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Modeling Eco-Hydrology Indicators for Water Resources Assessment in Eastern Sudan

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ABSTRACT

The aims of this study is concerned of modeling the combined eco-hydrological components and its spatial distribution effect and evaluate its impact on the potential water flow of selected catchment in eastern Sudan. Spatial variability of landcover types and magnitudes was assessed using landsat7 and sentinel 2 images for years 1996, 2011 and 2018, topographic and soil type factors were used to assess the potentiality for runoff at sub catchment level using Curve Number approach. Rainfall records, Curve Number map and one gauge readings for stream discharge were used to simulate the hydrograph using 10 years return period and assess volumetric flow at sub-catchment level. Land cover changes showed reduction in natural vegetation through the studied periods. Curve Number was reflect the catchment high potentiality for generating runoff. The hydrograph analysis was generated and the runoff peak by means of volume and time during the storm event was generated. This study demonstrates this approach that can be used in agricultural promising areas for water management and planning purposes.

1. Introduction

Over the past several decades climate warming is consistently associated with changes in a number of hydrological systems components such as precipitation patterns, intensity and extremes, changes in soil temperature, moisture and runoff (Baba et al., 2011). The significant natural variability on interannual to decadal time is one of the attributed variables of hydrological changes therefore the anthropogenic non-climatic variables become more important and play crucial role locally and globally as reported by Douville et al. (2013). Land cover is the most important element for description and study of the environment it detects the human interventions that affect the terrestrial ecosystem productivity and it is used as reference for many applications due to its database content that differentiates types, intensity and composition of the land, in Sudan the dominated type of land cover is herbaceous closed to sparse (HCO) followed by Agricultural lands (AG). For woody cover, Shrubs closed to sparse (SCO) is greater than trees close to sparse (TCO) as reported by FAO (2012). In dry lands where the ecological reconstructing processes alter due to harsh environment and climate change scenario, remote sensing techniques applied to monitor the land cover change is enhancing the timely information needed to reduce the impact of landcover change over time and space, that is subjected to social, economic and environmental circumstances triggered the ecological system as reported by Jing and Guangjin (2011) and Brink et al. (2009).

The land cover is a key factor in hydrological modeling, its impact is extended from water quality to its quantity and runoff, therefore, it is an essential parameter for runoff at catchment scale that represent major interest to water resources planners, managers and decision makers (Base et al., 2006). According to Baldyga et al. (2008) land cover change affects hydrologic response at a range of scales, it alters both the balance between rainfall and evaporation and the runoff response of the area and modifies patterns and rates of water flow by determining the characteristics of runoff processes and influences the runoff by increasing its speed and amount in addition to decreasing percolation rate. Many researches reveal that land use and land cover changes in arid areas particularly woodland removal implies less infiltration due to a decrease in soil permeability, less interception of rainfall by the tree canopies and thus more runoff and high flow peaks (Yao et al., 2010).

