

ANALYSIS OF SPATIO-TEMPORAL PATTERNS OF HYDRO-GEOMORPHIC SENSITIVITY AREAS AND DESERTIFICATION STATUS IN A PART OF BORNO-YOBE SEMI-ARID ZONE OF NIGERIA

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Abstract

The major goal of this study is to monitor spatio-temporal patterns of hydro-geomorphic sensitivity indicators to depict desertification status in the semi-arid zone of Nigeria over a period of 30 years (1987-2016). Four specific hydro-geomorphic indices; Topographic Wetness Index (TWI), Stream Power Index (SPI), Sediment Transport Index (STI) and Normalised Difference Water Index (NDWI), were evaluated and mapped into raster layers using appropriate algorithm on the Digital Elevation Model (DEM). These indicators represent soil moisture, surface run-off erosivity, soil erosion and surface water distribution respectively which represent the key hydro-geomorphic forms and processes of desertification. The MEDALUS (ESA) approach was applied to aggregate specific temporal indices into single component index; TWSI, SPSI, STSI NDWSI respectively and the four into the Hydro-geomorphic Sensitivity Index (HgSI). These respective indices were further segmented and mapped into five sensitivity areas and to determine their mean extents; Very High (VH), High (H), Moderate (M), Low (L) and Very Low (VL) based on natural Jenks method. The five hydro-geomorphic sensitivity classes were validated based on post classification field reconnaissance to interpret the corresponding landscape as follows; Very High (upslope catchment area with sparse shrubs), High (upslope catchment area with patchy dense shrubs), Moderate (light riparian/woody savanna), Low (wetland/floodplain/dense woody savanna) and Very Low (Broad river/Water bodies/Oases) respectively. Results showed average extents of Hydro-geomorphic sensitivity classes for the 30373 km² study area for the period as follows; VH: upslope catchment with sparse shrubs (6532 km²), H: upslope catchment with dense shrubs (11521 km²), M: Riparian/forest/woody savanna (5643 km²), L: wetland/floodplains (4563 km²) and VL: water bodies/broad river/Oases (2114 km²). Similarly annual rate of 1.20, 0.95 and 0.74 km²; change intensity for the period of 4.441, 0.991 and 0.277%; dynamic rate of 0.493, 0.122 and 1.363% respectively. The other two classes Moderate and Low showed declining trend at annual rate of 0.52 and 1.24 km²; change intensity for the period of 0.076 and 5.627% and dynamic rate of change for the period of 0.014 and 1.762% respectively. Although the observed hydro-geomorphic patterns of desertification status seem to be very slow, but these changes have very serious implications of on ecology of this zone especially as it is responsible for natural vegetation diminution and agricultural crop production. Therefore eco-remediation, rehabilitation and restoration can be targeted at hydrogeomorphic sensitivity levels based on sensitivity areas or based on improving the respective indicators such as soil moisture, erosion and surface water. This can be achieved through soil conservation measures to mitigate the flow acceleration and the erosive force of surface runoff.

Keywords: Hydrogeomorphic, Topographic, Erosivity, Sensitivity, Indicator, Semi-arid.

Introduction

The major hydro-geomorphic processes such as soil erosion, change in surface water, soil moisture and infiltration are serious geo-environmental problem causing desertification and land degradation all over the world. Land degradation or desertification is a problem prolific across semi-arid areas worldwide. To state its complex nature, Canacher and Sala (1998) defined land degradation and desertification as "alterations to all aspects of the natural (or biophysical) environment by human actions, to the detriment of vegetation, soils, landforms, water (surface and subsurface) and ecosystems". Previous attempts to understand ecosystem dynamics have largely been carried out within the disciplines of ecology and hydrology/geomorphology, which has led to significant limitations and to address the problem of desertification. Turnbull et al., (2008) have outlined an ecohydrological, otherwise similarly referred to as

ecogeomorphological or hydro-geomorphological framework, to provide a new direction for the study of land degradation in semi-arid ecosystems. This hydro-geomorphic framework is based upon the explicit linkage of processes operating over the continuum of temporal and spatial scales by perceiving the ecosystem as a series of structural and functional connections, within which interactions between biotic and abiotic components of the landscape occur Turnbull et al (2008). Maestre et al (2006) in their study focused on the importance of ecohydrological feedbacks and linkages in desertification.

