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Rainfall Erosivity, Land-Use and Land-Cover Change Analysis for Gadarif Region, Sudan

[1]*Muna M. Elhag and* [2]*Hussein M. Sulieman*

[1]Water Management and Irrigation Institute, University of Gezira, Wad Medani, Sudan
[2] Remote Sensing Unit, Faculty of Agricultural and Environmental Sciences,
University of Gadarif, Gadarif Sudan

Abstract: The purpose of this study was to analyze the combined impacts of rainfall erosivity and change in land-use and land-cover (LULC) on land degradation in three sites located in Gadarif region (eastern Sudan). Monthly rainfall dataset (1979 to 2009) were used to compute rainfall erosivity based on the Modified Fournier Index (MFI), while satellite images from three dates were utilized to detect the LULC change by means of the Maximum Likelihood Classification algorithm. The results showed no significant increasing trend in the rainfall and the rainfall erosion power is range from high to very high in the region. The general patterns of LULC change experienced rapid conversions in natural vegetation into mechanised agricultural land which later left as bare land. Land cover changes did not occur at equal rates during all time intervals, i.e. the agricultural land at Gadembaylia site was decreased from 73.31% in 1989 to 57.45% in 2009. While the bare land increased gradually from 12.10%, 20.34% and 38.64% in 1972, 1989 and 2009, respectively. However, the most consistent trend of LULC change was a progressive loss of the natural vegetation cover, between 1972 and 1989; natural vegetation experienced a strong loss at an annual rate ranged from 4.91% and 3.7%. Increasing trend of rainfall erosivity in conjunction with the disappearance of natural vegetation resulted in an accelerated impact on the land degradation in study area. LULC in Gadarif Region, Sudan are undergoing dramatic challenges. Therefore, the results of this study could be beneficial to stakeholders, decision makers and national planners.

Key words: Rainfall · Land degradation · Mechanized agriculture · Natural vegetation · Gadarif · Sudan

INTRODUCTION

Degradation of arid and semi-arid lands due to human impact and/or climatic change has been much debated since the mid-1970s. It is believed to be one of the most serious global environmental problems of our time [1]. Degradation processes include soil erosion, compaction and surface sealing, acidification, declining soil organic matter, soil fertility depletion [2]. Ellison [3] defined soil erosion as a process of detachment and transportation of soil material by erosive agents. The detachment of soil particles and runoff are linked to the intensity and duration of rainfall, as well as the slope and roughness of the landscape. UNEP [4] estimated that roughly 70% of all agriculturally used drylands are degraded to some degree, especially in terms of their soils and plant cover and up to 4 million hectares of rain-fed croplands are being lost each year in the world's drylands, chiefly as result of accelerated soil erosion and increasing urban growth.

In arid and semi-arid zones, rainfall is characterized by occurring as short spells of high intensity after several dry months, rainfall starts suddenly triggering a water erosion phenomenon due to low plant cover and dryness of soil surface. The intensity of soil particle removal depends on the energy of precipitation and the length of the dry season [5]. Rainfall erosivity is defined as the aggressiveness of the rain to cause erosion [6]. Rainfall erosivity has very little or null possibility of modification by humans, so it represents a natural environmental constrain that limits and conditions land use and management. In the context of climate change, the effect of altered rainfall characteristics on soil erosion is one of

Corresponding Author: Muna M. Elhag, Water Management and Irrigation Institute, University of Gezira, Wad Medani, Sudan. E-mail: munaelhag13@gmail.com.

the main concerns of soil conservation studies [7]. It is well known that a few, very intense rainfall events are responsible for the largest part of the soil erosion and sediment delivery Hence, the estimation of rainfall erosivity may contribute to a better prediction of soil erosion. The most common rainfall erosivity index is the R f`actor of USLE [8] and RUSLE [9]. Since daily rainfall data are not readily available in many parts of the world, mean annual and monthly rainfall amount have often been used to estimate the R factor for the USLE [10, 11]. In 1960 Fournier proposed an index (F) to estimate rainfall erosivity based on annual and monthly rainfall; this index was modified by [12]. The F index is a good approximation of R to which it is linearly correlated. Bagarello (1994) [13] analysing data on mean annual rainfall and the Modified Fournier Index, MFI, for different European regions the result showed that the F index is strongly linearly correlated to the annual rainfall.