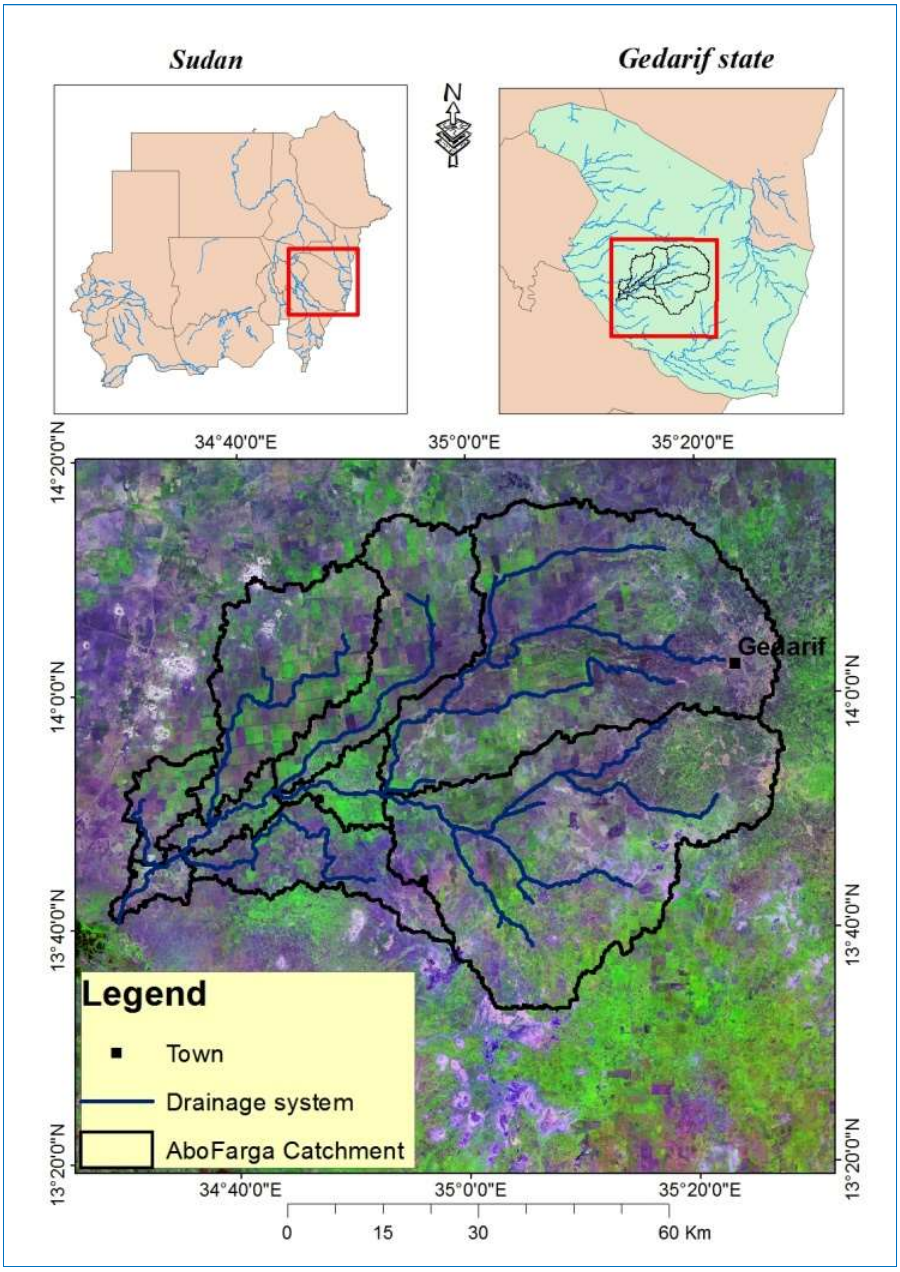

Fig. 1. Location of the catchment

Eco-hydrology is the science that links ecosystem with hydrological cycle and interrelations of two systems (Rodriguez-Iturbe, 2000). One of the most important relations are the plant water dynamics and the impact of change on the water quantity, particular in arid and semi-arid environment with temporal variation of annual rainfall. The effect of afforestation of grasslands and shrub lands can result in a loss of one-third to three-quarters of stream flow (Farley et al., 2005), or 35 to 70% in the arid and semi-arid areas of the Loess Plateau (Gao et al., 2009).

Combined factors of inter variable, unpredictable behavior of rainfall and great spatial variability in Sudan as reported by Zhange et al. (2011) associated with the impacts of LU/LC deteriorations on soil properties like bulk density and hydraulic properties as reported by Bormann et al. (2007) and increase runoff and stream flow dynamic was reported by many researches (Ellis et al., 2010; Hamadi et al., 2012; Gumindoga et al., 2014; Hassaballah et al., 2017). In these arid and semi-arid regions, hydrologic systems are commonly subjected to sporadic storms that vary greatly in time and space, (Lotfi et al., 2018) analyzed the records for rainfall stations between 1995 - 2014 in Gedarif states they stated that average difference was found for total rainfall and high coefficient of variability. Surface runoff is often the dominant runoff process due to high rainfall intensities, steep slope, closeness to urban areas and sparse vegetation factors. One of the main streams was studied due to its high response to rainfall it produced high runoff volumes that affected Gedaref major town and its surroundings within one day or less.

Therefore, understanding the stream flow regime, relationship between rainfall and runoff and other factors becomes of great importance for water yield. This research was conducted to support the efficient water use by complementary approach for different eco-hydrological factors to fill the gap of lacking continuous hydrologic data that are needed for flow characteristics of the watershed at sub basin levels and reflect the importance of runoff potential areas for water management.

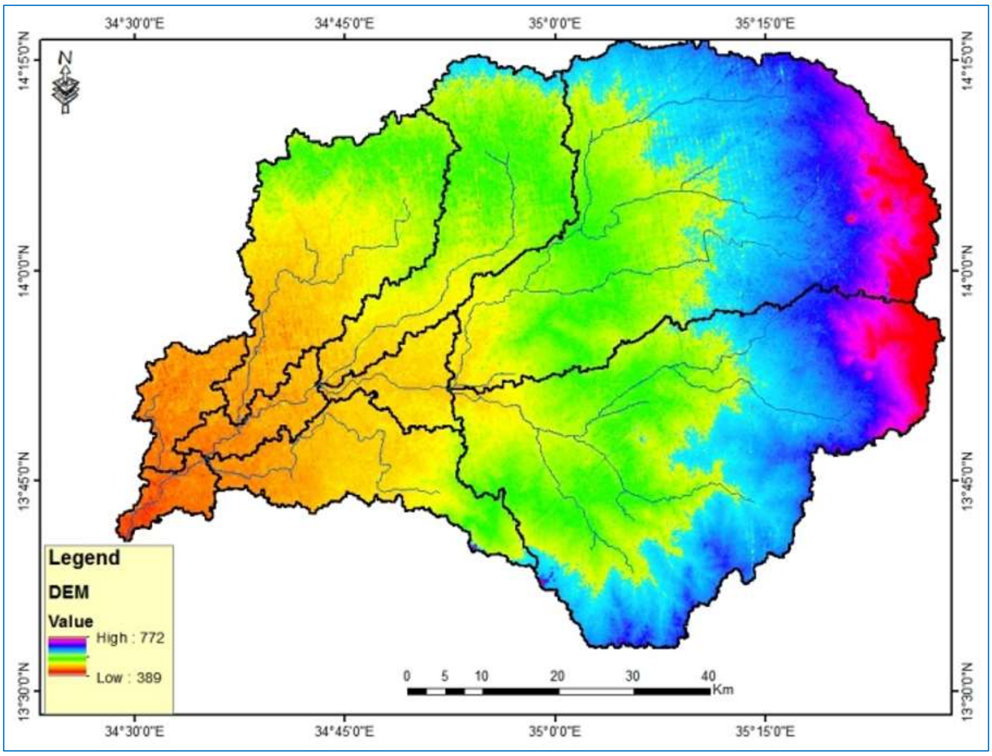

Fig. 2. Digital elevation model of catchment area

2. Materials and Methods

2.1. Study area

Gedarif state is considered as the first state in rainfed agriculture of economic crops like sesame, it is considered as an important area for water management planning because many streams cross this area from the east Ethiopian plateau to diverse directions across the Sudanese lands. The studied area is located between longitudes 33° 30`and 36° 30` to the East, and latitudes 12° 40` and 15° 46` to the North as showed in Fig. 1. over two-thirds of the population lives in rural areas and population density on a state-wide basis stands at around 19 persons per km², the majority of the state receives between 500-900 mm of rainfall annually. Annual average precipitation varies greatly in Sudan, in Gedarif state the coefficient of variation of annually total rainfall is range between 29- 49% and inter annually is ranged 137-260 (Lotfi et al., 2018), August is the month with the highest precipitation rates in Sudan; however, the biggest decreasing trend also occurred in this month (Zhange et al., 2001) ,that rain support the cultivation of large areas and the growth of valuable forestry and grassland outside of the rainy season. However, it suffers from water scarcity and conflicts have been known to escalate over access to water points. The watershed flows from east to west. Its elevation varies from 614 - 434 m above mean sea level. The shape of a watershed influences the shape of its characteristic hydrograph, U shaped watershed presents a lower concentration time and generates higher flow. The total catchment area is 5,504 km^2, it is fed by many attributes and the length of main course is 117 km.