Hydrological processes lie at the heart of desertification in drylands (Sharma, 1998). Semi-arid catchments commonly have a very rapid hydrological response (Hooke, 1996; Latron et al.2009). This means that semi-arid areas are very sensitive to changes in hydro-geomorphological processes and patterns. The processes of soil and water degradation, leading to desertification, are strongly linked to unfavourable

changes in the hydro-geomorphologic processes responsible for the soil water balance and for the soil moisture regime (Pla, 2005). Any disruption in these Hydro-geomorphological processes, which leads to a reduction in water availability, will reduce the capacity of the land to support plant growth and thus ecosystem functioning. Drylands are highly sensitive, such that any type of disturbance—ranging from *natural* (e.g., reduction in total precipitation, shifts in rainfall seasonality) to *anthropogenic* (overcultivation, overgrazing, etc.)—that negatively impact key structural components (e.g. plant cover) may initiate a ‘cascading’ effect on other components and processes, leading to a progressive deterioration of the ecological structure and functioning, and thus promoting desertification processes (Aguiar and Sala, 1999; Von Handberg et al., 2001; Seghieri and Galle, 1998; Puigdefábregas et al., 1999; Reynolds et al., 1997; Reynolds and Stafford Smith, 2002b).

Drylands are areas where precipitation is so scarce that water is the main factor controlling primary production (Whitford, 2002). The vegetation aspect or primary productivity of desertification is highly dependent on the hydrogeomorphological patterns. Rainfall amount, frequency and antecedent soil moisture are key drivers of plant performance in arid and semi-arid areas (Reynolds et al., 2004). Once rainfall reaches the soil surface, its redistribution is influenced by topography (Puigdefábregas et al., 1999). This is what account for the ecosystem structural attributes such as the number, width and spatial pattern of discrete plant patches (Ludwig and Tongway, 1995 and 1996). The maintenance of these vegetated patches and thus, the overall functioning of the ecosystem, is dependent upon inputs of rainfall and the redistribution of water, sediments and nutrients through hydro-geomorphological processes. Spatio-temporal patterns of hydro-geomorphic sensitivity to desertification focuses on water, sediment and nutrient loss/redistribution) across space and time and its implication on the eco-geomorphic system. Pla (2005) has described the inadequate conservation of soil and water in appropriate places, amounts and qualities as the main and direct cause of Land degradation and desertification. The main effects are a decrease in vegetation or plant growth, water supply, a non sustainable agricultural and food production, and increased vulnerability and risks of eco-geomorphic hazards such as sand dunes encroachment, flooding, sedimentation, decline or loss in vegetation quantity and compositio

Early definitions of ecohydrology, for example, Rodriguez-Iturbe (2000), who defines ecohydrology as ‘the science which seeks to describe the hydrological mechanisms that underlie ecologic pattern and processes’ focused primarily on the hydrological influences upon ecology and little on the ecological influences on hydrology. Newman *et al.* (2006) since soil moisture is perceived to be at the heart of the hydrological cycle and plants are the main components of the terrestrial ecosystem (Porporato and Rodriguez-Iturbe, 2002). There is a common perception that plant-available soil moisture can be determined by sparse measurements of soil moisture. However, this approach disregards the effects of other hydrological processes, namely, runoff and runoff infiltration in determining the spatial patterns and amount of available soil moisture.

Hydro-geomorphic Indicators of desertification include: changes in surface water bodies or broad rivers, surface erosion, sedimentation, surface runoff/stream discharge, soil moisture and underground water level etc. Since topography is the major factor driving and determining these processes, this study adopts the use of topographic derived indicators such as: topographic wetness index (TWI), surface runoff/stream discharge erosivity (SPI), sediment transport index (STI) and Normalised Difference water index (NDWI).

While soil moisture is a key ecohydrological variable, because it forms a crucial link between hydrological and biogeochemical processes (Rodriguez-Iturbe, 2000), consideration of soil moisture alone is insufficient to address the array of ecohydrological interactions that govern semi-arid vegetation dynamics (Huenneke and Schlesinger, 2004). However, even in more recent literature, such as *Dryland Ecohydrology* edited by D’Odorico and Porporato (2006), there is still insufficient recognition of the role of aspects of semi-arid hydrology other than soil moisture, in particular, surface runoff and its role in redistributing resources through the landscape is almost entirely neglected.