Assessment and monitoring of land degradation over large areas is difficult [14], resulting in a lack of reliable data that has even caused questions to be raised about the existence of land degradation [15] but the assessment can be done by using rainfall data, remote sensing imagery and test plot monitoring More specifically, GIS and/or remote sensing have been used in assessment of different kinds of soils degradation and conservation programs; to map temporal and spatial changes in land cover and land use; and to identify areas of degradation [16] Remote sensing imagery from different time periods allows the study of erosion dynamics, mainly the growth of rills and gullies [17]. Land degradation shows an increase in soil bareness/brightness which can be thus distinguished through the spectral reflectance change of land cover in time [18].

Despite the acknowledgment of land degradation as a major bottleneck of agricultural productivity and natural resources management the issue was not considered as a top priority in the national policy of poverty alleviation in the country [19]. Sole cropping system in Gadarif Region and the absence of fertilizer application have caused a decline in yields and degradation of the soils [20, 21]. The objective of this paper is bring better understanding of land degradation in Gadarif region (Eastern Sudan) through analyses and mapping of rainfall erosivity, land-use and land-cover changes.

Study Area: The study area is located in Eastern part of Sudan and extended in an area of approximately 78,000 km^2 (Figure 1). According to 2008 census the total population is 1,336,662 persons and the annual population growth rate is 4.7% which is higher than the national growth rate 2.8% [22]. This area was selected due to the fact that the area is one of the most important rain-fed agricultural regions in Sudan [23]. At the same time land degradation has become a serious environmental problem in the area [20].

The distribution of vegetation in the region depends largely on Soil and rainfall. In particular the amount of annual rainfall and the length of the rainy season; which vary along the climatic gradient from North to the South; thus rainfall had significant impact on season vegetation dynamics. Agriculture is the main economic activity, followed by livestock raising. Mechanized rain-fed crop production, have considerably reduced the land available for small-holder farming and for grazing [19]. Agricultural mechanization was introduce in the Gadarif region since 1944, when a government project was established to meet the food needs of army units stationed in the British colonies in eastern Africa. Nearly one third of Sorghum (*Sorghum bicolor*) and Sesame (*Sesamum indicum*) production is from this region. Three study sites namely Gadembalia, Doka and Simsim, were selected to represent the different land use/land cover classes in the region (Figure 1).

Data and Data Analysis

Rainfall Data: Rainfall is the most important single determining factor in the climate of Gadarif region, because the temperature is high all year around. The rainfall determines the vegetative life cycle and annual vegetative cover, land use and thus human occupation. It shows a substantial variation in incidence, amount, time received and annual distribution. Monthly rainfall data for three stations over a period from 1979 to 2009 was obtained from the Sudan Meteorological Authority (SMA). Rainfall erosivity index was compute using the Modified Fournier Index (MFI; Table 1). The MFI defined as

$$\mathrm{MFI} = \sum_{i=1}^{12} \frac{p_i 2}{p_a} \quad (1)$$

p_i = monthly rainfall (mm)
p_a = annual rainfall (mm)

Table 1: Scale for assessing Modified Fournier Index

MFI	Aggressively
0 – 60	Very low
60-90	Low
90-120	Moderate
120-160	High
Above 160	Very high

