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Spatial Diversity of Monthly and Annual Rainfall in Sudan: Using Rainfall Predictions and Geographical Information System (GIS) to Produce Rainfall Maps

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***Abstract*: This study presents mapping of rainfall predictions over Sudan using spatial analysis of climatological data. Geographic Information System ArcGIS provides the means to produce climatological surfaces for the entire Sudan between the years 2000–2012. The temporal resolution of the maps is monthly and annual. Spatial data were obtained from Central Bureau of Statistics Sudan for three levels (towns, states and regions). This study provides a deeper analysis of rainfall phenomenon in Sudan. Monthly and Annual variation in rainfall for 13 years was visualized in rainfall maps. Also analysis been made for rain at the same level for different months. Finally we analyzed rainfall with the most influenced variables such as temperature and relative humidity for different months and levels. Results from this study reveal the ability of GIS to explain and extract general patterns of rain phenomenon and its distribution over different geographical areas in Sudan.**

Keywords: rainfall prediction, geographical information system, spatial analysis, rainfall map.

I. Introduction

Rainfall prediction is one of the most imperatives, important and demanding operational tasks and challenge made by meteorological services around the world [1]. It is a complicated procedure that includes numerous specialized fields of knowledge. The task is complicated because in the field of meteorology all decisions are to be taken with a degree of uncertainty, because the chaotic nature of the atmosphere limits the validity of deterministic forecasts [2]. There are several types of weather forecasts made in relation to time:

- A short-range forecast is a weather forecast made for a time period up to 48 hours.
- Medium range forecasts are for a period extending from about three days to seven days in advance.
- Long-range forecasts are for a period greater than seven days in advance but there are no absolute limits to the period.

Weather forecasts still have their limitations despite the use of modern technology and improved techniques to predict the weather. For example, weather forecasts for today or tomorrow are likely to be more dependable than predictions about the weather about two weeks from now. Some sources state that weather forecast accuracy falls significantly beyond 10 days [3]. Weather forecasting is complex and not always accurate, especially for days further in the future, because the weather can be chaotic and unpredictable. For example, rain or snow cannot always be predicted with a simple yes or no. Moreover, the Earth’s atmosphere is a complicated system that is affected by many factors and can react in different ways.

Long-range weather forecasts are widely used in the energy industry, despite their limited skill; they can still be a valuable tool for managing weather risk. Long term Prediction of rainfall has several benefits for efficient resource planning and management including agriculture, famine and disease control, rainwater catchment and ground water management.

Understanding the spatial distribution of data from phenomena that occur in space constitute today a great challenge to the elucidation of central questions in many areas of knowledge, be it in health, in environment, in geology, in agronomy, among many others. Such studies are becoming more and more common, due to the availability of low cost Geographic Information System (GIS) with user-friendly interfaces. These systems allow the spatial visualization of variables such as individual populations, quality of life indexes or company sales in a region using maps. To achieve that it is enough to have a database and a geographic base (like a map of the municipalities), and the GIS is capable of presenting a colored map that allows the visualization of the spatial pattern of the phenomenon.

Besides the visual perception of the spatial distribution of the phenomenon, it is very useful to translate the existing patterns into objective and measurable considerations

The emphasis of Spatial Analysis is to measure properties and relationships, taking into account the spatial localization of the phenomenon under study in a direct way. That is, the central idea is to incorporate space into the analysis to be made.

Geographic Information System (GIS) is defined as an information system that is used to input, store, retrieve, manipulate, analyze and output geographically referenced data or geospatial data, in order to support decision making for planning and management of land use, natural resources, environment, transportation, urban facilities, health services so on [4]. A GIS is designed for the collection storage, and analysis of objects and phenomena where geographic location is an important characteristic or critical to the analysis. Combination of spatial and attribute data allows users to ask unique spatial questions [5].

Also a geographic information system (GIS) is defined as a computer-based tool for mapping and analyzing geographic phenomenon that exist, and events that occur, on Earth [6]. GIS technology integrates common database operations such as query and statistical analysis with the unique visualization and geographic analysis benefits offered by maps. These abilities distinguish GIS from other information systems and make it valuable to a wide range of public and private enterprises for explaining events, predicting outcomes, and planning strategies. Map making and geographic analysis are not new, but a GIS performs these tasks faster and with more sophistication than do traditional manual methods.

Spatial analysis the crux of GIS because it includes all of the transformations, manipulations, and methods that can be applied to geographic data to add value to them, to support decisions, and to reveal patterns and anomalies that are not immediately obvious [7]. Spatial analysis is the process, by which we turn raw data into useful information.

The term analytical cartography is sometimes used to refer to methods of analysis that can be applied to maps to make them more useful and informative [8].

The human eye and brain are also very sophisticated processors of geographic data and excellent detectors of patterns and anomalies in maps and images [9]. So the approach taken here is to regard spatial analysis as spread out along a continuum of sophistication, ranging from the simplest types that occur very quickly and intuitively when the eye and brain look at a map, to the types that require complex software and sophisticated mathematical understanding.

Spatial analysis can be [10]:

- Inductive, to examine empirical evidence in the search for patterns that might support new theories or general principles.
- Deductive, focusing on the testing of known theories or principles against data.
- Normative, using spatial analysis to develop or prescribe new or better designs.

There is a range of techniques for visualizing the data recorded by an eye tracker such as simple plots, fixation maps and heat maps [11].

A heat map is a graphical representation of data where the individual values contained in a matrix are represented as colors. Fractal maps and tree maps both often use a similar system of color-coding to represent the values taken by a variable in a hierarchy [12].

Heat maps uses differences in shading or color saturation to encode quantities, which means they are not suited for giving accurate readings, but they allow a lot of data points to be displayed side by side and can be good for spotting patterns and for giving an overview of the data.

Heat maps can simply be colored rectangles or circles in a row or on a grid, but heat mapping can also be combined with other chart types, giving them an extra quantitative axis. A common use case is heat mapping on geographical maps [13]. In the heat maps colors should be used consistently throughout a design; the same colors should not be used to represent different things. When using color to represent categories it's good to think about what people associate with different colors. Using a color the viewer naturally links with the category can reduce their cognitive load [14]. Also keep in mind that some colors are difficult to distinguish for colorblind persons, red and green being the most common.

The number of colors should be kept limited, and the colors used should mainly be soft and muted. Stronger more saturated colors can be used sparingly to highlighting important information. Too many and bright colors makes it hard to focus on the information and bright colors can also affect how the size of areas are perceived [15].

When using colors to represent ordinal or quantitative data such as in a heat map a “perceptually ordered" color scheme should be used. The strongest cue for perceived order is a color's lightness, so a good choice of scale is using a single color hue and gradually altering the lightness, going from light to dark. It's also possible to use a scale with changing hue, as long as the lightness also changes. If the data has a natural midpoint, such as a mean or zero value, a diverging color scheme, with two colors meeting in the middle, can be used.

Using light colors for smaller values and dark colors for larger values is a common cartographic convention [16]. This convention is perhaps confusing when using the common yellow-red color scale for people familiar with black-body radiation and color temperature, since a color gets darker and redder as the temperature decreases.

A rainfall map like heat map, it is a geographical representation of data in which values are represented by colors. Rainfall maps allow users to understand and analyze complex data sets. Rainfall maps make prediction rainfall data more realistic because, they connected rainfall predictions with their geographical locations. They leverage the human visual system to help users gain deeper and faster insights than other visualizations. Users can visually aggregate, determine relevance and detect micro-patterns in their data in ways other visualizations can’t match.

II. Related Research Works

Many studies used GIS technology and produced heat maps have been carried out to many disciplines such as risk assessment [17-19], weather and climate [20-22], agriculture [23-25], Health and Disease [26] and environmental studies [27-30].

In the field of Geostatistical modeling, Seng et al. [31] used GIS to model, analysis and map of Epidemiology of Dengue Fever in Johor State, Malaysia. In the same context Haarman et al. [32] proposed feature-expression heat maps as a new visual method to explore complex associations between two variable sets. Their results showed the feature-expression heat map is a useful graphical instrument to explore associations in complex biological systems where one-way direction is assumed, such as genotype-phenotype pathophysiological models. For mining the electronic medical record (EMR) to deliver new medical knowledge about causal effects, which are hidden in statistical associations between different patient attributes, Toddenroth et al. [33] utilized heat maps visualize tabulated metric datasets as grid-like choropleth maps, and thus present measures of association between numerous attribute pairs clearly arranged. Simulation results demonstrate that the proposed clustering procedure rearranges attributes similar to simulated statistical associations. Thus, heat maps are an excellent tool to indicate whether associations concern the same attributes or different ones, and whether affected attribute sets conform to any preexisting relationship between attributes. Koita et al. [34] examined the seasonality of malaria parasite prevalence in the dry northern part of Mali at the edge of the Sahara desert. Results showed lower prevalence in hot dry than cold dry, Malaria remained stable in the villages with ponds but varied between the 2 seasons in the villages without ponds Malaria was meso-endemic in the study area. Also as application of heat maps in medical field, Sudhakara et al. [35] used a combination of RS and GIS approach to develop landscape predictors of sand fly abundance. Result showed that rural villages surrounded by higher proportion of transitional swamps with soft stemmed edible plants and banana, sugarcane plantations had higher sand fly abundance and would, therefore, be at higher risk prone areas for man-vector contact.

In [36] Kawasaki et al employed GIS for assessing stream water chemistry in a forested watershed. Survey supporting maps were prepared for effective data collection in the field by considering some working hypotheses. Then, factors contributing to water chemistry were analyzed using fine-scale spatial data in an individual catchment. Finally “nitrogen leaching prediction map” was created for decision support concerning the type and location of actions to properly manage future forest ecosystems in the Tanzawa Mountains based on data from 51 sampling points.

In the field of hazard and risks assessment, Pramojanee et al. [37] applied remote sensing interpretation and GIS for mapping of Flood Hazard and Risk Area in Nakorn Sri Thammarat Province, South of Thailand. By means of weighting, a number of causative factors including annual rainfall, size of watershed, side slopes of watershed, gradient of river and stream, drainage density type of soil and land use, communication line and infrastructures, and population density were considered for rating the degree of hazard and risk. Maps of two scales, 1:250,000 of the region and 1:50,000 of two provinces were obtained. Their study discussed only the procedures that were applied for mapping flood hazard and risk areas in one of the two provinces. The study suggested that about 5 percent of the total area of the province is under a high risk of flooding whereas 17 and 22 percent are under moderate and low risk respectively. Comparing the moderate and high risk areas identified in this study with the ground truth data obtained from the field work however, it is found that the risk area obtained from the study is about 20-25 percent higher than the actual one. Also Dhakal et al. [38] applied GIS for landslide hazard assessment using multivariate statistical analysis, mapping, and the evaluation of the hazard maps. The study area was the Kulekhani watershed (124 km2) located in the central region of Nepal. To determine the factors and classes influencing landsliding, layers of topographic factors derived from a digital elevation model, geology, and land use-land cover were analyzed by quantification scaling type II (discriminant) analysis, and the results were used for hazard mapping. The geology was found to be the most important factor for landslide hazard. The scores of the classes of the factors quantified by the five analyses were used for the hazard mapping in the GIS, with four levels of relative hazard classes: high, moderate, less, and least. The evaluation of five hazard maps indicated higher accuracy for the combinations in which the non-landslide group was generated by the unaligned stratified random sampling method. The agreements in the hazard maps, produced from different sample combinations using unaligned stratified random sampling for selecting non landslide group, were within the acceptable range for the practical use of a hazard map. In [39] Chien-Yuan et al., analyzed time-varying rainfall infiltration induced landslide. Results of the analyses showed that under heavy rainfall conditions, the infiltrated slope is unstable and the time of debris masses movement initiated is correlated to the recorded time. While da Silva et al. [40] constructed risk maps for agricultural use from data obtained from remote sensing technology. They used ground temperature, or land surface temperature (LST), data distributed by EUMETSAT/LSASAF (with a spatial resolution of 3×3 km(nadir resolution) and a revisiting time of 15 min) to generate one of the most commonly used parameters in pest modeling and monitoring: “thermal integral over air temperature (accumulated degree-days)”. The results showed a clear association between the accumulated LST values over a threshold and the accumulated values computed from meteorological stations over the same threshold (specific to a particular tomato pest). The results were very promising and enabled the production of risk maps for agricultural pests with a degree of spatial and temporal detail that is difficult to achieve using in-situ meteorological stations.

