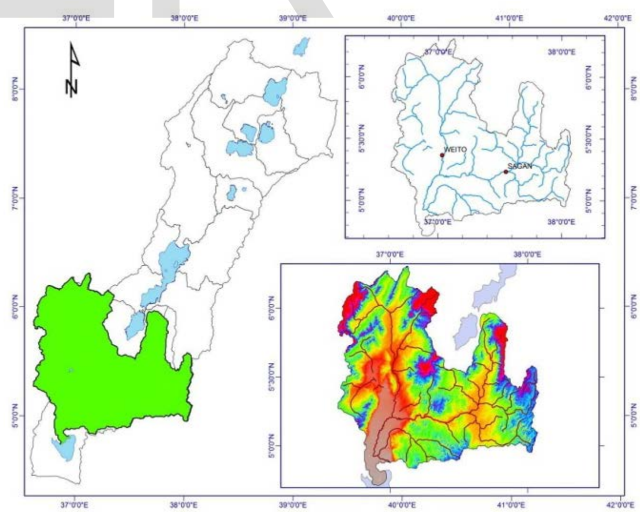

Fig. 2. Drainage pattern in Weito Watershed

The lithology i.e. the rock type is a major influence in groundwater capacity to store water. The nature of storage and transmission of water through the rocks can be through the pores of the intact rock and through discontinuities in the rock mass. The important attributes are accounted for through the lithologic map and lineaments i.e. geologic structures.

Geomorphology considerations in groundwater potential assessment hopes to incorporate the indirect influence of morphmetric variables such as relief and slope on rainfall availability, drainage vegetation cover etc. The landforms are the result of geologic process, which cannot readily be directly accounted for. Hence, inclusion of these morphmetric characteristics will incorporate the result of the geologic process in the groundwater potential assessment. These influence factors are neither exhaustive nor independent of each other. There is a varying degree of influence between each other.

Many studies have used GIS and remote sensing to study the groundwater potential of their region of interest, [5],[8],[10],[12],[13].The method is applied in various terrain and geologic formations. These papers have all included thematic layers for rainfall, soil type, slope, lithology, lineaments and drainage density, although the minimum number of factors and the mechanism of assigning weight to these factors shows variability.

Some studies have applied probabilistic models such as multi-criteria decision analysis and weights-of-evidence modeling for groundwater potential mapping. Other studies have used personal judgments or local information to assign weight to different thematic layers and their features, [15].

4 Data And Methodology

The various thematic layers for influence factors are prepared from multiple data sources. These data are collected in multiple formats. Landsat 8 OLI/TIRS data is used for land cover classification and lineament extraction. Scenes used in the analysis according to Landsat 8 nomenclatures are LC 81680562016024 LGN00, LC 81680572016024 LGN00 and LC 81690562015028 LGN00.

The slope, geomorphology and drainage maps are developed from SRTM 30m digital elevation models. The results are verified through multiple field trips in the watershed.

Geologic map, acquired from Ethiopian geologic survey, is digitized and converted to raster format. Rainfall data from gauging station in the watershed is complemented with climate model data to developed a representative rainfall raster.

Clay fraction, which is believed to be a major factor determining soil permeability there by infiltration, acquired from ISRIC soil information database at 250m spatial resolution for the top 200 cm and incorporated in the analysis.

The weight of individual layers in the overlay analysis to determine the groundwater potential map is computed using analytic hierarchy process (AHP). The method enables pair-wise comparison of influencing factors. It incorporates subjective judgment of experts in the field for the degree significance and objective analysis for determining individual weights. The methodology using in this paper is summarized as shown in fig.3.