2.2. Soil characteristics

Soils has dark colors, a high clay content and strong vitriolic properties including a large, rather uniform, clay plain intersected by streams. The clay content is very high and generally 75% to 80%. The organic matter and nitrogen content of the soil are low (Biro et al., 2011) but as there is no deficiency of other plant nutrients, the soil is moderately fertile. The water holding capacity of the soil material is very high. This, in combination with the deep penetration of water in the soil through the vertisolic cracks, causes the available water holding capacity of the soil to be very high. This high-water holding capacity allows crops to grow on stored water during dry spells and long after the rainy season. The soil also has undesirable physical characteristics, such as a low permeability when wet, causing the soil to be waterlogged for certain periods during the rainy season and flooding occurs which may lead to severe crop damage (Lotfi et al., 2018).

Also, the soil is difficult to cultivate as it is very hard when dry and very sticky and plastic when wet, causing the moisture range at which the soil can be cultivated to be very narrow.

2.3. Methodology

The method used was a multi-disciplinary approach that integrated many ecohydrological components as landcover, soil, topography and rainfall to assess the potential runoff and simulate the flow using limited discharge readings.

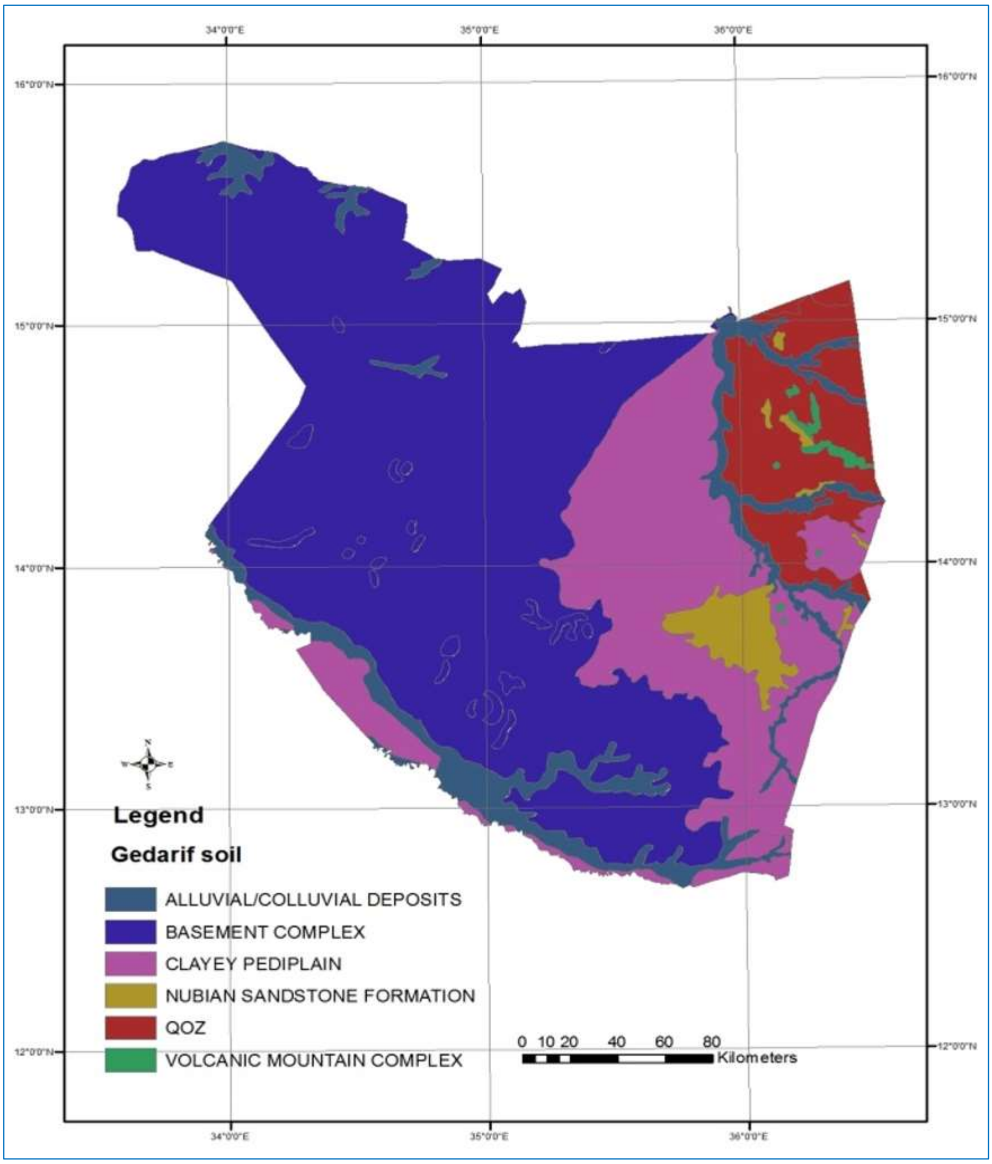

Fig. 3. Gedarif state soil map

2.3.1. Landcover classification and change detection

The landsat satellite images (30 m) year 1996 and 2011 and sentinel 2 satellite image (10 m) year 2017 are acquired and used as a primary source of information ,they are classified according to land cover classification system that classifies the land into two major landcover types ,cultivated and managed terrestrial areas and natural and semi-natural terrestrial vegetation that considered the mapability of the targeted area and the environmental attributes that influence the landcover Table 1. The classification results for the year

2018 were validated by field check for an ambiguous area, the change was detected in magnitude and type. The landcover classes were rated for the purposes of their influence on runoff speed and water infiltration of the soil.