In the field of the GIS and climate mapping, Daly et al. [41] applied the regression based Parameter-elevation Regressions on Independent Slopes Model (PRISM) to generate maps of mean monthly and annual precipitation and minimum and maximum temperature for the Caribbean islands of Puerto Rico, Vieques and Culebra over the 1963-1995 averaging period. Overall, the full PRISM approach resulted in greatly improved performance over simpler methods for precipitation and January minimum temperature, but only a small improvement for July maximum temperature. Comparisons of PRISM mean annual temperature and precipitation maps to previously-published, hand-drawn maps showed similar overall patterns and magnitudes, but the PRISM maps provided much more spatial detail. While Lindberg et al. [42] studied the Impact of city changes and weather on anthropogenic heat flux in Europe for the interval 1995–2015. They produced heat maps for population density, annual average and daily average of anthropogenic heat flux. In study of output prediction of large-scale photovoltaics by wind condition analysis using 3D topographic maps Obara et al. [43] developed an analysis method to determine the temperature distribution and electrical conversion efficiency of a photovoltaic module by considering the wind conditions at the installation site. Modular temperature distribution and DC electrical conversion efficiency were obtained by introducing the physical properties of the photovoltaic module, wind conditions, and climatic conditions (plane of array irradiance and ambient temperature) by using a digital three-dimensional topographic map in a heat-transfer calculation. The case analysis resulted suggest a high value for the power-production efficiency for low ambient temperature. However, the difference in the temperature distribution of the photovoltaic module in relation to the difference in the ambient temperature is strongly influenced by wind velocity and wind direction. Moreover, when a large-scale photovoltaic power plant is installed on a complicated mountain slope, the cooling effect is controlled so that the in draft wind velocity on the photovoltaic module decreases. Therefore, in order to maintain high electrical conversion efficiency in the photovoltaic module, the best location for installation is an airy and flat area, as much as possible. According to the case analysis, the electrical conversion efficiency of the photovoltaic module at the time of the analysis under wind condition increased 23% (maximum) compared with that without wind conditions. In [44] Wilk and Andersson determined the areal distribution of precipitation by using a GIS-supported method and other factors (altitude and slope). Also Ye et al. [45] studied glacier variations in the Geladandong mountain region of central Tibet using RS and GIS technics. Data from Landsat images at three different times, 1973–76, 1992 and 2002 were compared with glacier areas digitized from a topographic map based on aerial photographs taken in 1969. Findings showed that there was accelerated glacier retreat in recent years, attributable to increase in summer air temperature. Omuto [46] while tracing the footprint of vegetation dynamics modelled a relationship between Advanced Very High Resolution Radiometer (AVHRR) / Moderate Imaging Spectro-radiometer (MODIS) NDVI and rainfall using regression analysis. Results showed a high correlation between rainfall and NDVI which proved that vegetation trend monitoring with RS and GIS can give accurate indication of climate change

In environmental and public health researches Pleil et al. [47] studied the human systems interactions with the environment and they produced heat maps for that purpose. The results showed that visualization of complex measurement data via a heat map approach is a valuable screening tool for quickly testing broad hypotheses regarding relationships among exposure measurements, biomarkers, meta-data, and host factors before computational efforts are expended. Santhi et al. [48] used GIS based hydrological model for estimating canal irrigation demand in the Lower Rio Grande Valley in Texas. Estimated potential water savings were 234.2, 65.9, and 194.0 Mm3 for conservation measures related to on−farm management improvements. It concluded that GIS would be useful for irrigation planning. Yelwa and Eniolorunda [49] simulated the spatial trend of desertification in Sokoto and its environs, Nigeria, using a time series 1-km SPOT Normalized Difference Vegetation Index (NDVI) and GIS. Results showed the direction of desertification movement and that the inter-annual vegetation vigour exhibited a diminishing trend over the time series.

Choo, et al. [50] presented iVisClassifier, which is a system based on supervised linear discriminant analysis that allows the user to iteratively label data and recomputed clusters and projections. By using heat maps, iVisClassifier gives an overview about the cluster relationship in terms of pair wise distances between cluster centroids both in the original space and in the reduced dimensional space.

The monitoring of vegetation degradation processes is an important component in developing appropriate conservation strategies aimed at landscape management for continued human existence [51], RS and GIS can suitably be used for characterizing vegetation phenology.

The main objective of this study is to provide a deeper spatial analysis of rainfall phenomenon in Sudan and produce rainfall maps, by using rainfall prediction and GIS.

III. Data and Method

A. Meteorological Data

The meteorological data that used in this study has been brought from Central Bureau of Statistics, Sudan for 13 years from 2000 to 2012 for 24 meteorological stations over the country with 3732 total number of examples.

The dataset had eight (8) attributes (station name, date, maximum temperature, minimum temperature, relative humidity, wind direction, wind speed and rainfall) containing monthly averages data. In this study only the numerical most influencing variables (Date, Minimum Temperature, and Humidity) that affect on the long term rainfall prediction out of the 7 variables [52] have been used.

Figures (1- 3) show the monthly numerical data of our dataset (minimum temperature, humidity and rainfall) respectively for 13 years (2000-2012).

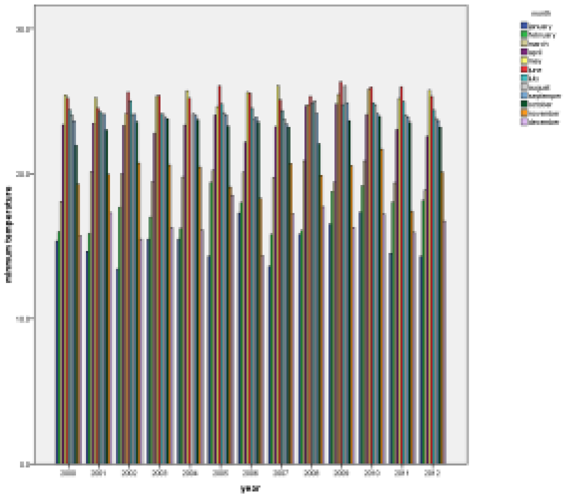

Figure 1. Minimum temperature.

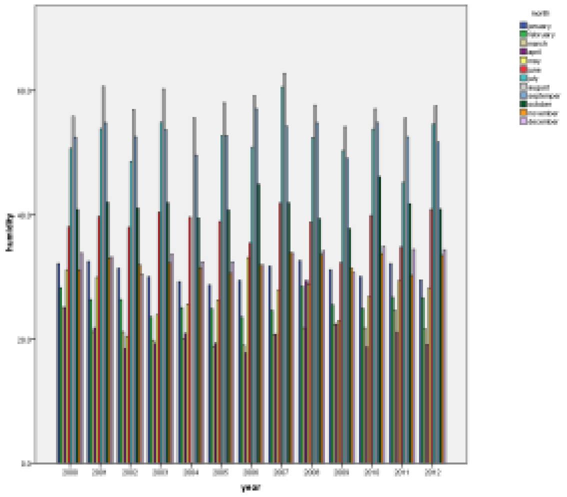

Figure 2. Relative humidity.

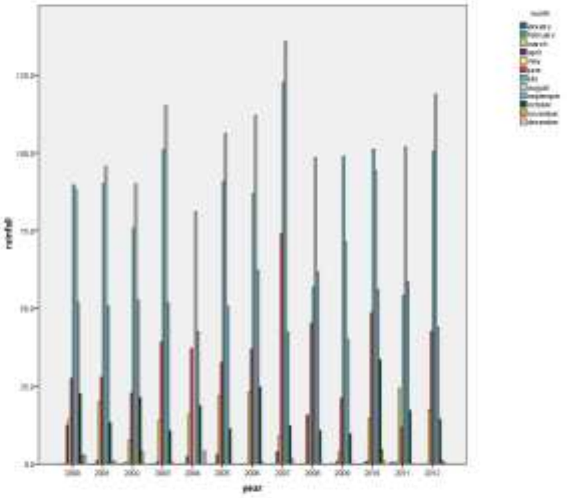

Figure 3. Rainfall amount.

B. Spatial Data

The term spatial data means according to GIS dictionary "the Information about the locations and shapes of geographic features and the relationships between them, usually stored as coordinates and topology". Thus it represents data that are inherently geographic; that is, they describe geographic features.

Also it defined as the data or information that identifies the geographic location of features and boundaries on Earth, such as natural or constructed features, oceans, etc [53]. Spatial data is usually stored as coordinates and topology, and is data that can be mapped. Spatial data is often accessed, manipulated or analyzed through Geographic Information Systems (GIS).

In this study the coordinates such as latitude and longitude, which determined any position on the earth have been taken by using GPS device of type GPSMAP Garmin60cs with 0-10 meters expected error for 24 meteorological stations, 15 states and 6 regions in Sudan. Table 1 shows the meteorological stations with their corresponding states and regions.

Region	States	Stations
Northern	Northern and River Nile.	Dongola, Atbara, Abu Hamad, Karima and Wadi Halfa.
Eastern	Red Sea, Kassala and El Gadarif.	Kassala, Port Sudan, El Gadarif and New Halfa.
Khartoum	Khartoum.	Khartoum.
Central	Al Jazeera, White Nile, Sinnar and Blue Nile.	Wad Medani, El Deweim, Kosti, El damazen, Abu Naama and Sinnar.
Kordofan	North Kordofan and South Kordofan.	Elobied, El Nihood, Kadugli, Babanusa and Rashad.
Darfur	North Darfur, West Darfur and South Darfur.	Nyala, Elgeneina and El Fashir.

Table 1. The meteorological stations, states and regions.

C. General framework

The spatial data for the study area which represented in a form of position and boundaries of regions, states and meteorological stations in towns has been collected by using Geographic Position System (GPS) device of type GPSMAP Garmin60cs with 0-10 meters expected error. Next, we downloaded the spatial data from GPS device into computer device and create a shape file contained three layers for regions, states and meteorological stations in towns.

The polygon has been used to represent regions, states and meteorological stations at town level in the map.