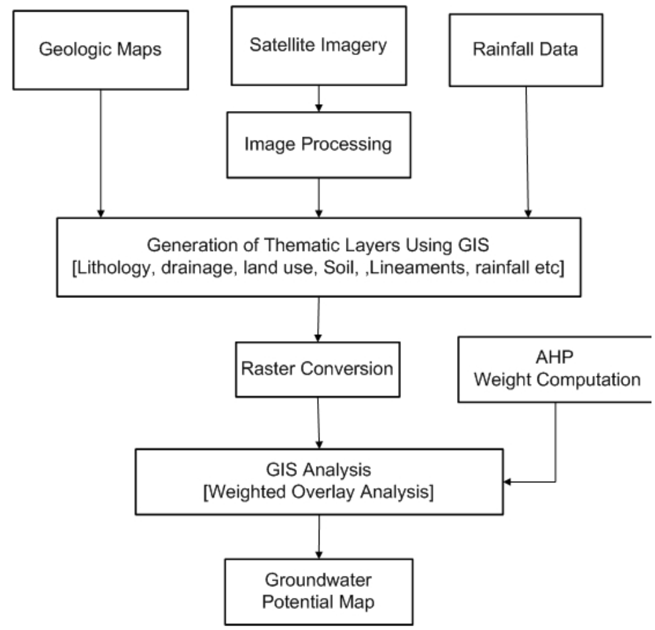

Fig. 3 Methodology Diagram for Groundwater Potential Mapping

5 Results and Discussions

5.1 Rainfall

The mean annual rainfall Weito watershed and its surrounding areas was collected from the National Meteorological Agency (NMA) and augmented by other data sources such as climate-Data.org [3]. The national meteorological data sets are measured point data from rain gauge stations. Mean annual rainfall of towns/villages around the watershed collected from climate-data.org generated by a climate model. The model has more than 220 million data points and a resolution of 30 arc seconds. The model uses weather data from thousands of weather stations from all over the world collected between 1982 and 2012,[3].

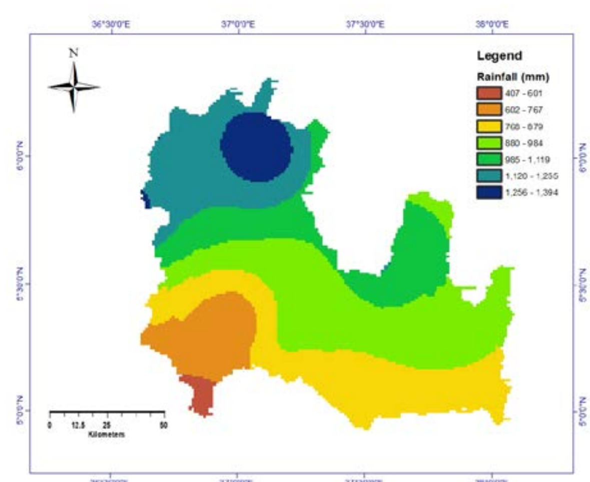

Fig. 4 Rainfall Raster for Weito watershed

The mean annual rainfall is computed for twenty-four station spatially spread in and around the watershed and length of record ranging between 3-11 years between 2005-2016. The rainfall raster, shown in fig.4, is computed using IDW interpolation in ArcGIS geostatistical analysis tools and resample to 30m resolution to facilitate overlay analysis.

5.2 Slope

The slope map for the Weito watershed, fig. 5, is computed from Shuttle Radar Topography Missions (SRTM) 30m resolution digital elevation model (DEM). The data had voids in some areas. These voids are filled by using a filled 90m DEM provided by the same source, resampled to 30m using raster calculator in ArcGIS's map algebra. The remaining sinks where taken care of using the fill the sink algorithm in ArcGIS's spatial analyst hydrology tool.