Table 1. The land cover classes

Code	Land cover type
AG	Agriculture in terrestrial and aquatic/regularly flooded land
HCO	Herbaceous closed to sparse in terrestrial and aquatic/regularly flooded land
SCO	Shrubs closed to sparse in terrestrial and aquatic/regularly flooded land
TCO	Trees closed to very open in terrestrial and aquatic/regularly flooded land
URB	Urban areas
WAT	Seasonal/perennial, natural/ (artificial) water bodies

Table 2. The SCS hydrologic soil groups

Group	Description
A	Soils with low runoff potential
B	Soils with moderately low runoff potential
C	Soils with moderately to high runoff potential
D	Soils with high runoff potential rates

2.3.2. Digital elevation model (DEM)

DEM from shuttle radar topography mission (30 m) was used in this model to detect the topography and other characteristics of the watershed, the highest elevations is 772 m in the north east of the catchment and the lowest elevations is 389 m in the south west as showed in Fig. 2. Runoff of the monthly rainfall for the study area was obtained from the only one available rain gauge reading.

2.3.3. Soil map

Developed soil map based on (FAO soil map) using sentinel 2 satellite (10 m) distinguished clearly soil unites for this research (Fig. 3). The main characteristic is basement complex dominating the state adjacent to a high clay content soil to the east. Generally, the clay plains intersected by small valleys. The soil map of the studied area was classified as showed in Table 2 according to its hydrological properties and its infiltration rate as recommended by united states soil conservation service.

2.3.4. Rainfall

Rainfall records for the 64 years (1941-2005) were used to investigate the hydrological characteristics of the study area. Generally, in Sudan the rainy season extends from July to September. By analyzing these data, the maximum daily rainfall for this period was found to be 450 mm. Rainfall of the area is of high variability and it fluctuates up and down the mean, the departure from the mean is high, Fig. 4 show the rainfall variability.

2.3.5. Hydrological model

The soil conservation services (SCS) Curve Number (CN) method (SCS, 1972) was utilized for the estimation of catchment runoff. The model was developed by studying overland flow in many small experimental catchments and it is one of the most widely used methods to compute direct storm runoff (SCS, 1972; Maidment, 1993). CN represents the runoff volumetric potential of the land cover-soil complex governed by soil property, cover type and hydrologic condition of the land surface. CN was generated from modeling of landcover map, soil map, and topography in GIS environment. Season average peak discharge was used to generate the hydrograph for the basins along the stream. Hydrograph was simulated by combining CN layer, time lag data that represented the difference between the centered of the effective rainfall to the maximum runoff and sub basin areas, junctions and rainfall data. One day time step was used for the simulation because generally the flow rate was reported in daily basis, the time of peak and flow rate (volume/mm) were generated. Return period of 10 years was used to simulate the storm effect on peak runoff rate.

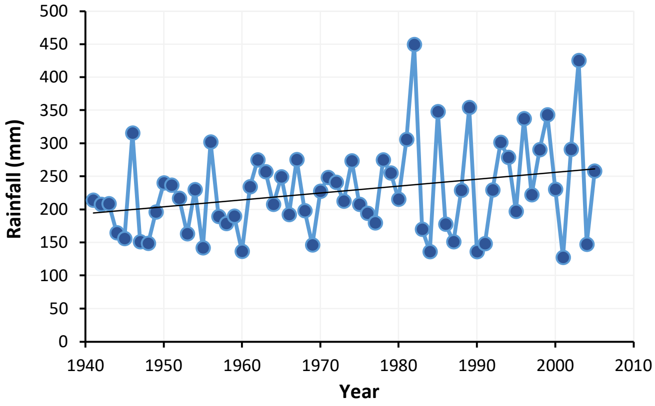

Fig. 4. The variation of the annual maximum rainfall

3. Results and Discussions

Comparison of Figs. 5-7 are illustrated that Landcover changes in Gedarif state was characterized by expansion of agricultural areas by 1.7%, the woody vegetation is declined in the center of study area where the catchment under study is located, shrubs and trees are facing wide cutting by 1366.44 ha between 1996 and 2010 while minor declined was found between 2010 and 2017 because most of the areas was converted to agriculture during the last period. The urban areas were grown and expense of natural woody vegetation is dominant, Table 3 reflect the trend of land cover change classes. The targeted catchment experienced similar changes trees nearby are removed through the years and crop lands are dominated except a strip of woody trees alongside the stream as showed in Fig. 8. that dominant soil type of catchment area is basement complex that has shallow soils pediment nonbearing basal rocks in its geological formation, according to the soil hydrological criteria, it was classified as C group as showed in Fig. 9 but in the eastern part soil have more clay content soil was classified as D group. The study area is characterized by gentle slope towards the entire watershed, the slope steepness plays a crucial role in depicting areas of perfect runoff, thus steep sloping areas have high runoff potentials as showed in Fig. 10.

3.1. Hydrological analysis

From the results of hydrological analysis, the targeted catchment was divided into seven basins according to its structures as showed in Fig. 10; the soil conservation services (SCS) curve number (CN) model estimated the basin potential to generate more runoff. High CN values are associated with rainfed crops landcover type and dominated by soil hydrological class C which have high runoff potentials; therefore, CN was found between 87 to 85.6, located in basin 3, 4, 6 and 7, respectively as shown in the Fig. 11.