Adjustment process (Georeference) has been made by using GIS to ensure that positions, coordinates and boundaries for towns, states and regions are correct.

After that we created attribute file contained monthly and annual rain dataset which consist of the rainfall predictions and the effect numerical factors that influence on rainfall such as date, minimum temperature and relative humidity.

Finally, advanced GIS software has been used to visualize, compare and analyze the distribution of rainfall and other predictors among town, state and region levels by using different graduated mapping methods such as graduation by size and graduation by color. Figure 4 shows the mechanism which has been followed to produce the rainfall maps.

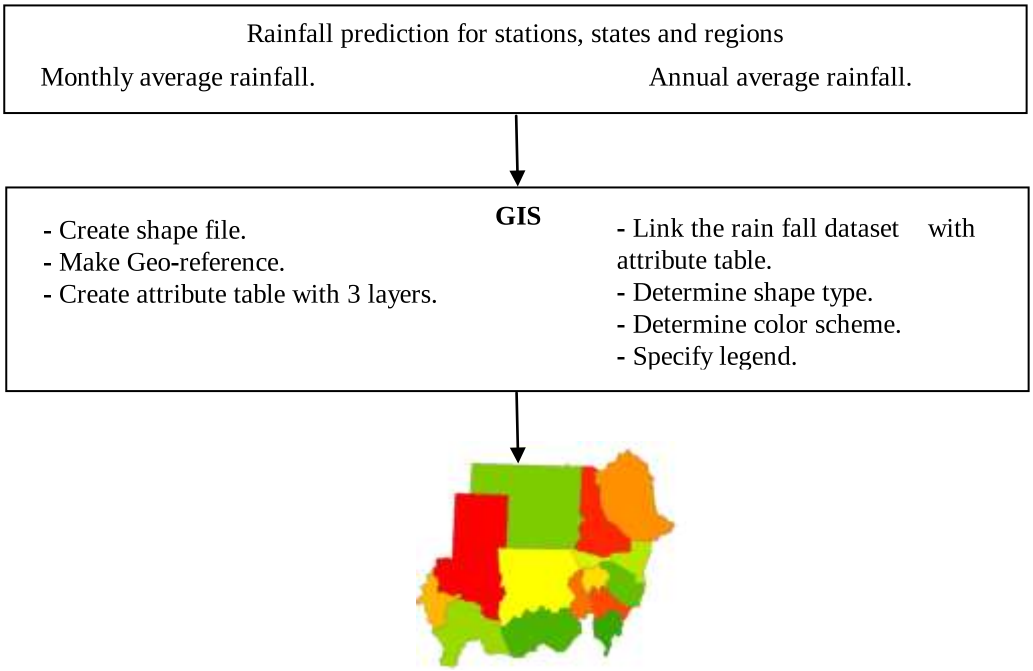

Figure 4. The methodology to produce rainfall maps.

D. Data representation

Real world data are represented by one of four features in a GIS. They include point, line, polygon, and image features [54].

1) Point feature

A point feature is a discrete location that is usually depicted by a symbol or label.

2) Line feature

A line feature is a geographic feature that can be represented by a line or set of lines.

3) Polygon feature

A polygon feature is a multisided figure represented by a closed set of lines.

4) Image feature

An image feature is a vertical photo taken from a satellite or a plane that is digitized and placed within the geographic information system coordinate system so that there are -x and -y coordinates associated with it.

Each type of feature has “attributes” or a table of data that describe it. All the attributes for three of the four types of features (point, line, and polygon) are stored in a GIS as a data table (Note that a digital orthophotograph has an –x and –y coordinate but does not have an associated data table worthy of analysis). The ability to view, query, relate, and manipulate data behind these features is the true power of a GIS. A manual pin map and a computer map depict points, lines, and polygons but do not have data associated with the features and are not easily manipulated. In a GIS, simply clicking on a point, line, or polygon can produce the data table associated with that particular feature.

In this study the polygon has been used to represent regions, states and meteorological stations at town level in the map.

E. Data Projection and registration

To georeference means to associate something with locations in physical space. The term is commonly used in the geographic information systems field to describe the process of associating a physical map or raster image of a map with spatial locations. Georeferencing may be applied to any kind of object or structure that can be related to a geographical location, such as points of interest, roads, places, bridges, or buildings [55].

Geographic projections and their parameters (datums, geoids etc) are ways to model the earth’s curved surface to a flat plane [55].

Registration is necessary to “tie” geographic data to specific points on the Earth’s surface to allow accurate mapping and analysis between different GIS layers

Geospatial data should be geographically referenced (called georeferenced or geocoded) in a common coordinate system. The reference points are called tic masks or ground control points. One of the most convenient way of locating points is to use plane orthogonal coordinates with x (horizontal) and y (vertical) axis.

In this research adjustment process (Georeference) has been made by using GIS to ensure that positions, coordinates and boundaries for towns, states and regions are correct.

F. Spatial Analysis Techniques

There are two main spatial analysis techniques:

1) Single Symbol Mapping

Single symbol mapping refers to the use of individual symbols to represent point, line, and polygon features [56]. The utility of single symbol maps is that they allow for a detailed analysis of small amounts of data.

A drawback of single symbol mapping is that if two incidents have the same address, they are placed exactly on top of one another and cannot be differentiated by looking at the map. The following map is a better example of single symbol mapping that uses an appropriate scale. However, to avoid confusion since the points may still be placed on top of one another, one should list the number of incidents in the legend. Single symbol maps are more useful for small amounts of data.

2) Graduated Mapping

Graduated mapping consists of aggregating data into groupings that are displayed on the map [56].

These groupings can be graduated by size or by color and can be classified statistically in various ways.

(a) Graduation by Size

Graduated size mapping is the process by which data are summarized so that symbols (point or line features) are altered in size to reflect the frequencies in the data.

In other words, in this type of map, more than one incident at a given point or line is represented with a larger symbol or a thicker line. One drawback is that oftentimes, the size of the symbol or line is difficult to distinguish and the actual value associated with that symbol is not clearly displayed. In addition, similar to single symbol mapping, this type of map is most helpful with smaller amounts of data, since too many incidents make the map unclear and difficult to read.

(b) Graduation by color

In graduated color mapping, symbols (point, line, or polygon features) are altered in color to reflect a particular value of the feature.

Each location must only represent one incident since it would be impossible to shade one point with data from two incidents. As with single symbol mapping, this map is most helpful when examining a small number of data.

In this study GIS software has been used to visualize, compare and analyze the distribution of rainfall and other predictors among town, state and region levels by using different graduated mapping methods such as graduation by size and graduation by color.

G. Classification Methods

There are several different statistical methods for classifying numeric data in a GIS when creating both graduated size and graduated color maps. In this study the natural breaks has been used as classification method.

Natural breaks

This is the default classification in most GIS programs and identifies the natural break points within the data using a statistical formula [57].

The software program examines the selected data and their distribution, identifies natural break points, and creates the categories based on the best fit to the data. With each data set, the natural breaks classification would result in different ranges of categories; thus, the classification is data dependent.

IV. Experimental Results and Discussion

In graduated color mapping, polygon feature is altered in color to reflect a particular value of the rainfall. Figure 5 shows rainfall on regions level for period 2000 – 2012 by using graduation by color, Kordofan region had the biggest amount of rainfall comparing with other regions but it had been decreased since 2003 there was a climatic change. In 2003 Darfur region recorded the highest rainfall amount sharing the Kordofan region however, that was exception and it generally recorded fewer amounts. For years 2008, 2009, 2010 and 2012 Central region shared Kordofan in the first order of rainfall amount. Northern region had the lowest rainfall amount in range 0.070667 - 3.44.

Figure 7 displays rainfall on states level for period 2000 – 2012 using graduation by color, generally Sinnar, Blue Nile, El Gadarif, South Kordofan and West Darfur had the highest rainfall amount, while Northern, River Nile, Red Sea had the lowest. A marked increase in the average amount of rain appeared in the years 2000 and 2005 in the North Darfur state.

Figure 9 illustrates rainfall on stations level for period 2000 – 2012 using graduation by color. Areas which appear in dark blue color (Wadi Halfa, Dongola, Karima, Atbara and Abu Hamad) acquired the lowest rainfall amount in range 0 - 5.541667. Towns such as El Fashir, Port Sudan, El Deweim and Kassala that represented by light blue in the most rainfall maps got amount of rain between 5.541668 and 25.141667. Green color which used to represent cities such as Kosti, El Deweim and Elobied covers the range 25.141668 – 39.3750. While the yellow color that represents the range 39.375001 – 54.40, appeared in some places, such as Elgeneina, Nyala, Kadugli and Babanusa. Areas that had the highest proportion of rain like El Gadarif, El damazen, Rashad, Abu Naama Babanusa and Kadugli been represented on the maps using the red color, which indicates the extent to 54.400001-77.2250. Wadi Halfa is considered as desert areas of few rains but it showed a marked increase in the amount of rainfall in 2006. There is also a decrease in the amount of rain that fell in the town of Rashad in the years 2003, 2008 and 2010.

Figure 11 shows average monthly rainfall on stations level for year 2012 using graduation by color. In winter (November, December, January and February) there were little or no rain in most cities except for some stations such as Port Sudan, Rashad, Elobied, El Deweim, Babanusa El damazen and Abu Naama. In March and April a light rain (0.338463 – 7.661538) in the southern and western parts such as Nyala, Elgeneina, Elobied, Kadugli, Babanusa, El Gadarif, Kosti, El damazen, Abu Naama and Sinnar. In May and June moderate and heavy rain (27.623078 – 111.253846) in El damazen, Kadugli, El Gadarif, Rashad, Babanusa and Abu Naama. Beside few or no rain (0 – 11.830769) in the northern parts, Khartoum, El Fashir and Port Sudan. The months of July and August represent the peak of the fall, light rains (0.538462 – 21.6385) in each of Port Sudan, Khartoum, Wad Medani, and northern parts, while moderate rains (21.6386 – 104.115385) in El Fashir, El Deweim and Kassala, whilst heavy rains (104.115386 – 162.7) in Kosti, Sinnar, Elobied, El Nihood, Kadugli, Babanusa and Rashad and Nyala, however very heavy rains (162.700001 – 221.369231) in Elgeneina, El damazen, El Gadarif and Abu Naama. Only in January happened there was a marked increase in the rain pattern in Wadi Halfa station.

As shown in figure 13 which appears comparison between average monthly rainfall on stations level for years 2003, 2007 and 2012 using graduation by color. There are constant patterns of rain, which often the possibility of their occurrence in the months July, August and September. In year 2003 there was very small quantity of rain in all months in Khartoum, Port Sudan and all towns of the northern region except Atbara, which it had more amount of rain in August. The highest rate of rain for the month of September was in Kadugli, Rashad, Wad Medani, El damazen and Sinnar. In 2007 it increased the amount of rain in Dongola, Karima and Khartoum, compared to 2003, as it rained in April in New Halfa, Khartoum, Wad Medani, Sinnar and Rashad. And also it rained in October in Wad Medani, El damazen, Abu Naama, Sinnar, Kadugli and Rashad. In year 2012 the amount of rain decreased significantly in Kassala, Khartoum and Northern region compared to 2007.