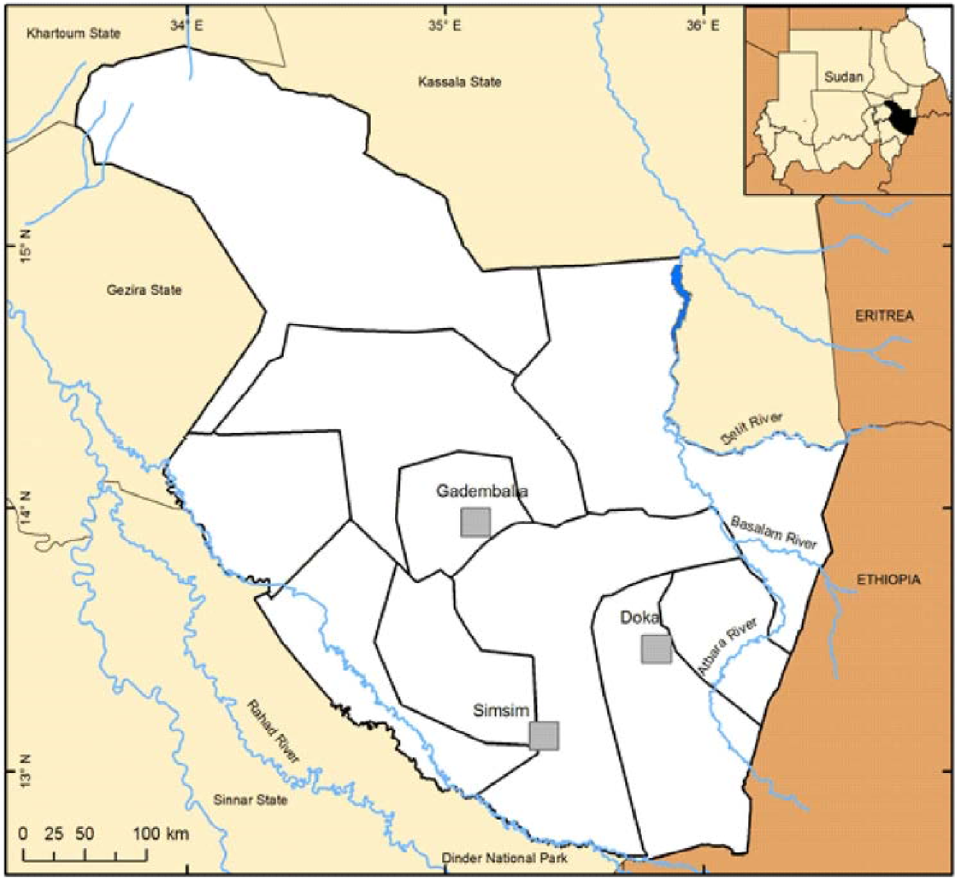

Fig. 1: Map of the study area showing the location of the three study sites in Gadarif

The MFI is well correlated with the capacity of precipitation water to cause water erosion. To evaluate the degree of seasonal concentration of precipitation, Precipitation Concentration Index (PCI) was calculated (equation 2). The more concentrated is the precipitation, the more difficult is the water management, irrigation control, soil erosion prevention and rainfed agriculture. Very often concentration is associated with variability [24, 5].

$$\text{PCI} = 100\sum_{i=1}^{12}\frac{p_i^2}{p_a 2} \qquad (2)$$

The Conceptual scale to evaluate the PCI index are uniform (8.3–10), moderately seasonal (10–15), seasonal (15–20), highly seasonal (20–50) and irregular (50–100).

The annual time series of MFI, PCI were used to test the trends and to detect changes during the study period, observed changes were estimated by using linear regression techniques [5, 25].

Table 2: Satellite imagery used for the multi-temporal change detection

Satellite	Sensor	Path/row	Acquisition date	Spatial resolution (m)
Landsat 1	MSS	184/050	1972-12-11	60
Landsat 1	MSS	184/051	1972-12-11	60
Landsat 3	MSS	184/051	1979-11-23	60
Landsat 4	MSS	171/051	1989-12-12	60
Landsat 7	ETM	171/050	2005-02-07	30
ASTER	Terra	171/051	2007-03-17	30
ASTER	Terra	171/050	2009-01-17	15

Satellite Imagery: In this study, Landsat Multi-spectral Scanner (MSS), Enhanced Thematic Mapper (ETM) and ASTER Terra imagery have been utilized for the multi-temporal change detection (Table 2). All scenes were taken under relatively clear sky conditions (<10% cloud cover). To avoid major differences in phenology, all images obtained were taken during the dry season (image dates from November to March), All images resampled to 30*30 m in order to get same spatial resolution. Three subset images were extracted from the satellite scene of the entire study area and used as individual study sites. Each sub-set is 30 x 30 km^2.