Predictions of soil moisture have also been made using reflectance measurements from the visible, near infrared, and shortwave infrared regions of the spectrum (Lobell and Asner, 2002). However, these measurements are made over bare soils and would therefore have limited use over vegetated transport earthworks. The use of Digital Elevation Models (DEMs) in hydrology is well established (Srenson et al., 2006), and is based on the relationship between soil moisture distribution and topography (B’ardossy and Lehmann, 1998).

Topographic wetness index (TWI) is designed to quantify the effect of local topography on hydrological processes and for modeling the spatial distribution of soil moisture and surface saturation. Topographic index has been introduced by Beven and Kirkby (1979) in their ‘Topography based Watershed Model’ (TOPMODEL) for characterizing the distribution of moisture status in a basin (Quinn and Beven 1993; Huang and Jiang 2002; Hjerdt *et al.* 2004; Tombul 2007). It reflects the spatial distribution of soil saturation (Beven and Kirkby 1979) and indicates the accumulated water flow at any point in a catchment. A high value of the topographic index indicates the region has higher potential to be saturated (Raaflaub and Collins 2006). A high value of upslope drainage area and low slope results in a high topographic index, hence a high probability of occurrence of soil saturation.

This index is formulated as $TWI = \ln(a/\tan b)$, where a is the upslope contributing area per unit contour length (or Specific Catchment Area, SCA) and $\tan b$ is the local slope gradient for estimating a hydraulic gradient. The computation of both a and $\tan b$ need to reflect impacts of local terrain on local drainage. b is often approximated by slope gradient around the pixel. In fact, the downslope gradient of the pixel is a better approximation of b .

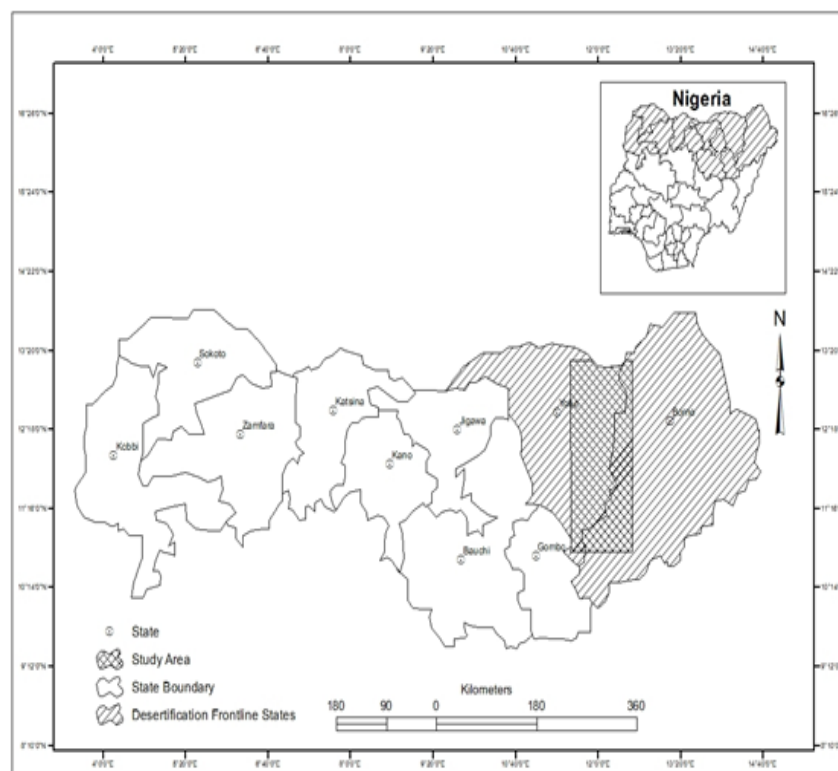
Land degradation and desertification are known to have adverse impacts on hydro-geomorphic landscape especially in the semi-arid regions. Therefore, the use of hydro-geomorphic indicators will greatly improve the mapping of land degradation and desertification. Hydro-geomorphological mapping has been applied in agro-ecological, water resources and watershed management. The application of hydro-

geomorphological mapping for land degradation and desertification studies is still low in the literature. The adoption of eco-remediation in the management of eco-geomorphic hazards such as land degradation and desertification requires understanding of the spatial and temporal dynamics of hydro-geomorphological processes and forms.