Figure 14 shows Comparison between average monthly temperature, humidity and rainfall on regions level for January, May, August and December 2012. In January temperature decreased, humidity increased and rainfall almost absent in all regions. While in May the temperature increased with rain in all regions except Northern and Khartoum. In August rains fell in all the regions and then returned to a decrease in December and absent except in the eastern region.

As shown in figure 15 a comparison between average monthly rainfalls on regions level for year 2000, 2006, 2011 and 2012 been made. In the Northern region few or no rain in 2000 and 2012, little rain in July, August and September 2006 and a few rain in July 2011. The eastern region like other regions rainy season limited between May and October and up to a peak in July and August. Central, Kordofan and Darfur regions are considered the most rain compared to the rest, while we find that Khartoum and North are the least rain, but the eastern region is characterized medium rains. 2006 saw a clear change in the pattern of rainfall, increase of rain amount in all regions of Sudan.

Figure 16 compared between average monthly temperature, humidity and rainfall on states level for January, May, July, August, November and December 2012. In January rain absent from all States, while in May temperature increased, humidity decreased and rains began in most states except Northern, River Nile, Red Sea, Kassala and Khartoum. July and August period represent a fall season in most states except Northern, River Nile and the Red sea. In November and December temperature decreased and rain disappeared in most places except the Red Sea, Blue Nile, Sinnar, North Kordofan who witnessed rain in that period .

As shown in figure 17 comparisons between average monthly rainfall on states level for year 2000, 2006 and 2012 been made. Rains were scarce or non-existent in the Nile River and the North, while rain was felt in the state of the Red Sea in October, November and December. It rained in other states in July, August and September, while it rained in April and May in El Gadarif, North Kordofan, South Kordofan, North Darfur, West Darfur, South Darfur, Sinnar and Blue Nile.

Figure 18 Compared between average monthly temperature, humidity and rainfall on stations level for years 2012. In January temperature decreased, humidly increased and no rain in all stations. In May temperature increased, humidity decreased and it rained in most stations except Dongola, Atbara, Abu Hamad, Karima, Wadi Halfa, Kassala, Port Sudan, New Halfa and Khartoum. While in July and August it rained in most stations except Dongola, Atbara, Abu Hamad, Karima and Port Sudan. Whilst in November and December humidity increased, temperature decreased and rain disappeared from all stations except Port Sudan, El damazen, Abu Naama and Rashad.

Also in graduated color mapping there is another technique known as graduation by size which used to produce the rainfall maps in figures (6, 8, 10 and 12), polygon feature which used to represent stations, states and regions is altered in size to reflect the frequencies in the data. In this type of map, more than one incident at a given location is represented with a larger symbol.

Figure 6 shows rainfall on regions level for interval 2000 – 2012 using graduation by size. It can easily discriminate between the amounts of rain in the regions; we find that Northern region is least rain, followed by Khartoum, eastern and western regions respectively, finally Central and Kordofan comes as the two most rain regions.

Figure 8 displays rainfall maps on states level for interval 2000 – 2012 using graduation by size. It has been considered that states such as Northern, River Nile, Red Sea, Khartoum and North Darfur have the lowest rain in Sudan, while states such as El Gadarif, Sinnar, Blue Nile, South Kordofan, West Darfur and South Darfur have the highest amount of rain. In 2000 and 2010 Al Jazeera state recorded the lowest amount of rain compared with other years, while White Nile state obtained its minimum rain quantity in 2005.

In figure 10 there is a comparison of rainfall on stations level for interval 2000 – 2012 using graduation by size. It appears that stations such as Dongola, Atbara, Abu Hamad, Karima and Wadi Halfa have few or no rain, while station such as Kassala, Khartoum, Port Sudan, and El Fashir recorded medium amount of rain, where stations like El Gadarif, El damazen, Abu Naama, Kadugli, Babanusa, Rashad, Nyala and Elgeneina recorded high amount of rain.

Figure 12 shows average monthly rainfall on states level for year 2012 using gradation by size. In January and February it rained few (0.000001 – 0.323077) in Khartoum, Eastern and Kordofan and no rain elsewhere. From March to June no or very few rain in Khartoum, Northern and Darfur, while a few and moderate rain in Central, Eastern region and Kordofan. Interval of July and August recorded few or medium (5.313846 – 88.656769) rain in Khartoum, Northern and Eastern and heavy and very heavy (88.656770 – 152.007652) rain in Central, Kordofan and Darfur. In September and October low rain (0.763077 – 13.384620) in Northern and Khartoum, while medium rain (13.384621 – 51.174350) in Darfur and Eastern, and high (51.174350 – 97.669231). In period of November and December no rain in Northern, Khartoum, Darfur and Central while very few (0.038453 – 0.736923) rain in Kordofan and few rain (0.736924 – 5.134615) in Eastern region.

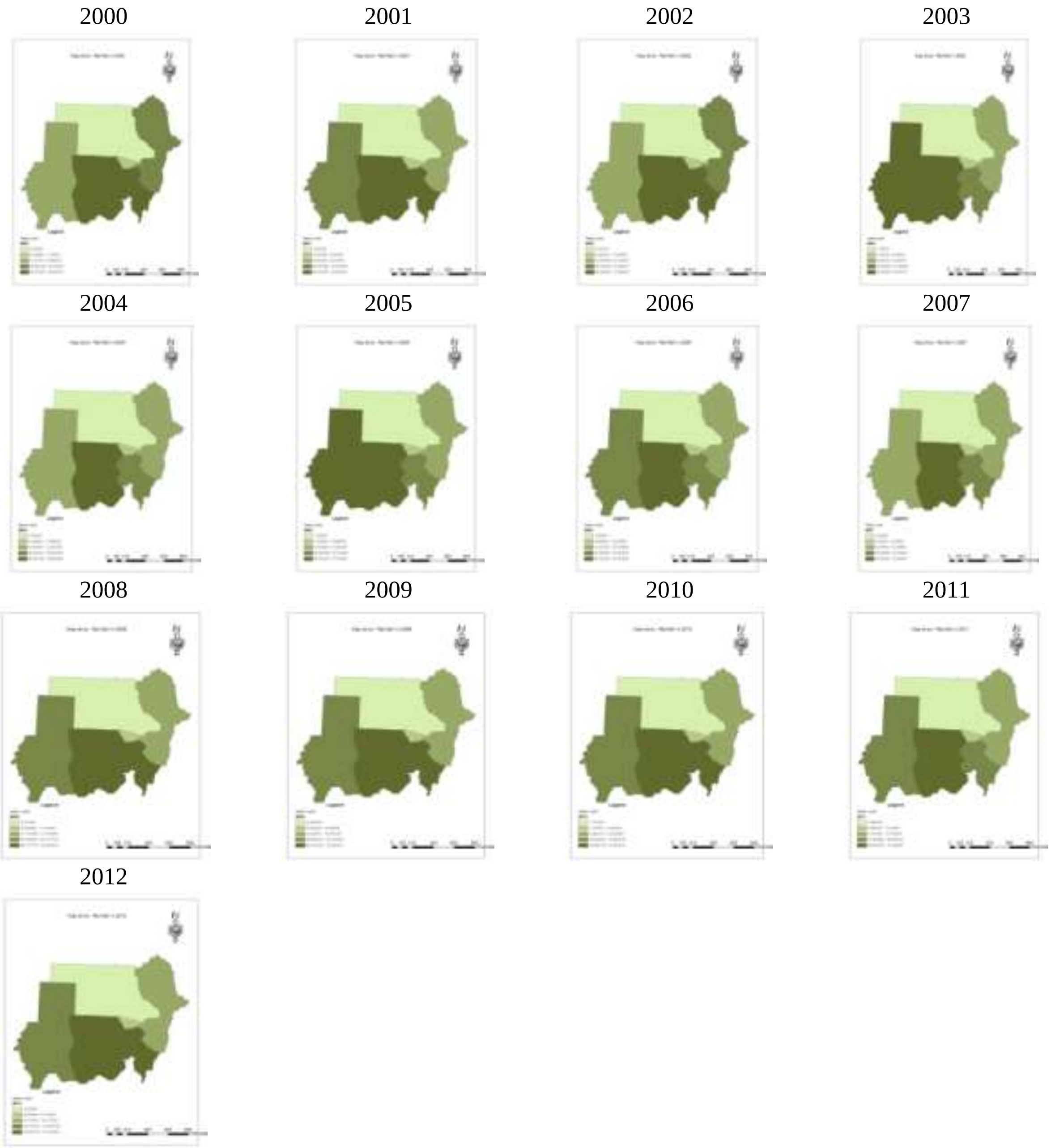

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Figure 5. The Rainfall on regions level for interval 2000 – 2012 by using graduation by color.

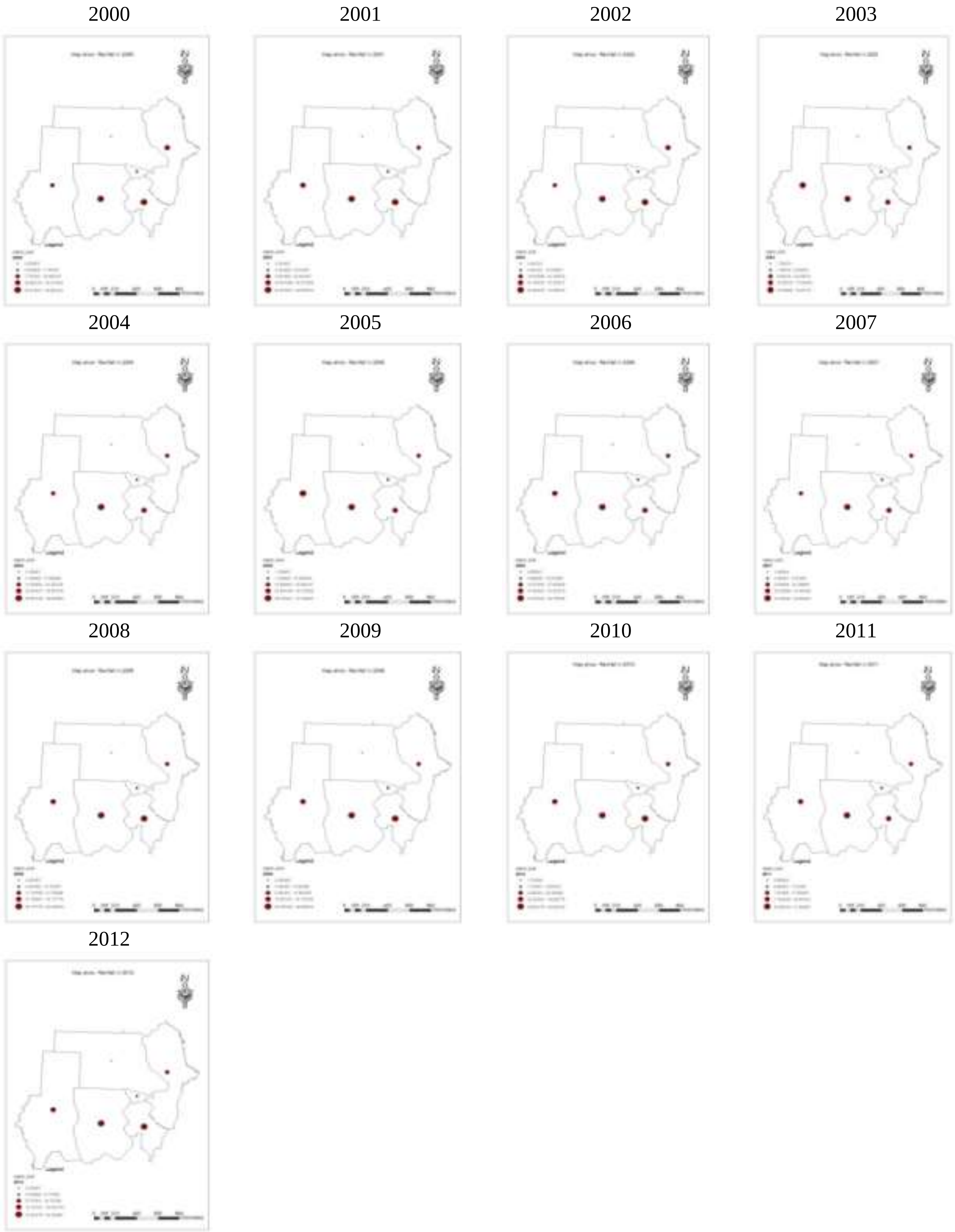

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Figure 6. Rainfall on regions level for interval 2000 – 2012 using graduation by size.