The subsets were located adjacent to the Rainfall Gauge Stations (Figure 1). Each subset image had the same LULC types. Thus three LULC classes were identified during the filed surveys namely, bare land, natural vegetation and agricultural land.

Satellite Imagery *processing*: In order to achieve accurate LULC change detection, the satellite imagery set were pre-processed using standard procedures including geo-referencing and geo-coding corrections. The images were geometrically corrected and geo-coded to the Universal Transfer Mercator projection, World Geological Service 84 datum and using Sudan Survey topographic maps (date: 1983) at scale 1:100,000. The accuracy of image rectification was within one pixel. In performing this image pre-processing, ERDAS Imagine Version 9.1, was used. Classification of the LULC classes was performed using the maximum likelihood algorithm. This procedure has proven to be a robust and consistent classifier for multi-date classifications [18, 26]. For accuracy assessment of the classified imageries, 120 points were assigned to the classes for each site in a stratified random pattern using ERDAS Imagine software [27].

In order to quantify changes of certain LULC type during certain time period, the calculation formula followed was:

$$\text{LULCC} = \frac{U_b - U_a}{U_a \times T} \times 100\%$$

where LULCC is the change of certain LULC type for certain time period; U_a and U_b are the area of certain LULC type at the beginning and the end of a time period, respectively; and T is the time period. A positive value means that there is an increasing trend for a specific time period for an area of a certain LULC type; otherwise, a deceasing trend is occurring for the area assessed.

RESULTS

Rainfall Characteristics: Gadarif rainfall data is mostly available as monthly and total annual values. Figure (2) show that the total annual rainfall for the three stations used in this study. Simsim station is characterized by the highest annual rainfall (715 mm) followed by Doka (661 mm) and Gadamblyia (523 mm). It is clear that the northern part of the area receives lower rainfall There is increasing trend of annual rainfall at Gadambalyia and Doka, but it was not significant (p= 0.35 and 0.447. While there is no significant decreasing trend at Simsim (p= 0.267)

Figure 3 shows the percentage of monthly rainfall contribution. The monthly contribution reaches its maximum in July and August for the all stations while the minimum (i.e. traces) rainfall in April.

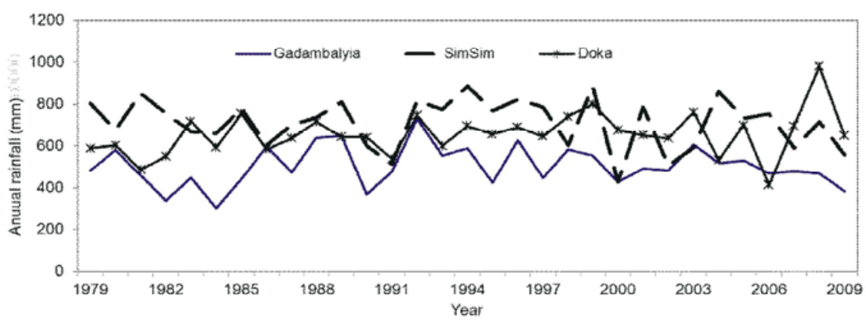

Fig. 2: Total annual rainfall for three weather stations at Gadaref region (1979-2009)