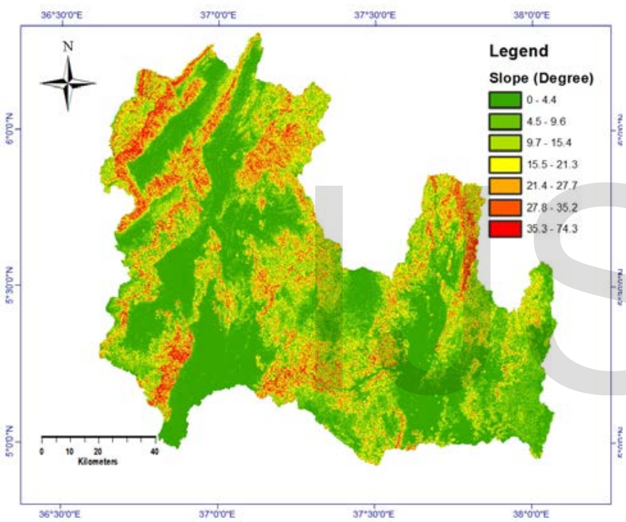

Fig. 5 Slope map for Weito Watershed

5.3 Drainage Density

The drainage density map is calculated from the shuttle and radar topographic mission (SRTM) 30m digital elevation model using ESRI's hydrology tool. The united sates geological survey (USGS) recommends 5000 cells of total area 4.5 km² to define a stream. These recommendations result in unrealistic drainage network, largely due to the rugged terrain of the catchment. Hence, an area of nine square kilometer(10,000 cells) is used to define streams. The resulting drainage patterns are shown in fig. 6a. The drainage density is prepared using ArcGIS's spatial analyst's line density tool and presented in fig. 6b.

5.4 Lineament Density

A lineament is usually defined as a straight or somewhat-curved feature in an image. In a satellite image, lineaments can be the result of man-made structures such as transportation networks (roads, canals, etc.), or natural structures such as geological structures (faults/fractures, lithologic boundaries, unconformities) or drainage networks (rivers). A lineament is distinguishable by the change in image intensity as measured by gradient. By applying edge detection filters to the image, a numerical method for lineament detection can be constructed.

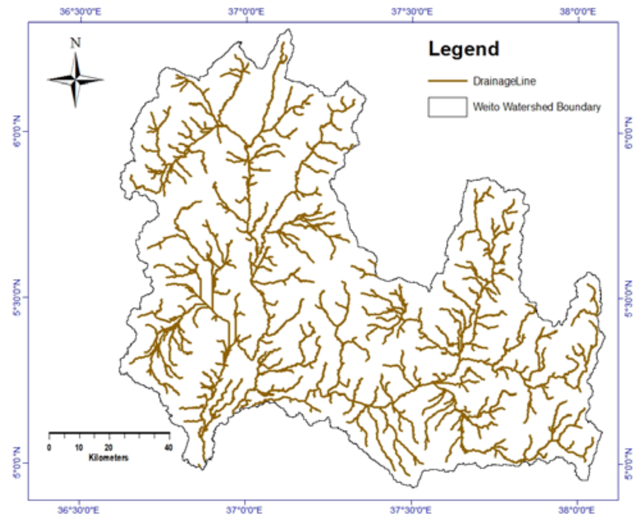

Fig. 6a Drainage Lines for Weito Sub Basin

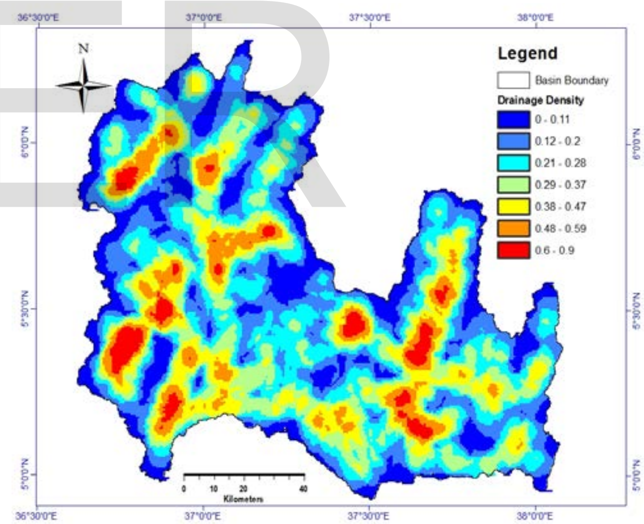

Fig. 6b Drainage Density Map for Weito Sub Basin

Lineaments for lineament density computation are extracted from Landsat 8 OLI/TIRS path 168, row 57 and 58 and path 169 row 56 according to WS2. The image date is January 2016 and 2015. The dates of these scenes were selected to improve the probability of cloud free images. The Landsat 8 OLI /TIRS band 8 is used to extract line elements due to its higher spatial resolution. Using the line algorithm in PCI Geomatica toolbox. The algorithm comprises of three stages; edge detection, thresholding and curve extraction. The resulting lineaments are presented in fig.7a.