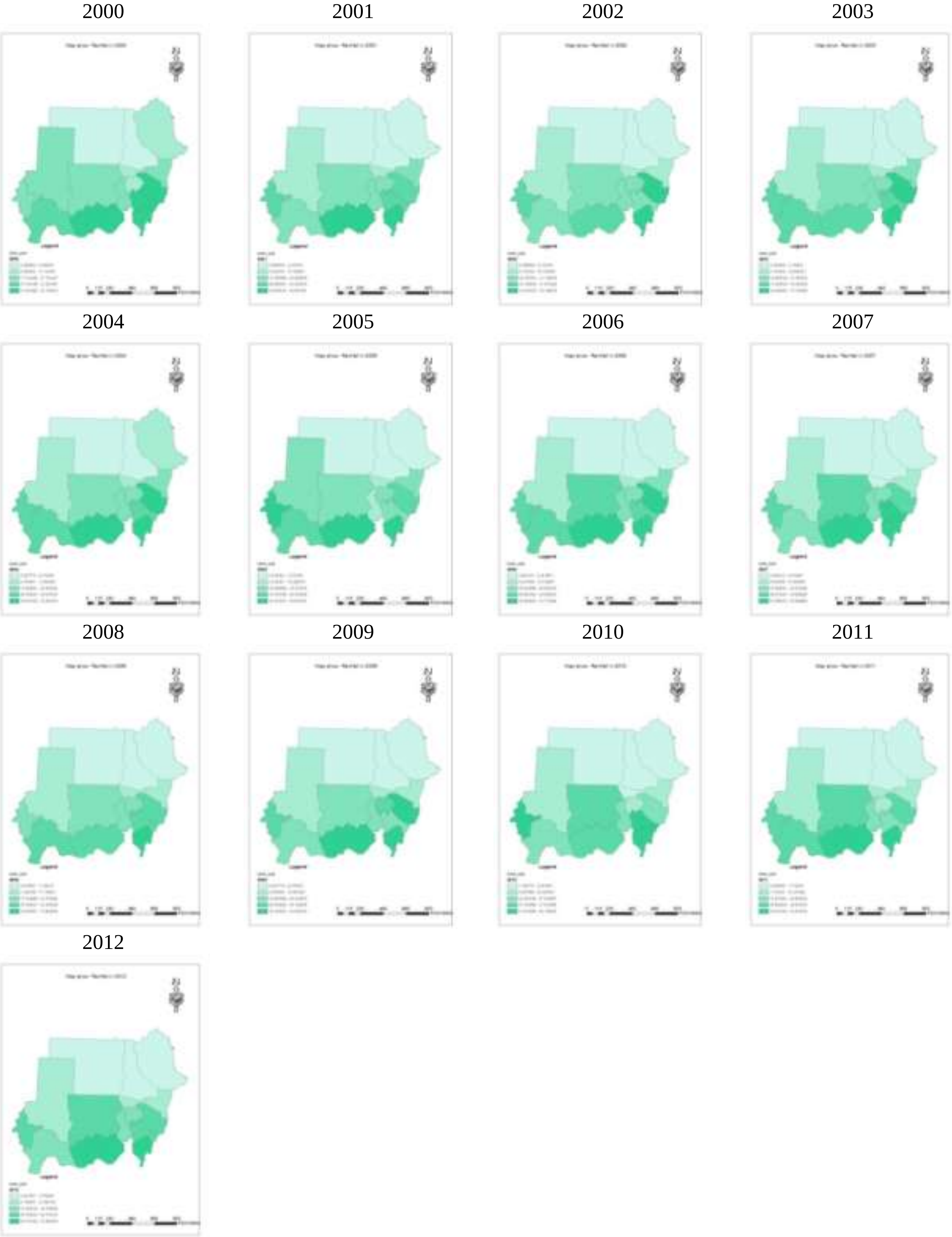
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Figure 7. Rainfall on states level for interval 2000 – 2012 using graduation by color.

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Figure 8. Rainfall maps on states level for interval 2000 – 2012 using graduation by size.

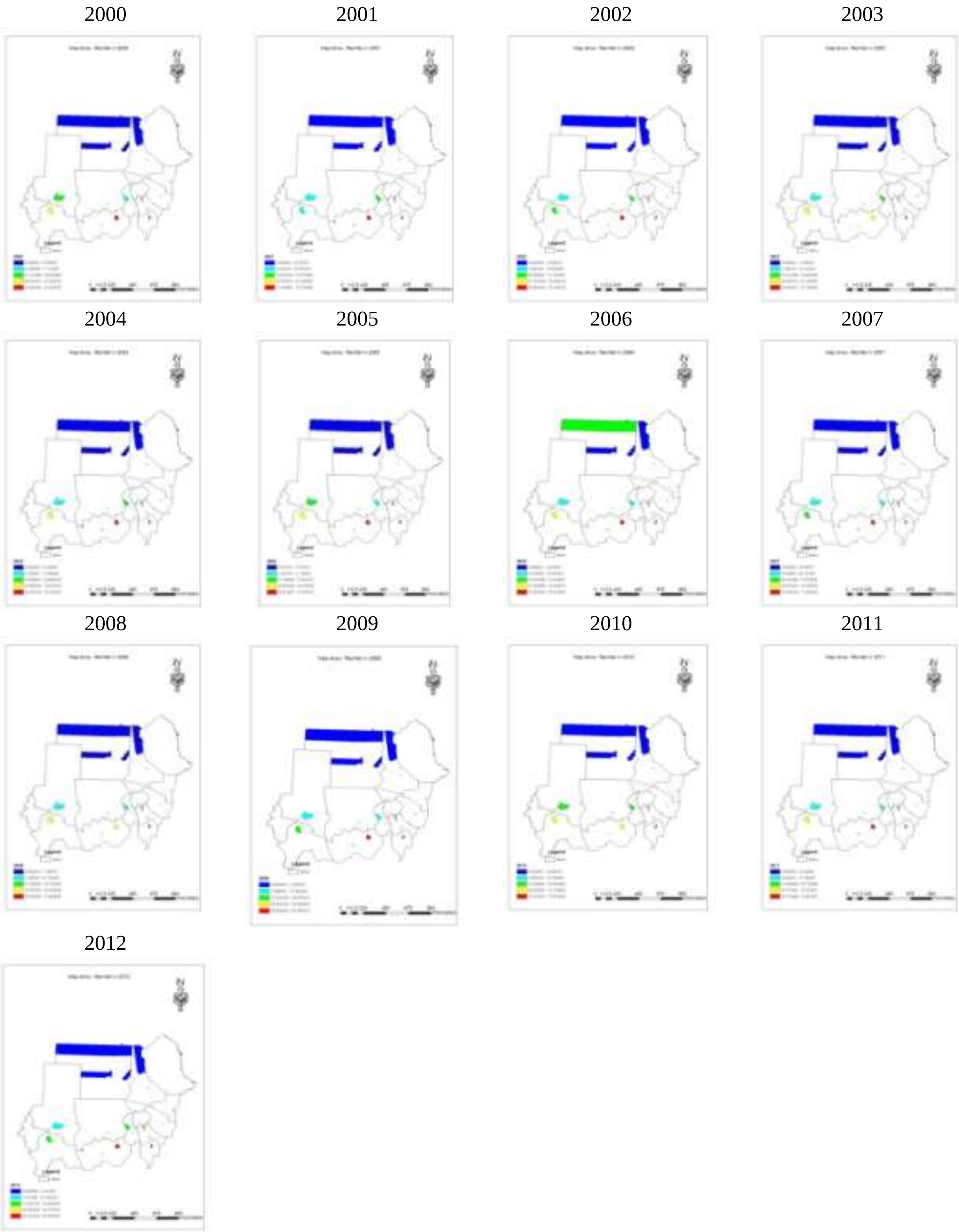

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Figure 9. Rainfall on stations level for interval 2000 – 2012 using graduation by color.