A sound understanding of hydro-geomorphological sensitivity is thus essential in order to develop more specific and robust management strategies that address both the causes and consequences of land degradation in drylands and especially semi-arid zones. Therefore the understanding of hydro-geomorphic sensitivity in the semi-arid is very important in combating desertification. Hydro-geomorphic sensitivity encompasses hydrological, pedological, topographic and ecologic aspects of desertification processes..

Study Area

The Semi-arid zone of Nigeria has its southern boundary crossing latitude 12°N on the western frontier to latitude 10° 30' N on the eastern frontier, extending to latitude 14° 00' N as the northernmost boundary (Kowal and Knabe, 1972). This corresponds with the ecological area classified as sudano-sahelian (Mortimore, 1989). About 10 States are classified as frontline States; Bauchi, Borno, Gombe, Jigawa, Kano, Katsina, Kebbi, Sokoto, Yobe and Zamfara States in Nigeria. Borno and Yobe States are the most North easterly States of Nigeria and lie between 10° and 14°N of equator and 10° and 15°E. These two states occupy a total of 116,392km² (10.6%) of the total semi-arid land area of Nigeria.



Fjg A: Nigerian Desertification

Frontline States Showing the Study Area Source: Ndabula, 2015

The Physical Setting

Climatologically the semi-arid zone is characterized by short rainy season of about 4-5 months and means annual rainfall varying between 1000-500 mm from south to north. Rainfall is highly variable in space and time with high intensities (Ati, 2006). Recent years have seen decreasing annual rainfall totals and dry spell is becoming a frequent problem in the area (Oladipo, 1994). Ecologically, the vegetation is mainly savannah grasslands with thorny shrubs and scattered trees. Presently this vegetation is being threatened by physical stress of overgrazing and deforestation due to demands for firewood thereby aggravating widespread grassland degradation and

desertification. The areas is blessed with extensive wetlands. Major soils classes include the Vertisols (dark heavy clay soils (firkin)) dominate the flat plains close to Lake Chad and most parts of wetlands and floodplains. Regosols found mainly in the sand dunes are shallow with weakly developed profiles. While alluvial soils are found in the major river valley on floodplain. The profile of soils is poorly developed, and it has low water retention capacity. The geotechnical properties of soil such as plasticity index, moisture contents, shear strength and compaction tend to prove soils in this region to high have erodibility or susceptibility to erosion.

Socio-economic setting

Borno-Yobe area is home to about 4,008,079 people majority of whom are into crop cultivation and grazing for livelihood.

Due to inadequate alternative sources of energy in the sudano-sahelian zone, demand for fuel wood has been on steady increase by the increasing population and rapid urbanization. Selling of fuel wood has become a very lucrative business and a major source of supplementary livelihood to many families. In addition wood is also exploited for building, arts, crafts, fencing in this area.

Materials and Method

The methodology adopted the following;

- Four topographic indices; TWI, SPI, STI and NDWI were evaluated and used as hydro-geomorphic indicators
- Evaluation of the indices was achieved through established algorithms on the DEM using ArcGIS algebraic raster calculator of the spatial analyst tool to determine stretched and unique raster values
- MEDALLUS ESAs (Kosmas et al, 1999, Ndabula et al., 2013) model approach was used to map the study area into hydro-geomorphic sensitivity areas using multi-temporal indicator raster datasets generated from multi-temporal satellite images of the same season, DEM and rainfall data.
- Assessment of desertification status considered not just current status but three (3) regularly spaced temporal periods 1987, 2000 and 2015 which facilitated assessment of spatio-temporal patterns by merging the static hydro-geomorphic indicators above with annual mean rain surface raster generated for respective and corresponding years..
- Assessment of status include; extent for the temporal years 1987 (U_{ai}), 2000 and , current extent, 2015 (C_{ext}), average extent for the period (A_{ext}), change in extent for the period (Δ_{ext}), dynamic rate of change (K_i) for the period, change intensity (L_i)for the period and annual rate (AR) of change.
- Bi-directional further analysis of the above indicators to derived sensitivity indices; TWSI, SPSI, STSI and NDWSI used to estimate the average extents (A_{ext}) of the hydro-geomorphic sensitivity areas for the period.
- Dynamic rate of change (K_i) for the period, change intensity (L_i) for the period were calculated using landscape change structures suggested by Wang (2010)
- Annual rate (AR) was estimated using logarithmic approach according to (Landis, 2001) gives better estimates than the direct approach that divides rate of change by time ($(U_{bi}-U_{ai})/T$)
- The natural Jenks (1977) method was used to classify the hydro-geomorphic sensitivity areas into five (5); Very High (VH), High (H), Moderate (M), Low (L) and Very Low (VL) depending on degree or magnitude of land degradation and desertification
- Statistical Analysis of Variance (ANOVA) was used to observe spatio-temporal variations in the status desertification among the four indices and among the five hydro-geomorphic sensitivity areas