The resulting vector image is edited manually for

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image boundaries, mountain ridges and other features, which are unlikely to positively influence the potential infiltration of precipitation water. The resulting vector layer of lineaments is compared to large scale geologic map of the watershed and found to be satisfactory. The vector layer is imported to ESRI's ArcGIS 10.0 and line density tool in spatial analyst toolbox is used to compile the density map fig. 7b.

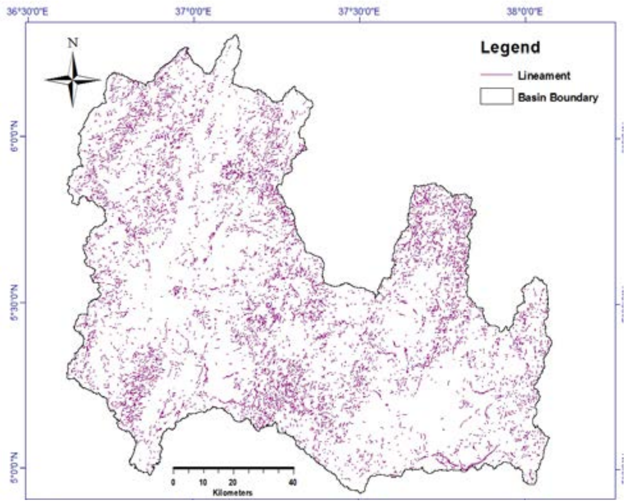

Fig. 7a Lineament Extracted from Landsat 8 Band 8

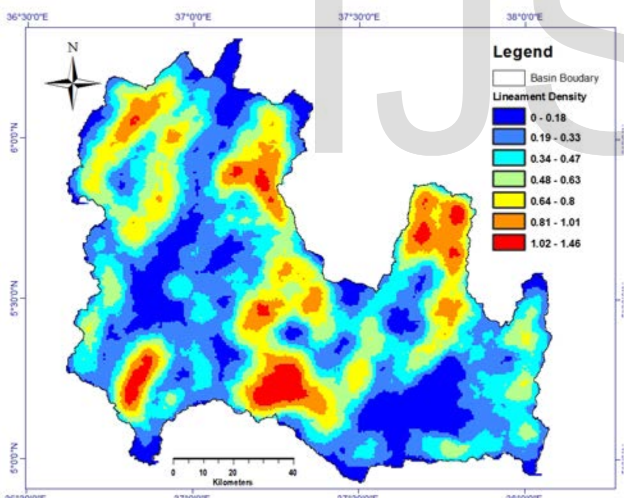

Fig 7b Lineament density map for Weito Watershed

5.5 Lithology

The lithology map is developed from 1:2,000,000 and 1:500,000 geologic map published by Ethiopian geologic survey published in 1973 and 1979. The later map, although with a higher resolution, does not cover the entire study area and hence used to identify and interpreted undifferentiated lithologic units.

These maps were geo-referenced and clipped to the study area's shape. The shape files for nine lithologic units within the study area are drawn to create a vector layer and the vector layer converted to a raster layer of the same in ArcMap 10.0. The symbols from the original map are adopted from in fig.8 the description of which is given in the table 1.