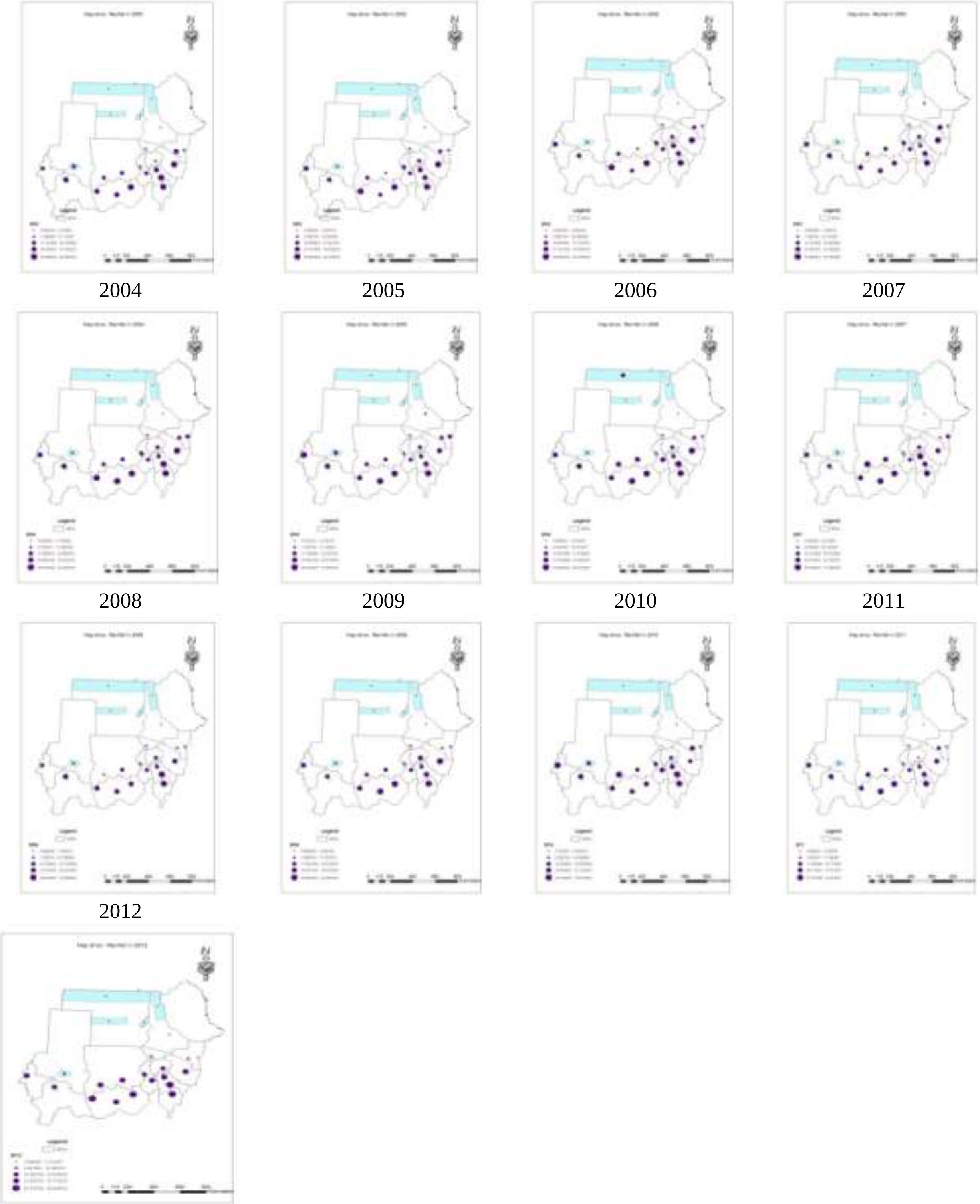

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Figure 10. Rainfall on stations level for interval 2000 – 2012 using graduation by size.

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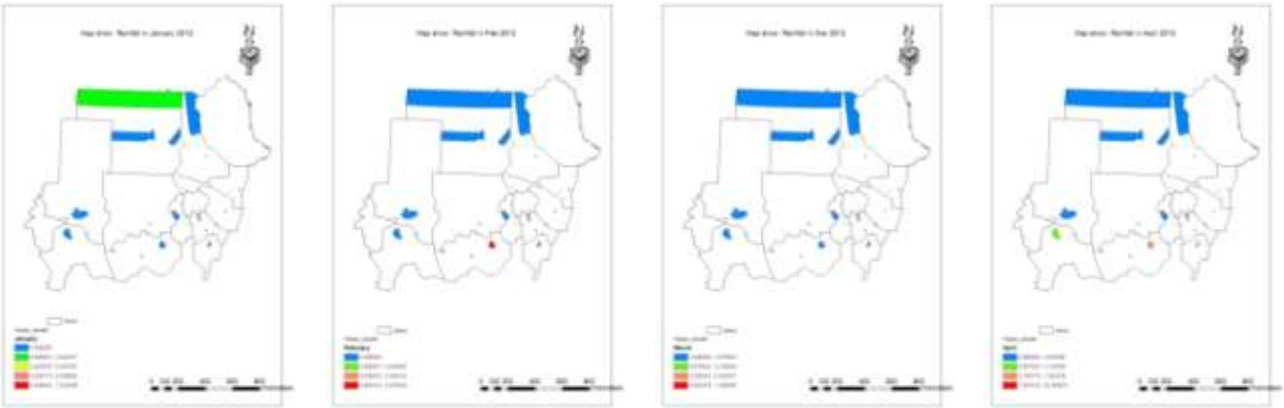

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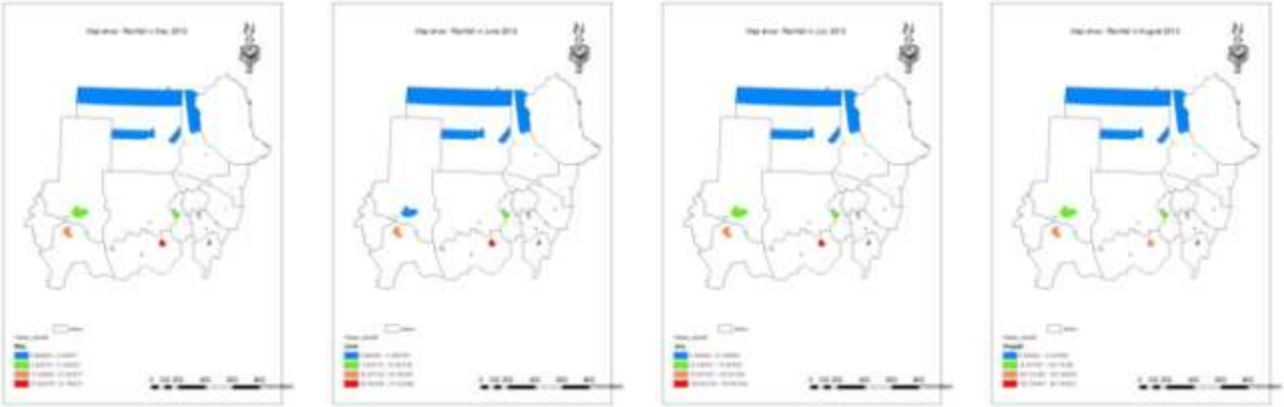

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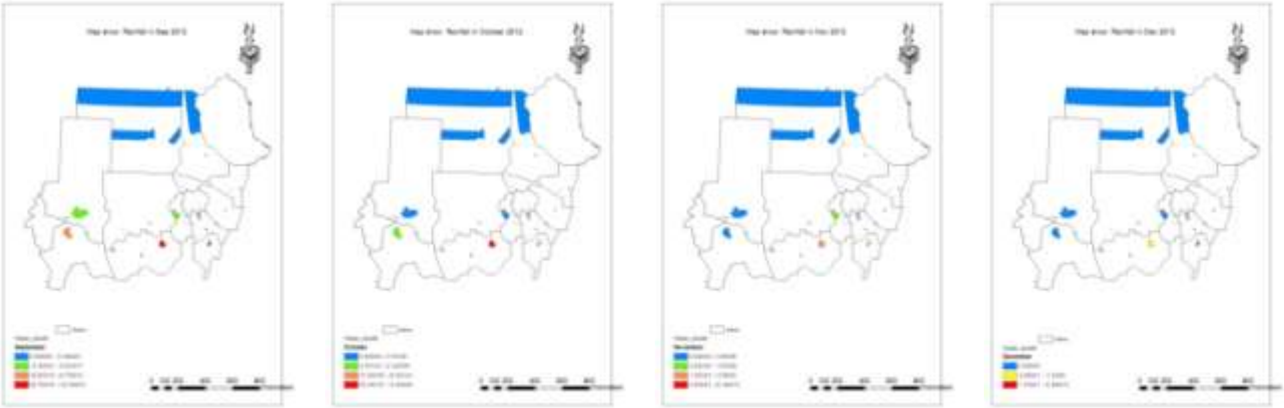
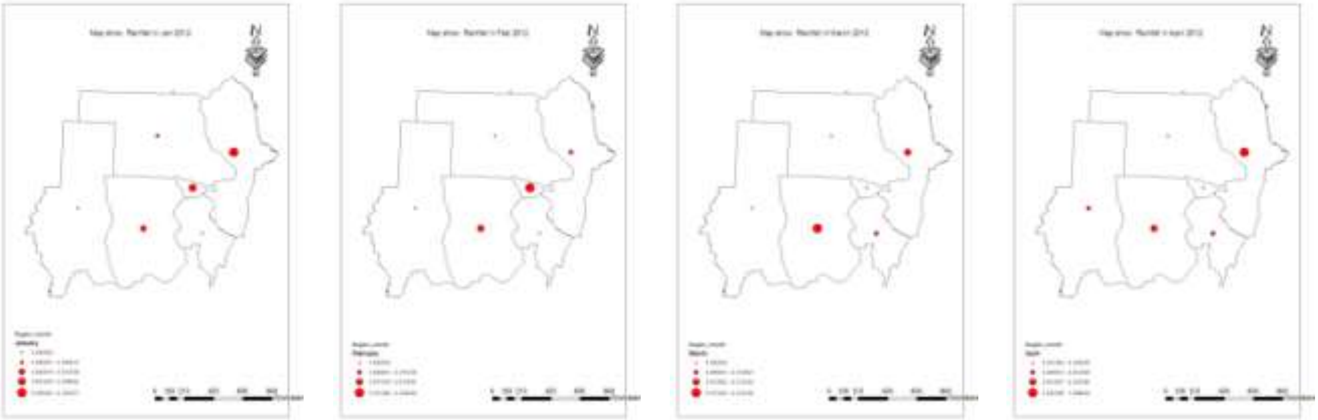


Figure 11. Average monthly rainfall on stations level for year 2012 using gradation by color.



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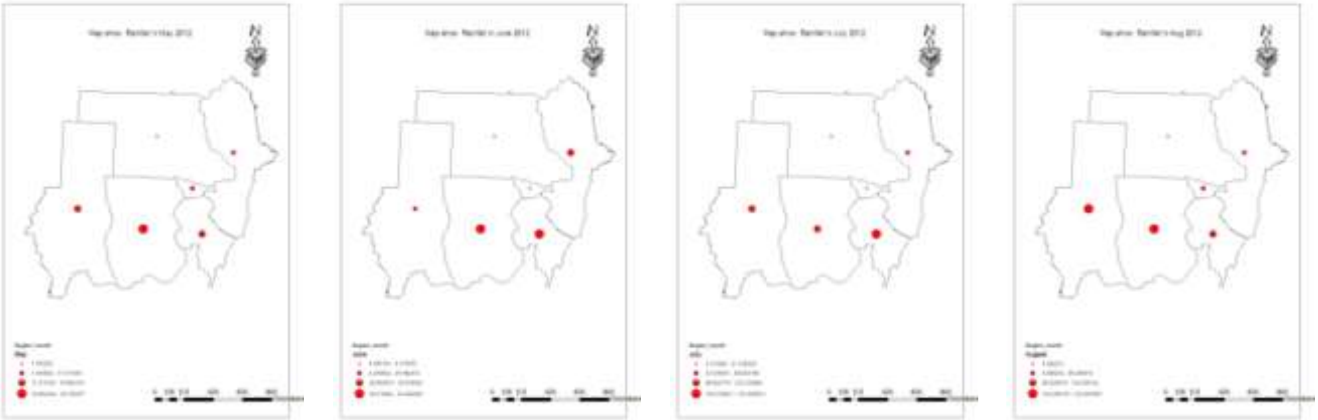

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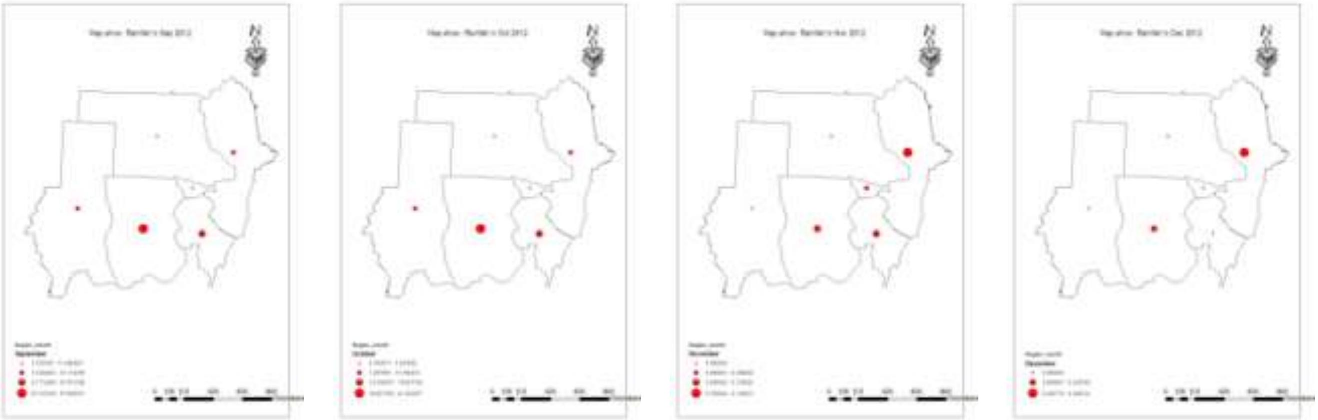

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Figure 12. Average monthly rainfall on states level for year 2012 using gradation by size.