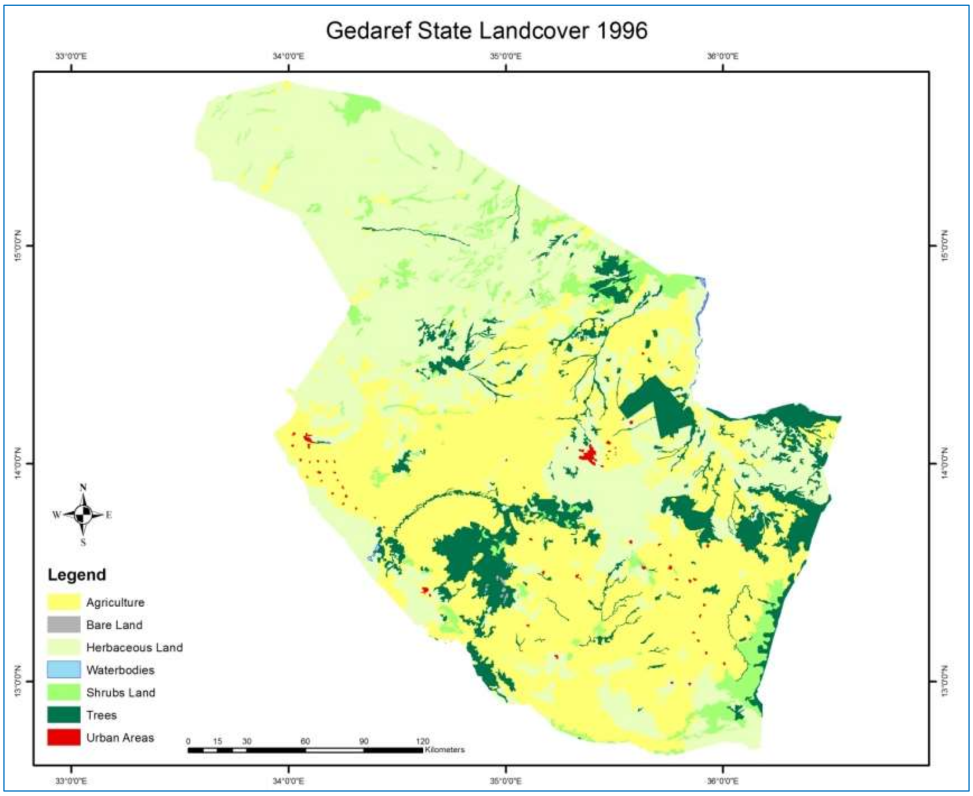

Fig. 5. Land cover of year 1996

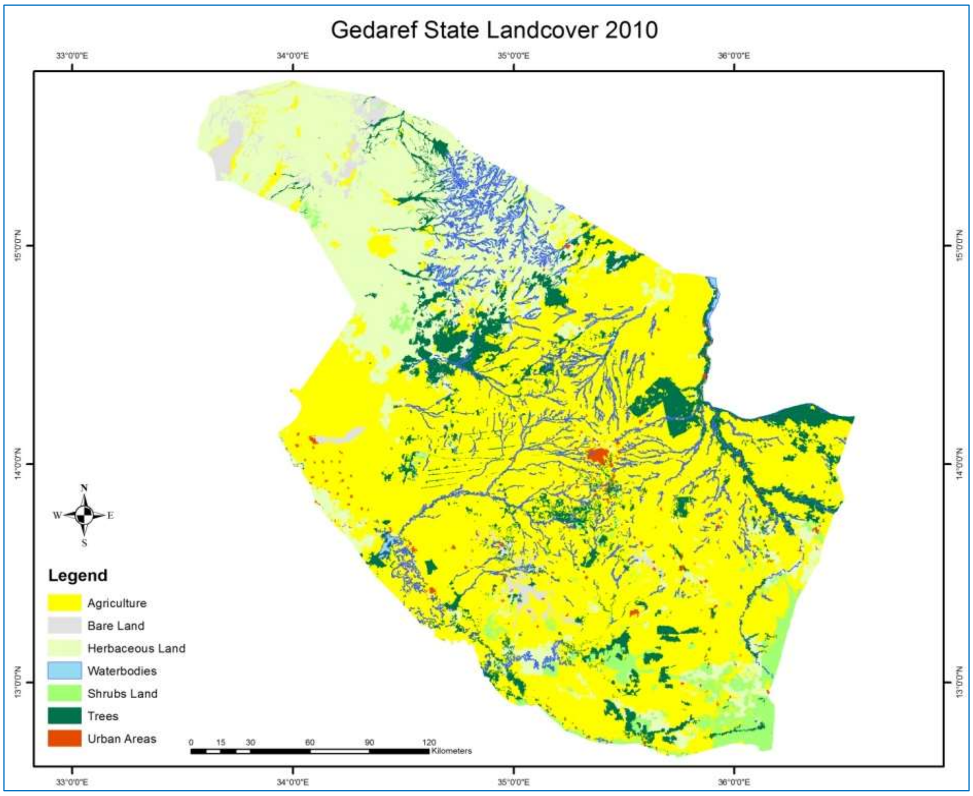

Fig. 6. Land cover of year 2010

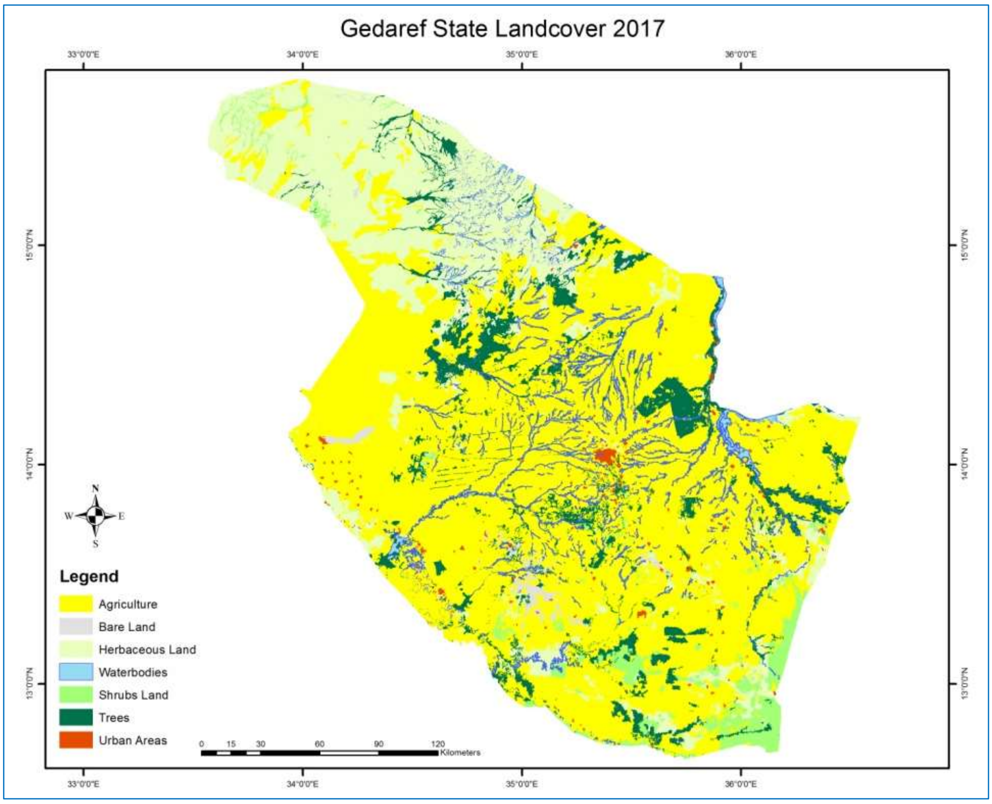

Fig. 7. Land cover of year 2017

Table 3. Land covers change trends

Land cover type	AREA (1996) km^2	AREA (2010) km^2	Ch% (1996-2010)	AREA (2017) km^2	Ch% (2010-2017)	Ch/area
AG	24486.66	34895.71	+42.5	38230.99	+56.1	+13744.33
BS	29.86	189.98	+536	590.39	+95	+560.53
HCO	25752.58	14302.18	-44.4	12243.13	-52.4	-13509.45
SCO	3098.90	2078.30	-32.9	2070.25	-33.1	-1028.65
TCO	6015.36	5369.52	-10.7	4623.65	-23.1	-1391.71
URB	146.28	401.14	+174	418.76	+186	+272.48
WAT	45.45	1242.27	+263	1402.08	+298	+1356.63

However, the CN value of basin 3 is the highest (87) due to its steeper topography and longest sub basin shape compared to other basins. The lower CN values of 82 are associated with strip dense land cover types consists of trees and shrubs. Generally, the watershed area considered has high CN