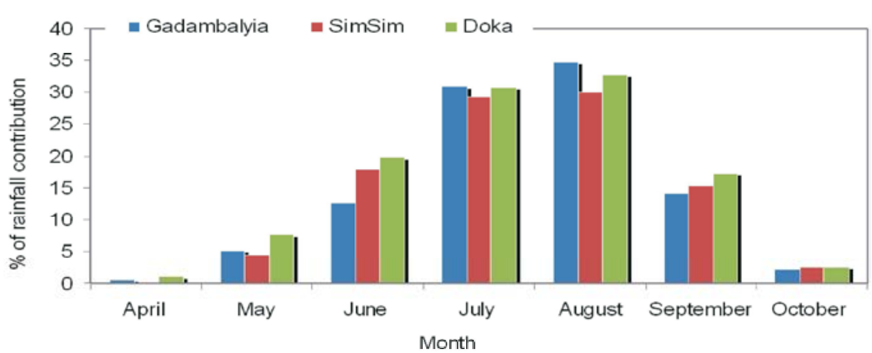

Fig. 3: Monthly Rainfall contribution for period 1979-2009

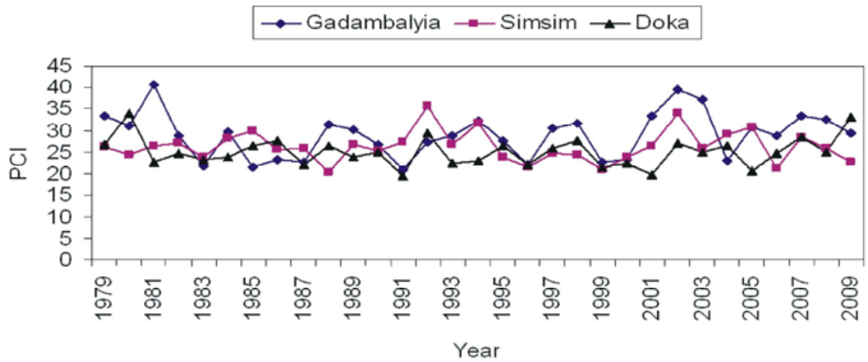

Fig. 4: Precipitation Concentration Index for the three weather stations (1979-2009)

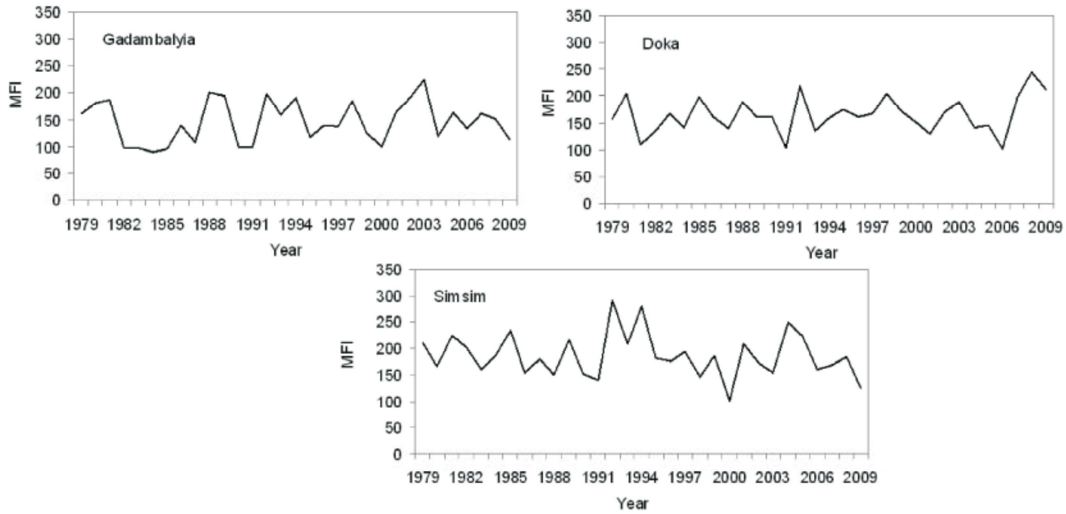

Fig. 5: Rainfall erosivity for the three weather stations for period 1979- 2009

The PCI values showed that the rainfall in Gadarif region is dominated by highly seasonal classes, with highest value of PCI found in Gadambalyia i.e. 42, while the values range between 20 – 34 for Doka and 20-36 for Simsim (Figure 4).

Rainfall Erosivity Analysis: The rainfall erosivity was expressed by Modified Fournier Index for the three stations. It was noticed that 20 years during period from 1979 – 2009 have high to very high erosivity for Gadambalyia station, while at Doka there is 28 years is ranging from high to very high erosivity. The moderate erosivity was registered only in one year at Simsim and three years at Doka station (Figure 5). These result indicate that the effect rainfall erosivity were very high in Simsim compare with two other sites during the study period.