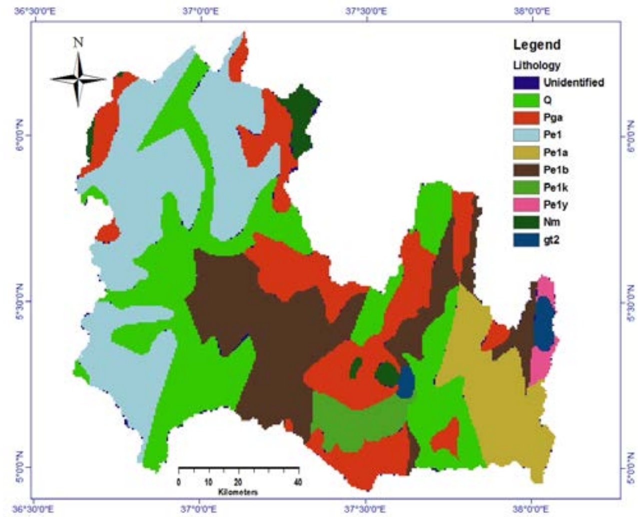

Fig. 8 Lithologic Map of Weito Watershed

5.6 Land Cover

The land cover classification for Weito watershed is prepared using PCI geomatica 2013 software. unsupervised classification with k-mean algorithm is employed on a multispectral, seven band composite, bands 1-7, image of Landsat 8 OLI/TIRS is prepared after atmospheric and haze correction in PCI geomatica focus fig. 9a. The result is aggregated to five group, namely; hills sides, forest/vegetation, bare soils, water bodies and sand, wadi and dry river beds (DRB) are selected with their prospect of influencing groundwater recharge. The dates of the acquired scenes coincides with the after harvest period in the study area. Hence, the majority of the land area identified in the classification image as bare soils is likely to be agricultural land, fig.9b.

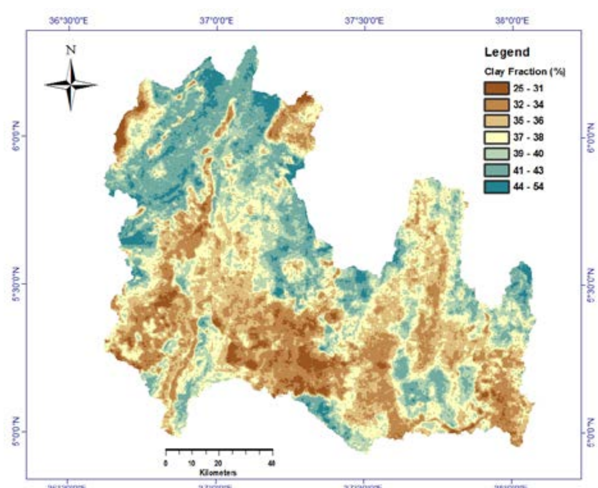

Fig. 10 Clay fraction map for Weito Watershed

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Table 1 Lithologic Units in Weito watershed [18]

Symbol	Description	Period	Remarks
Q	Alluvial, Fluvial, Lacustrine Sediments	Pleistocene, Holocene	
Pga	Alkali Oliven basalt and Tuffs with Rhyolites	Paleocene-Oligocene-Miocene	Ashangi Group
Pe1 • Pgbh* • Pebh* • Pgh*	Undivided Gneiss predominantly Biotite and Horneblende gneiss; Migmatite impart with minor metasedimentary Gneiss; quartzo-feldspathic Gneiss Amphibolites Aranitoid ortho Gnesis	Precambrian Lower Complex	Hamar Domain
Pe1a	Awata Gnesis, Biotite and Amphibole-biotite Gnesis subordinate quartzo-feldspathic rocks quartizite, ironstones, calc-silicates	Precambrian Lower Complex	The Arero group
Pe1b	Fine foliate Biotite, Gneiss and Schist	Precambrian Lower Complex	Burji Gneiss
Pe1k	Pyroxene, Amphebole Pyroxene Pyroxene-Granit Gneiss	Precambrian Lower Complex	Konso Gneiss
Pe1y	Massive quartzo-feldspathic rocks interbedded with Gneiss	Precambrian Lower Complex	Yabelo Gneiss
Nm	Rhyolite, Trachyte, Rhyolite and Trychyte Tuffs: Ignimbrite agglomerates, basalts	Upper Miocene Pleistocene	Magdala Group
gt2	Post tectonic Granitoids	Precambrian Lower Complex Upper Proterozoic	

*Detail description adopted from 1:500,000 geological map of Omo River Project Area from Ethiopian Geological Survey 1

5.7 Soil Map (Clay Fraction)

Soil map is acquired from ISRIC world soil information. ISRIC is an independent science based foundation, which operates in soil data and mapping as one of its priority areas. The data is available at the portal https://www.soilgrids.org/ at 1000m and 250m spatial resolution covering global extents. "Soilgrids" is a system for automated soil mapping based on global soil profile and environmental covariate data. It represents a collection of updatable soil property and class maps produced using automated soil mapping based on machine learning algorithms. "Soilgrids" predictions are updated on a regular basis (at least every few months).