values; the amount of CN generated for each basin is summarized in Table 4. Hydrograph analysis for a return period of 10 years' results is showed in Table 5.

Table 4. Basins curve number values

Basin name	CN	Area (km²)
BS1	85.3	1734.9
BS2	82.5	1718.3
BS3	87	569.73
BS4	85.6	756.55
BS5	82.6	133.6
BS6	85.6	381.45
BS7	85.6	209.62

The result indicates that significant amount of water at sub basins could be produced, the maximum volume produced is 278.11 m3 in outlet J4 which estimated has highest peak discharge in the watershed.

Table 5. Result of hydrograph model

Basin/junction	Drainage area (km)	Peak discharge (m^3/s)	Peak time	Volume (m^3)
BS1	173.90	20659.2	18:28	279.52
BS2	1718.30	18631.2	18:48	273.77
J1	3453.20	39149.8	18:38	276.66
BS3	569.73	8169.0	17:48	284.43
BS5	133.60	3344.7	16:18	273.57
J2	4156.53	47265.0	18:23	277.63
BS4	756.55	10414.4	17:53	280.71
BS6	381.45	5174.3	17:58	281.09
J3	5294.53	62394.1	18:13	278.32
BS7	209.62	3817.3	17:00	272.83
J4	5504.15	64852.5	18:08	278.11