Non parametric analysis showed that there was highly significant correlation between the MFI and the July, August months (July, August had high rainfall contribution; Figure 2) and annual rainfall (r = 0.73 to 0.76). However, these relations are not significant for the rest of the rainy months Also there was strong correlation between PCI and MFI for the three stations.

Land Use and Land Cover Change Analysis: The LULC change of the three study sites in Gadarif for the periods of 1972–1989 and 1989–2009 were analyzed using Maximum Likelihood Classification algorithm. Figure 6 depicted multi-temporal LULC change maps and its respective percentages. Over the whole study period, agricultural land was the predominant land cover type. The general patterns of LULC change is the rapid conversion of natural vegetation into mechanised agricultural land which later left as bare land.

In Gadembaylia (Figure 6), for example, agricultural land covers was decreased from 73.31% (294845.4ha) in 1989 to 57.45% (230371.7ha) in 2009, additionally, the natural vegetation areas were declined from 15.84% (64145.0ha) in 1972 to 3.76% (15081.75ha) in 2009.

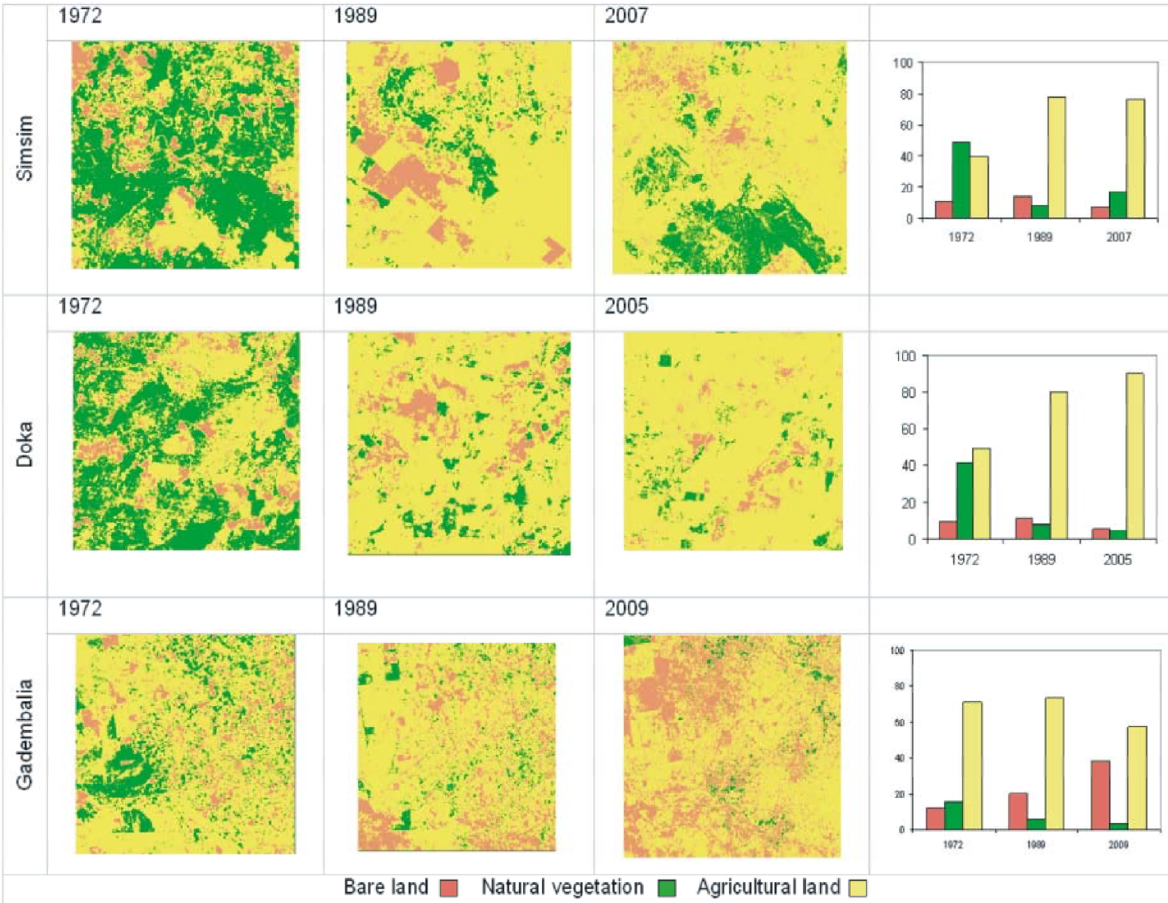

Fig. 6: LULC maps and its respective percentages of the three study sites in Gadarif

In the site bare increased gradually from 12.10% (49001.42ha), 20.34% (81790.2ha) and 38.64% (154946.5ha) in 1972, 1989 and 2009, respectively.