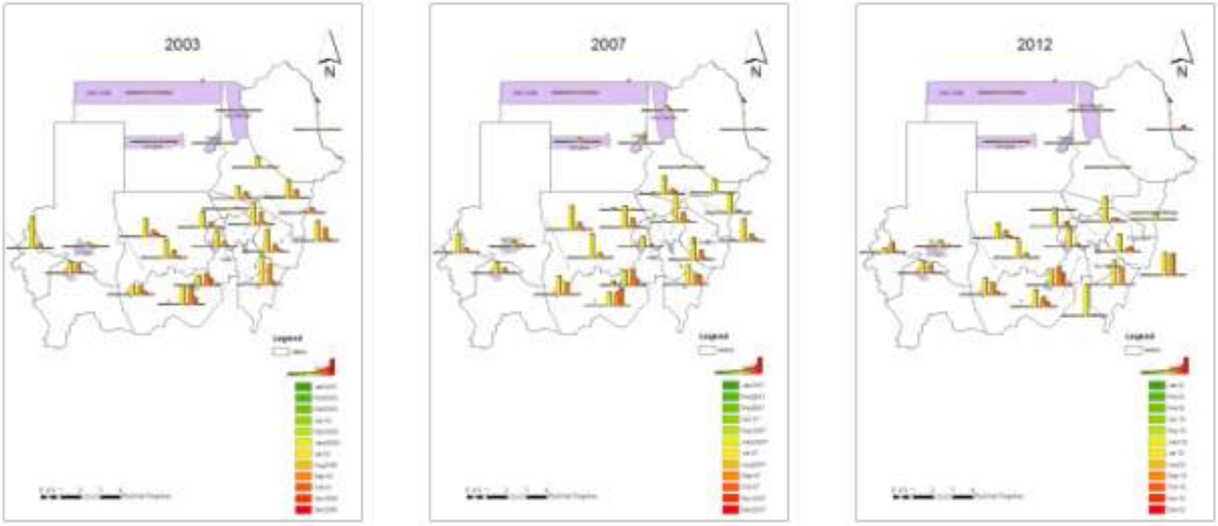
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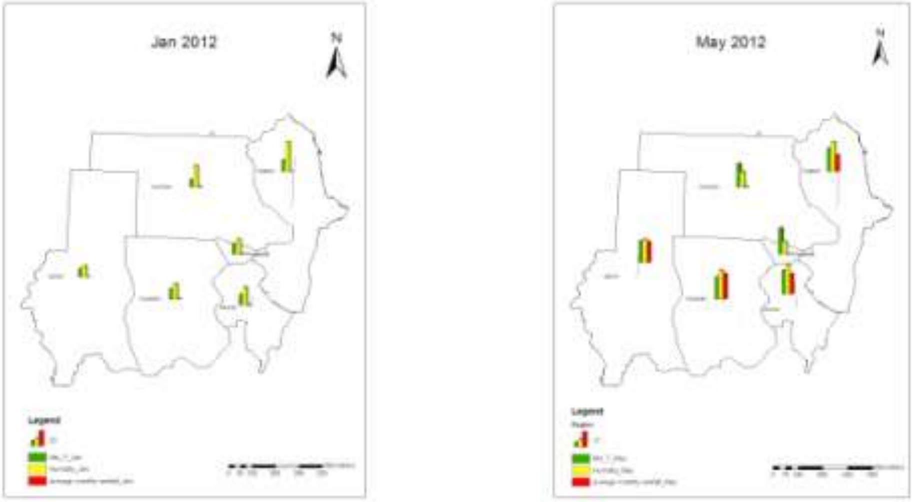
Figure 13. Comparison between average monthly rainfall on stations level for years 2003, 2007 and 2012.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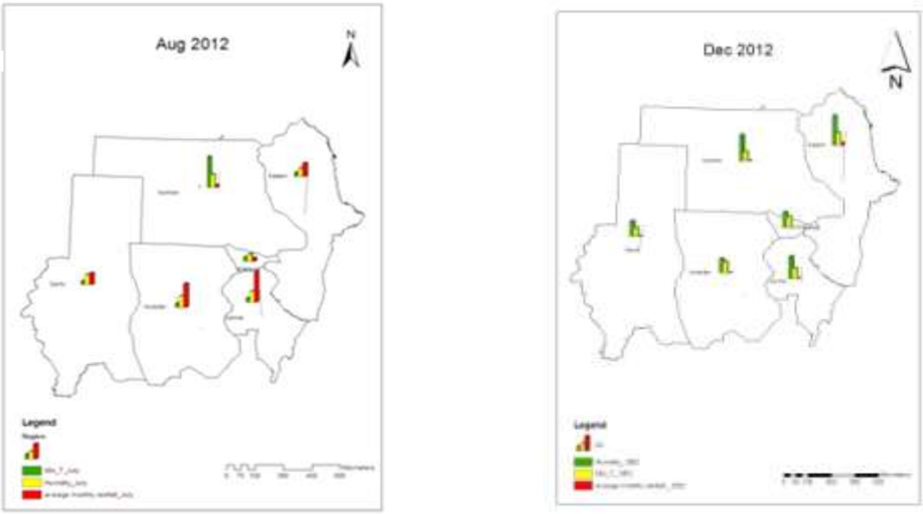
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Figure 14. Comparison between average monthly temperature, humidity and rainfall on regions level for January, May, August and December 2012.

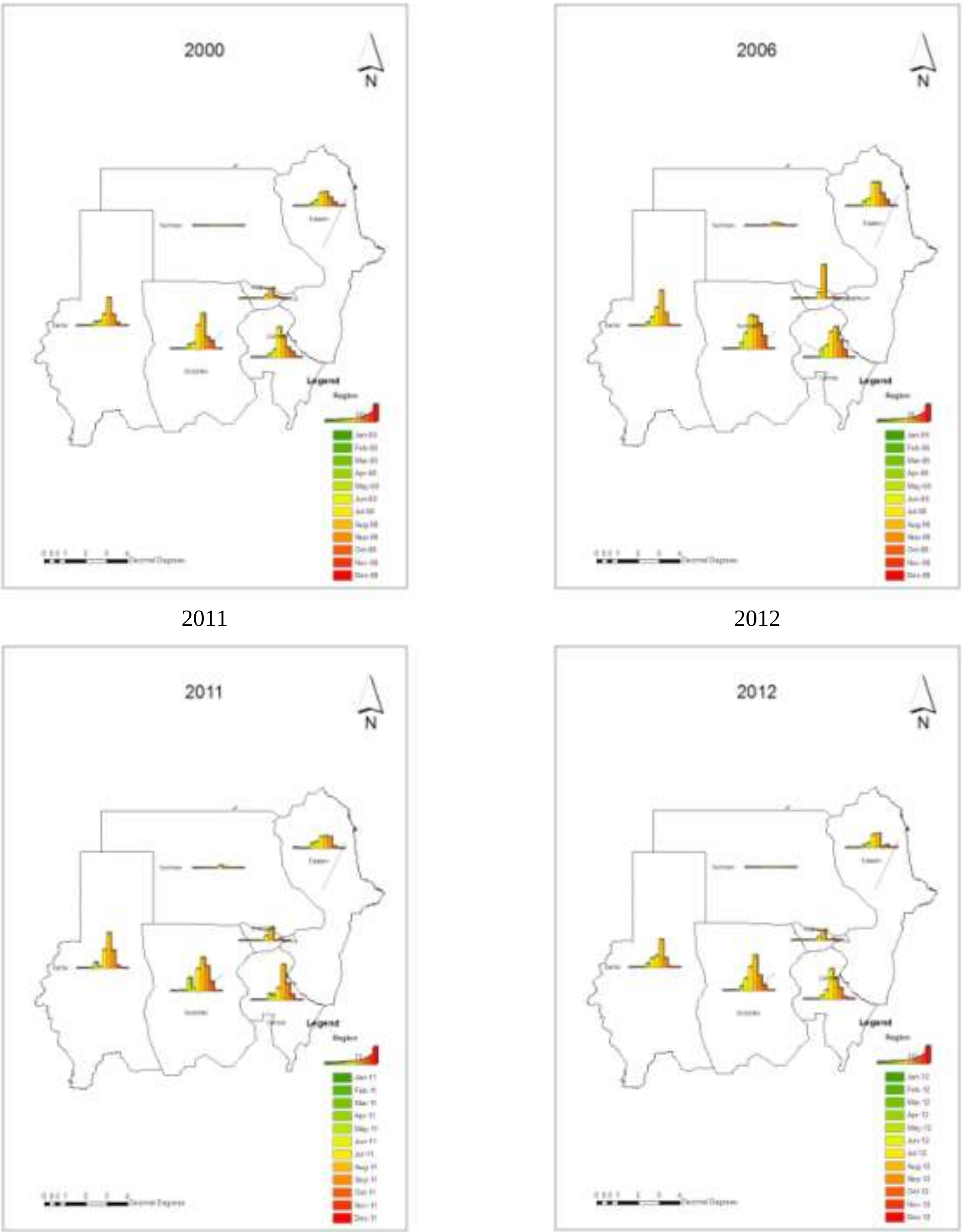

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Figure 15. Comparison between average monthly rainfall on regions level for year 2000, 2006, 2011 and 2012.