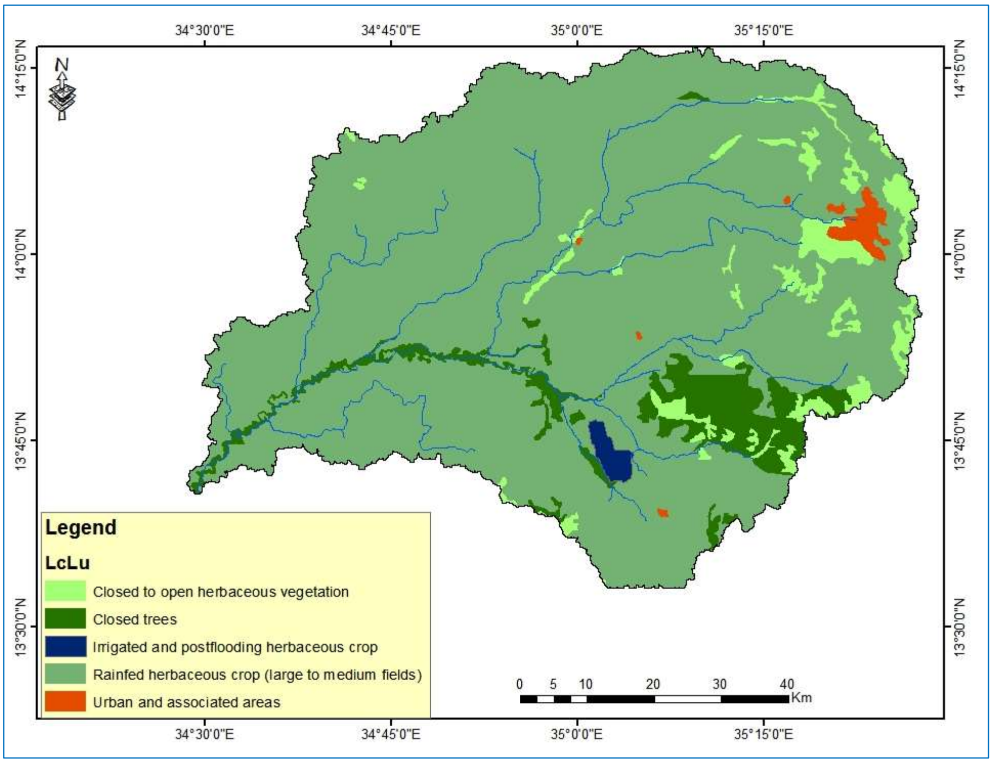

Fig. 8. The landcover of the catchment

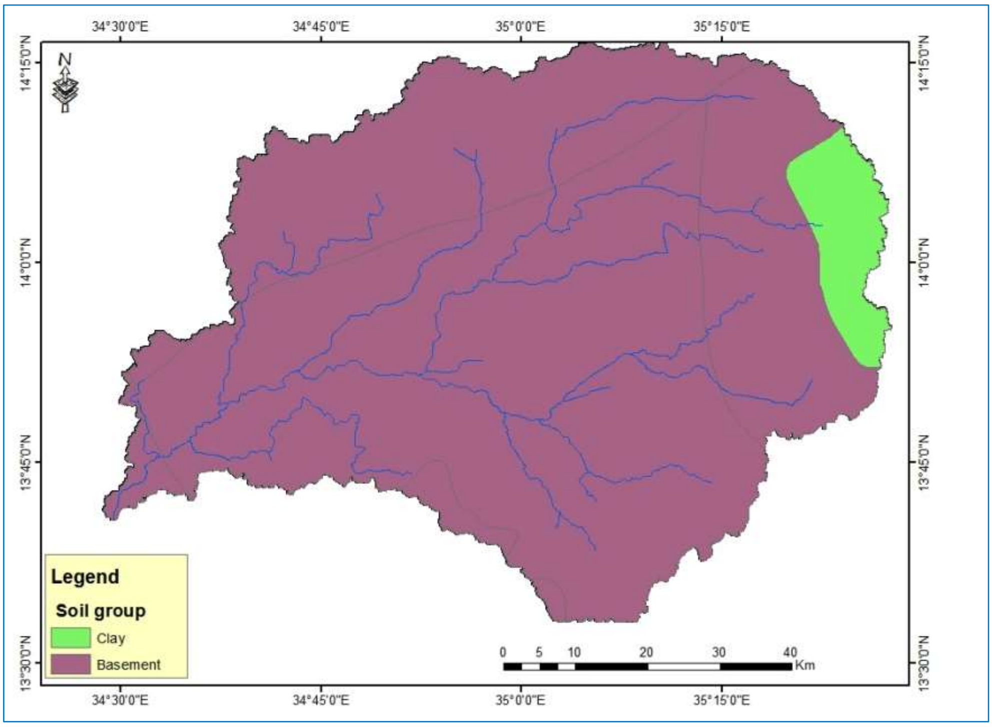

Fig. 9. Soil hydrological group map for the catchment

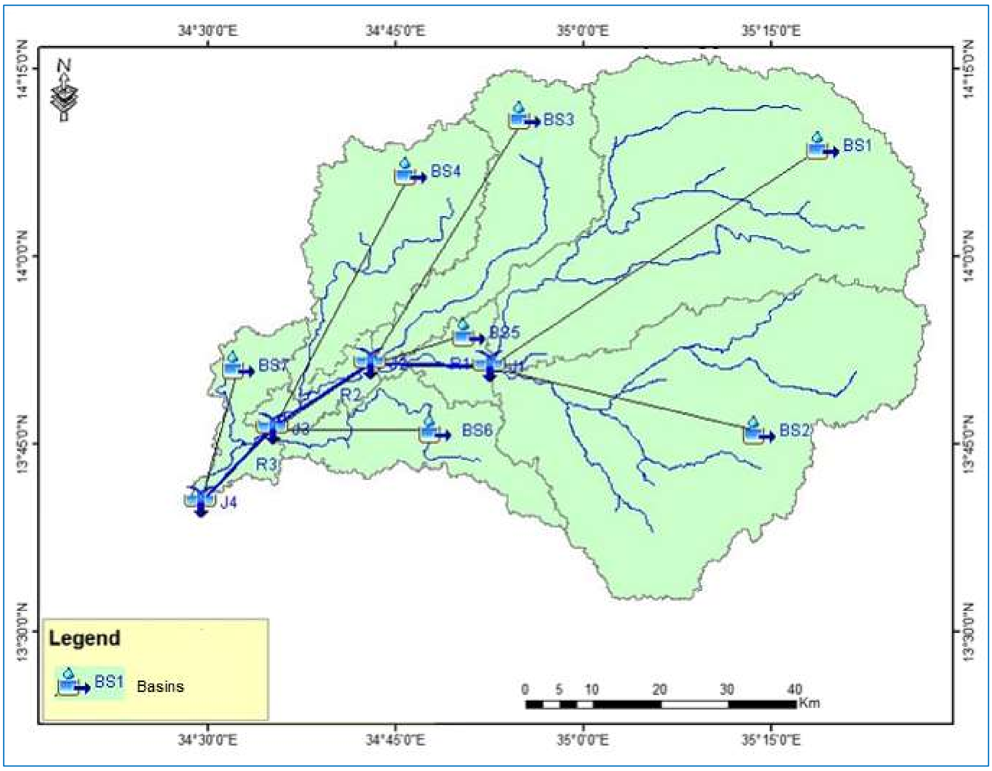

Fig. 10. Basins of the catchment

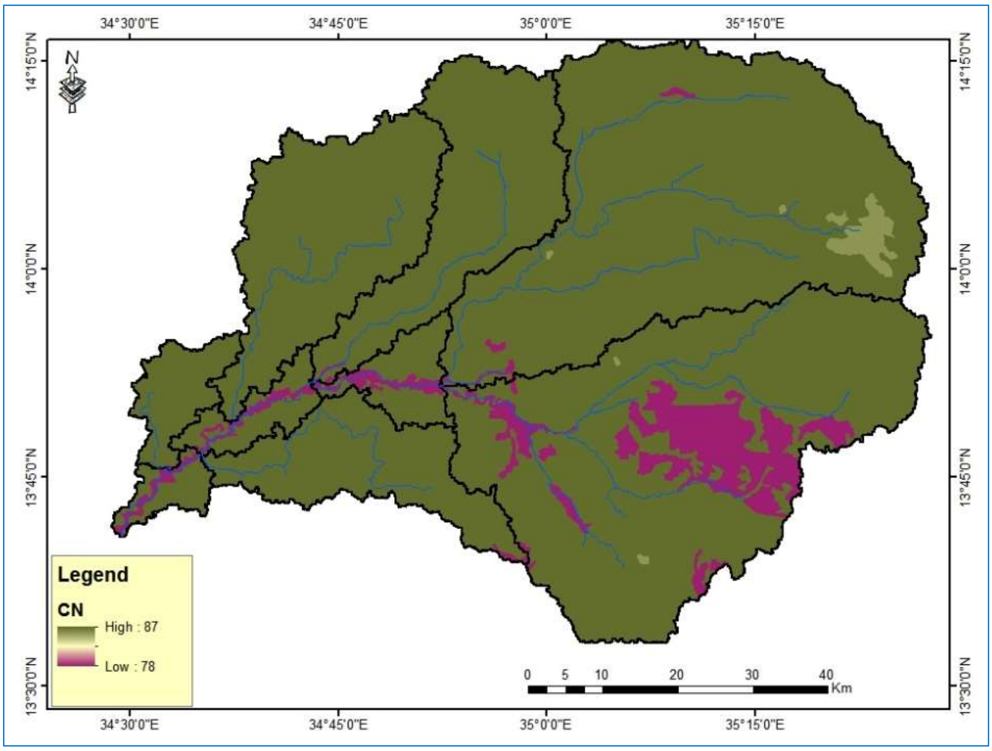

Fig. 11. Curve number of the watershed

4. Discussions

The spatial distribution of landcover type, as important eco-hydrological indicator, play important role on water infiltration capacity and soil porosity capability, both are increased by the presence of deep root system of trees and shrubs, as found in this research the landcover of studied area is converted from natural trees and shrubs to agricultural crops causes reduction of the water infiltration capacity and generates more run off. The sparse scattered natural vegetation cover causes rapid runoff especially on undulated slopes since the surface flow opportunity to infiltrate through the soil is less, thus the catchment area poses high runoff potentials.

The analysis carried out in this research showed that landcover type of trees and shrubs was reduced by percentage ranged between 10 – 32% for fourteen years' time period and 23-33 % for seven years' time period. Increased of agricultural lands is dominant feature in landcover type that reach to 56% in twenty years' time period, this significant decrease of forests due to agricultural expansion and removal of trees for fuel wood and buildings is agreed with HCNER (2009) that the present natural forest in Sudan is estimated to have declined to approximately 0.8 billion m^2 standing crop, while it was 2.4 billion m^2 in mid-seventies.

The other eco-hydrological indicators such as soil type is essential for the infiltration capacity and the saturation point, the study showed that the soil dominated the catchment area has high clay content percentage, produced low soil infiltration through time of rainfall and generate higher runoff, in addition, the catchment elevation and slope of sub basins are essential factors in flow direction and runoff peak values, the study found that there are some basins produce more runoff while it has the same landcover type but steeper slope. The spatial pattern of curve number as indicators of soil runoff potentials are related to landcover type density that explained by finding of landcover changes trends, soil and topography explain the results of increasing curve number values at areas of degraded vegetation cover and decreased where dense vegetation was found, this agreed with other researches in dry regions and east Africa (Ellis et al., 2010; Hamadi et al., 2012; Gumindoga et al., 2014; Hassaballah et al., 2017).