Doka site (Figure 6) showed that in 1972 natural vegetation covered 138484.3 ha, accounting for 41.39% of the total area. However, this proportion was substantially declined to 8.17% (27424.8ha) in 1989 and further to 4.30% (14325.5ha) in 2005. On the other hand agricultural land was increased from 49.31% (164961.4ha) in 1972, to 79.99% (268536.9ha) in1989 and to 90% (300135.7ha) in 2005. One of the noticeable changes is the increase in bare land during the first period, while it decreased during recent years. This increase was related partially to re-cultivation of bare land (Figure 6).

Concerning the LULC change in Simsim (Figure 6), natural vegetation was severely reduced from around 50% (164897.0ha) in 1972 to 16.80% (55991.6ha) in 2007. Nevertheless, agricultural lands increased from 39.82% (133210.3) to 77.78% (259549.4ha) in 1989 and almost remain the same until 2007. Bare land in this site represents 10.89% (36439.7ha) in 1972 and then 14.03% (46846.2ha) in 1989 and reduced to 6.72% (22388.3ha) in 2007.

LULC Change Rate: LULC change did not occur at equal rates during all time intervals over the three sites (Figure 7). The average LULC change rate was 0.91%, -2.05 and 1.50 for bare land, natural vegetation and agricultural land, respectively. Between 1972 and 1989, natural vegetation experienced a strong loss at an annual rate of ranged from -4.91% and -3.7%. This annual change rate declined during the successive period and even showed positive increase in Simsim. Agriculture rose very rapidly between 1972 and 1989. The most intense change dynamics were located in Simsim. During the second period Gadembalia and Simsim showed reduction of area under cultivation. Bare land showed appositive increment and a fluctuating way of change rate during the second period (Figure 7).