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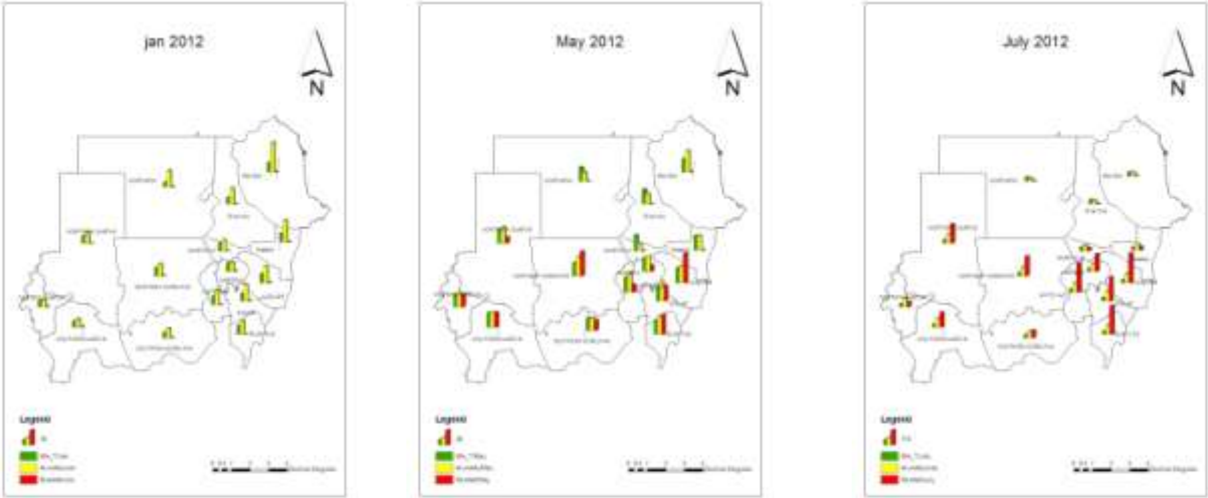

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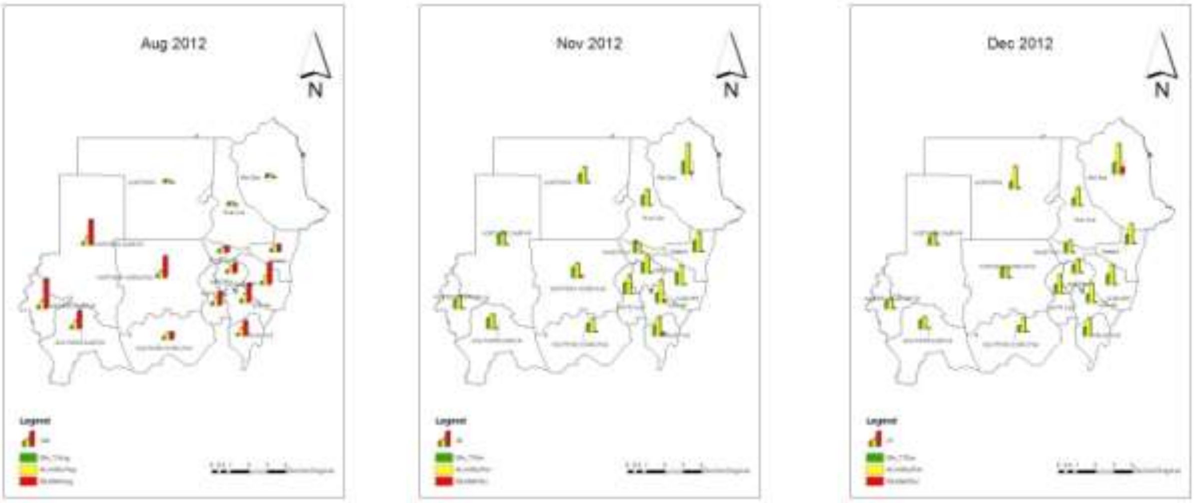

Figure 16. Comparison between average monthly temperature, humidity and rainfall on states level for January, May, July, August, November and December 2012.

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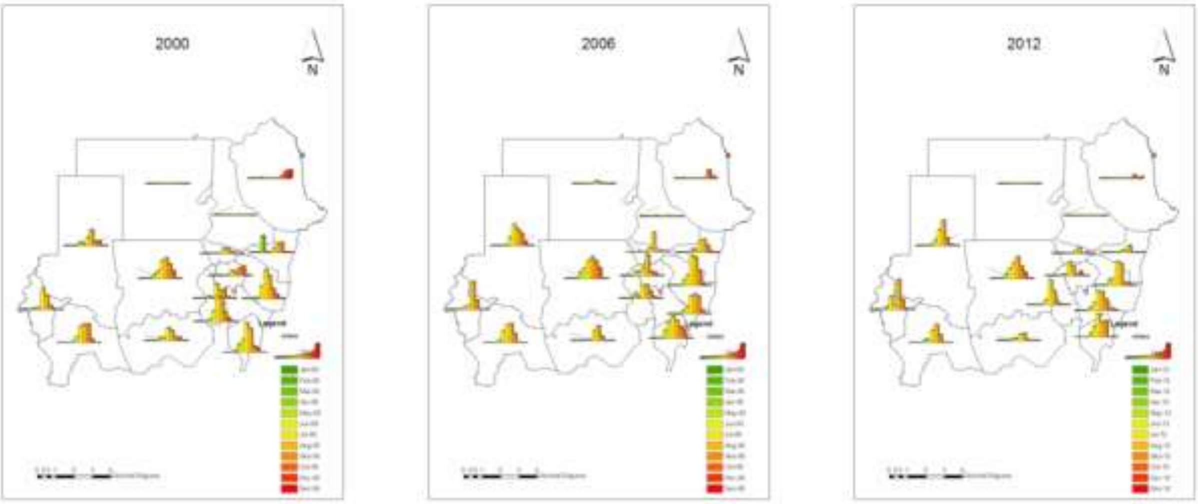

Figure 17. Comparison between average monthly rainfall on states level for year 2000, 2006 and 2012.

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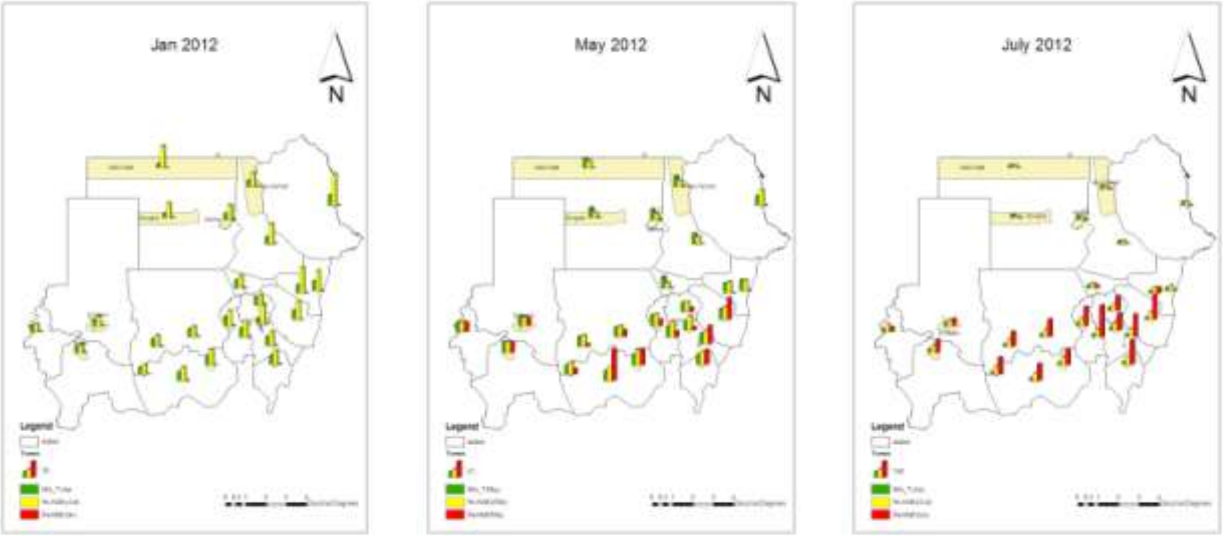

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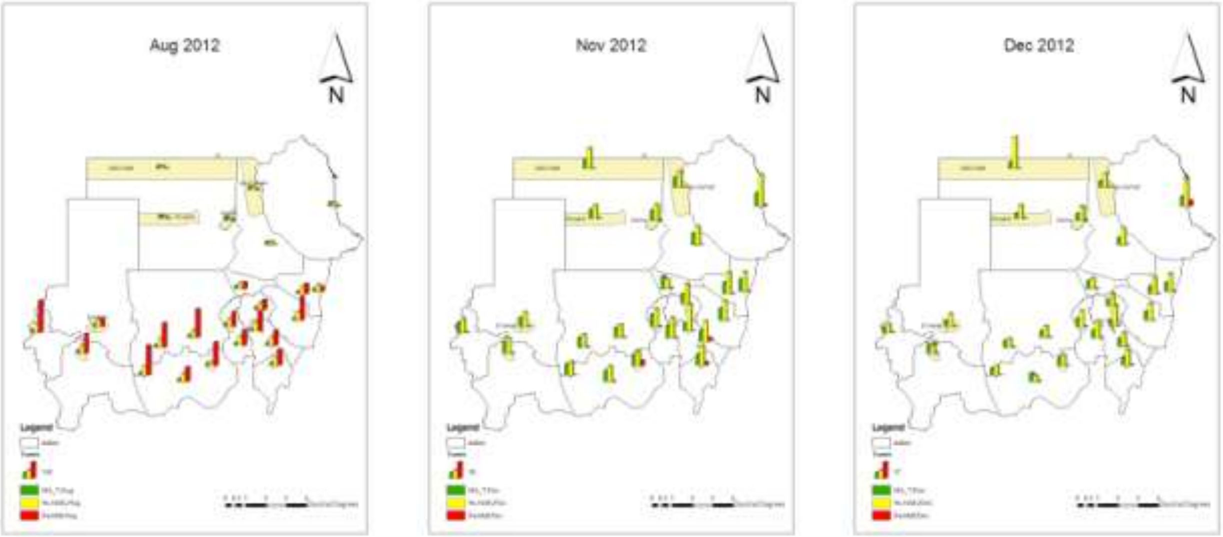

Figure 18. Comparison between average monthly temperature, humidity and rainfall on stations level for January, May, July, August, November and December 2012.

V. Conclusions

rainfall Maps proved that, they are very useful in analysis and comparisons based on rainfall data between different geographical areas, so as to its ability to display too much information in maps which link data with geographical location, that form of visualization is easy to read and understand. Also using rainfall maps enable us to work a large number of comparisons for further study and deeper understanding of the phenomenon.

From the spatial analysis of the phenomenon of rainfall and its distribution and based on the geographical location of stations, states and regions in Sudan we can come up with the following conclusions:

Rain is natural phenomenon do not adhere to a strict pattern in its occurrence and distribution, because it influenced by many variables in the atmosphere.

The interval From May to October represents the rainy season in most regions of Sudan and both July and August represent its peak, But In some stations such as Port Sudan, El damazen, Abu Naama and Rashad, few rains falls in the period from November to January.

Southern stations such as Elgeneina, Nyala, Kadugli, Babanusa, Rashad, El damazen, Abu Naama, Sinnar and El Gadarif are considered the areas which obtain the most amount of rainfall among the whole country, while stations such as Dongola, Atbara, Abu Hamad, Karima, Wadi Halfa, Port Sudan and Khartoum are considered the areas that obtain the least amount of rainfall. Other stations like Kassala, New Halfa, Wad Medani, El Deweim, Kosti, Elobied and El Nihood get a medium quantity of rainfall.

Some notable changes in the distribution pattern of rain appeared in some places for example, lack of rainfall in Kordofan since 2003. Also In 2003 Darfur region recorded the highest rainfall amount sharing Kordofan region, however, that was exception and it generally recorded fewer amounts.

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