The vertisolic soil type of the watershed has clay rich properties able to swell when it is wet, thus the water flow associated with topography difference of 300 m in studied area was responsible for considerable amount of runoff.

Hydrograph analysis for the catchment is important for the water sector in dry lands like Sudan that facing fluctuations in rainfall and high excess rainfall. This study concluded that this catchment received significant amount of water, but due to steep sub basin slopes faster runoff and more peaked hydrographs occurring earlier in time than sub basins with flatter slopes where has become more suitable area for water conservation practices.

Possibilities of flood damage for properties and agriculture become higher in this watershed. This study is suitable for estimation of runoff from un-gauged catchments crucial for the strategic design of dams and help in planning for water-crop management in this dry region of Sudan.

5. Conclusions

This study indirectly contributes to the socio-economic development of catchment basins in developing countries such as Sudan, providing good knowledge of catchment management and rainfall-runoff relations for efficient utilization and management of the water resources for agriculture. Without a sustainable plan in place for managing the water resources, lack of water will be persisted, therefore, use this research and similar approaches assist in providing water irrigation for crop in rainfed agriculture and maintain water supply in dry spells through constructing small dams when rain fluctuate took place, hence contributed to climate change mitigation practices. Storm hydrographs in this study uses 10 years of the return period, it is providing water volume and timing critical for damage or flood situation. This study has given some insight about the surface water potential of the study area; it could be used directly or associated with other studies for water management, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation.

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