With respect to groundwater recharge and potential assessment, the infiltration and percolation capacity is assessed in terms of the clay fraction, which is presumed to be the major attribute that influences soil permeability, fig.10.

5.7 Geomorphology

Geomorphology i.e. landforms of Weito watershed is developed from SRTM 30m digital elevation model using Hammond (1964) macro land form mapping as presented by Morgan et al (2005) procedure in ArcGIS's spatial analyst tool. Land from is a combination of slope, relief and profile. The classification and description is adopted from Dikau's landform codes,[7] fig.11.

Technically a landform map is not complete without the geologic history and the process that resulted in for the landforms presented in the maps. In this case, however, the map is satisfactory for the intended purpose.

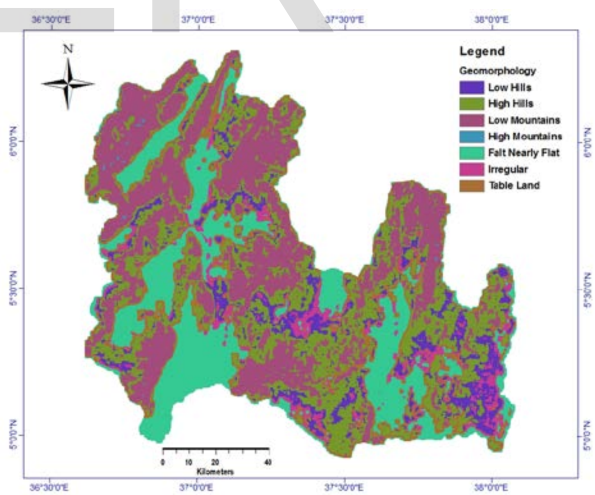

Fig. 11 Geomorphology map for Weito Watershed

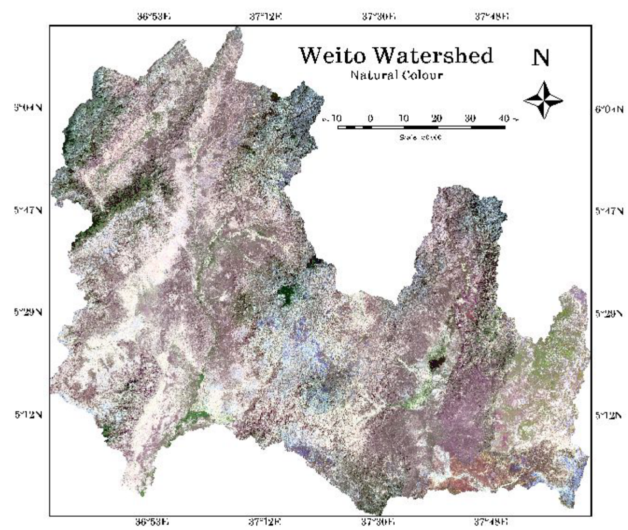

Fig.9a Natural Colur Landsat 8 Image of Weito Watersed

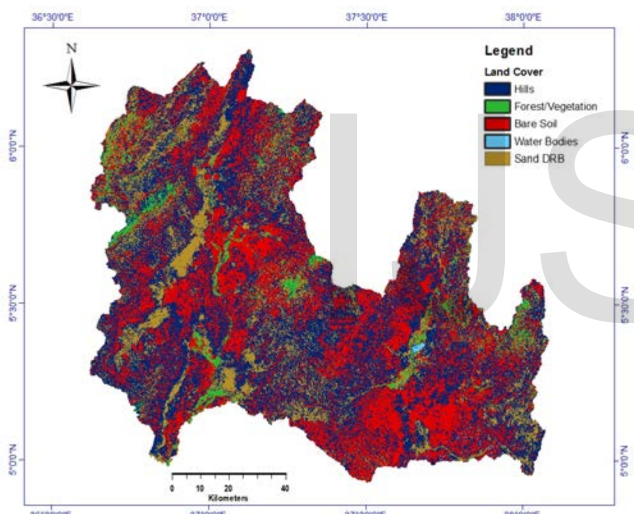

Fig. 9b Land cover classification of Weito Watershed

5.8 Analytic Hierarchy Process (AHP)

The rainfall map, slope map, lithology map, lineament density, drainage density, geomorphologic map, land cover map, and clay fraction maps were complied in raster format for input in overlay analysis.

The weight of each layer is computed using analytical hierarchy process. The analytic hierarchy process (AHP) introduce by Thomas Saaty (1980) is one of a family of methods known multi-criterion analysis for decision-making when the attributes and of decision variable are interrelated and cannot be quantified through measurement [6].

By reducing complex decisions to a series of pair-wise comparisons, and then synthesizing the results, the AHP captures both subjective and objective aspects of a decision. The weights for the thematic layers adopted from AHP are show in table 2.