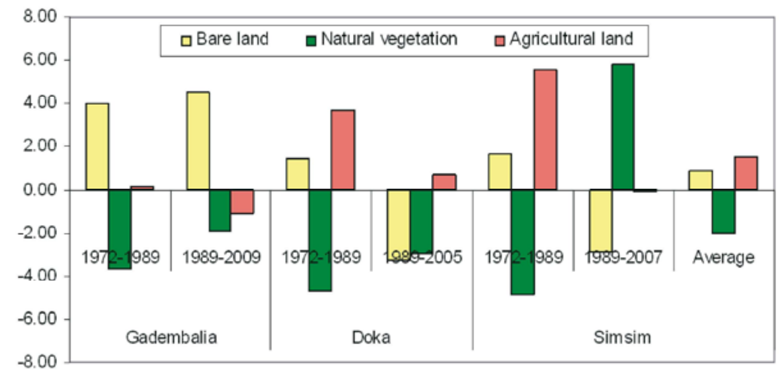

Fig. 7: LULC change rate in the three study sites

DISCUSSION

Soil erosion and land degradation are the main environmental problem facing Gadarif Region in eastern Sudan [19, 20]. The rainfall concentration and the rainfall erosivity in conjunction with LULC changes are the key elements to understand the impact of climate and human activities in land degradation. Rainfall pattern in the study sites is characterize by erratic and high variability in distribution and intensity, there is no significant increasing trend in Gadembalia site, the Northern part of the region. There are several hypothesis have been reported by and [28] and [29] for the substantial changes and variability in rainfall for the Sahel in general and Gadarif in particular. Elagib, 2010 [29] reported that the total annual rainfall at Gadarif is highly depending on the heavy rainfall. This means the heavy rainfall is reduced in drought years and increased in wet years. This explain the result obtained in this study that the PCI has lowest values during the 1980's when the region exposed to drought, while there is high MFI values and high correlation with the July, August and annual rainfall for the three stations in wet years. These findings also are agreement with those obtained by [24] and [5].

LULC change analysis reveals a general trend of a continuous reduction in natural vegetation, i.e. forest and savannah cover where in some sites there is hardly any natural vegetation e.g. Gadembalia in 2009. This process takes place as a progressive modification from natural vegetation and a highly dynamic conversion to agricultural land. A recent LULC change study in Gadembalia founded that 81% of the woodland area was changed to the cultivated land in the period 1979–2009 [21].

Natural vegetation clearance rates in this region are higher compared to the national rate [23] for a country that has scored the highest deforestation rate all over the continent [30]. Consequently, it could be stated that the region is one of the hotspots of vegetation clearance worldwide. This is probably due to the fact that the this parts of the clay plains in Sudan has been densely populated since the times of colonisation and major conversions of forest cover had taken place long before the 1970s.

The possible reason for reduction in cropland in some cases might be degradation of cropland due to soil erosion and nutrient depletion because of the lack of required soil conservation measures [31]. It is common that farmers leave their land abandoned to restore its fertility. It is interesting to note that natural vegetation was increased in some sites e.g. Simsim in 2007. The spatial allocation of such changes was abandoned agricultural land and barren areas. Land abandonment/fallowing to restore soils are well known practice in the region [20].

The increasing the rainfall erosivity with increasing pressure on the land, in areas like Gadambaylia has led to re-cultivation of bare abandoned agricultural land was cultivated and the removing of natural vegetation cover through the agency of cutting, burning and grazing all these factors will accelerate soil erosion and eventually the land degradation. Sometimes the results will be obvious; for example when major gully systems rapidly develop. Other results may have less immediate effect on landforms but are, nevertheless, of great importance. Indirectly, humans can create subsidence features, trigger mass movements such as landslides.

Removal of the original vegetation, for whatever reason, often initiates a process of soil degradation, causing the site to become less productive [32]. In Gadarif Region the growing season for the two main crops i.e. sorghum and sesame is ranged between 3 to 4 months which is followed by harvesting and collecting of crop residue, especially sorghum residue, to be used as fodder or building materials. This illustrated that even the land has been classified as agricultural land was also left bare for the rest of the year. This significant proportion of bare land increases the vulnerability of further degradation.

CONCLUSION

This study shows that the combinations of rainfall data and multi-temporal satellite, from different locations, potentially can be used to monitor land degradation at regional scale. These outcomes go towards providing of objective information on such types and rates of changes in Gadarif. Agriculture remains the mainstay of the economy. The rapid expansion of rain-fed mechanized cultivation was due to attain self-sufficiency in food production. Large scale mechanized farming has been the main factor contributing to deforestation.

The continuous degradation of the vegetation cover could have a strong impact on human livelihood and well-being in Gadarif, as there are increasing demands for agricultural products and human consumption due to large population increases. Consequently, strategies for adapted land use, including the optimisation of the spatial configuration of uses and restoration of the natural vegetation cover should be developed quickly. There are several policy and legal provisions stipulating the integration of trees into agricultural areas. For example, legislation in the Sudan requires that trees be retained on at least 10 percent of areas under rain-fed cultivation. This is to prevent the total clearance of woodland in the process of expanding mechanized farming. However, this regulation was hardly followed by few farmers.

Concern about the growing competition for land by a rapid increasing number of users in the region and the risk of further degradation of land under cultivation, calls for a more rational and sustainable use of natural resources. Regional land-use planning are therefore major issues for decision-makers.

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