Table 2 Weights calculated from AHP for overlay Analysis

S.No	Thematic Layer	Weight,%	Remark
1	Rainfall, RF	17.4	
2	Lineament Density, LD	12.7	
3	Slope, S	17.7	
4	Drainage Density, DD	9.6	
5	Clay Fraction, CF	7.6	
6	Geomorphology, GEO	15.3	
7	Land Cover, LC	6.8	
8	Lithology, LIT	13.8	

5.10 Groundwater Potential Map

The groundwater potential map is developed in ArcGIS's spatial analyst weighted overlay analysis tool using Eq.(1).

$$\mathrm{GWP} = 0.174\mathrm{RF} + 0.127\mathrm{LD} + 0.171\mathrm{S} + 0.096\mathrm{DD} + 0.07\mathrm{CF} + 0.153\mathrm{GEO} + 0.068\mathrm{LC} + 0.135\mathrm{LIT} \quad (1)$$

The resulting maps is reclassified to five qualitative groups described as excellent very good, good , poor, and very poor, fig.12.

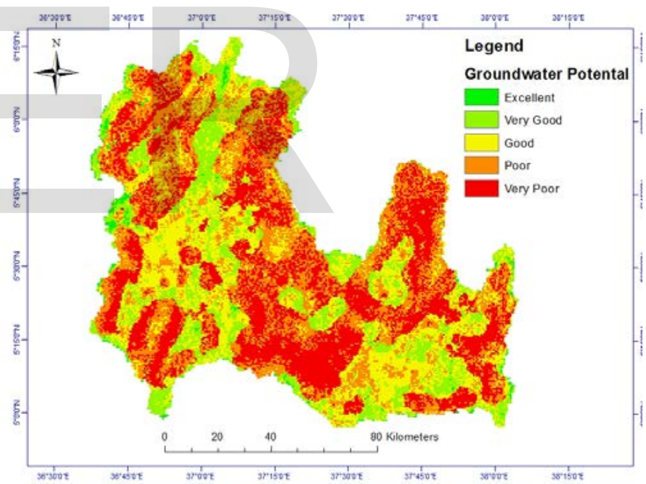

Fig. 12 Groundwater Potential Map for Weito Watershed

6 CONCLUSION

The watershed has low to medium potential with 1, 15 and 23 per cent of the watershed classified as excellent, very good or good respectively, while the remaining 60 percent of the land area is either poor or very poor groundwater potential.

The resulting groundwater map conforms to initial assessment based on secondary data sources such as landform and geological information. The use of soil data from ISRC as opposed to large-scale shape files from FAO has delivered promising results. With continuous improvement of the data set and the ease with which it can be incorporated in the analysis will make it a preferred data source for similar analysis.

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Detail investigation of the groundwater conditions using direct methods such as boreholes or indirect methods, geophysical investigation, can be lead by this map or other derivative results of proximity analysis that can incorporate distance from demand areas.

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