Four (4) major hydro-geomorphic parameters used to compute indicators of sensitivity to desertification as follows;

Topographic Wetness Index (TWI)

Stream power index (SPI)

Sediment Transport Index (STI)

Normalised Difference Water Index (NDWI)

These indices represent the underlying physics of natural processes that have important hydrological and geomorphological consequences in many landscapes.

The four (4) parameters were combined based on sensitivity analysis and classified into five (5) major hydro-geomorphic units and sensitivity areas using natural Jenks (1977) method. The identification and categorisation of hydro-geomorphic units was achieved based on detail post classification field reconnaissance. This is shown in the Table5a below:

The spatio-temporal pattern of these hydro-geomorphic sensitivity areas was assessed from respective SPSI, TWSI, STSI and NDWSI. The SPSI, TWSI, STSI and TWSI were respectively computed from temporal raster sets of SPI, TWI, STI and NDWI of 1987, 2000 and 2015.

Evaluating and Mapping Hydro-geomorphic Indices and Sensitivity Indices

This was achieved using Digital Elevation Model (DEM) to evaluate TWI, SPI and STI. These indices are static based on the DEM. Therefore, to make them dynamic to show temporal patterns they were further evaluated in combination with generated raster rain-surfaces for the years that corresponded with the landsat images used for vegetation and soil indices (1987, 2000 and 2015). The rain-surface raster map was generated using GIS interpolation (kriging) method from rainfall totals points generated from the three synoptic stations in the study area.

Sediment yield is a very good indicator for monitoring desertification and depends on sediment transportation index from the catchment.

Evaluation and mapping of topographic wetness index (TWI) and sensitivity index (TWSI)

Topography is the first order control on the spatial variation of hydrological conditions. It affects the spatial distribution of soil moisture, surface water and underground water flow (Burt and Butcher, 1986; Zinko et al., 2005). Topographic indices have been used to describe the spatial soil moisture patterns (Moore et al., 1991).

The TWI was first generated using the equation by (Beven and Kirkby, 1993)

$$TWI = \ln (A_s / \tan \beta) \dots\dots\dots(1)$$

Where A_s = flow accumulation of an upstream catchment area

β = slope gradient in percentage

Flow accumulation was determined using DEM hydro-processing in spatial analyst tool of ArcGIS which involves fill sink – flow direction and flow accumulation order of analysis.

Multi-temporal sets of the TWI were then generated by integrating with rain-surface raster maps of 1987, 2000 and 2015 to have TWI_87, TWI_2000 and TWI_2015 respectively

Then the TWSI was generated from the geometric mean of the three multi-temporal TWI mapsets.

$$TWSI = \sqrt[3]{TWI_{87} + TWI_{2000} + TWI_{2015}}$$

Topographic wetness index which combines local upslope contributing area and slope is commonly used to quantify topographic control on hydrological processes and also soil moisture patterns. TWI reflects the multiple influences of the terrain on saturation excess runoff processes.

Evaluation and mapping of stream power index (SPI) and sensitivity index (SPSI)

Once rainfall reaches the soil surface, its redistribution is influenced by topography (Puigdefábregas et al., 1999). Stream power is the time rate of energy expenditure and has been used extensively in studies of erosion and sediment transport as a measure of the erosive power of flowing water. It computes the spatial distribution of soil loss potential by assuming uniform rainfall excess runoff and that the erosion rate is transport rather than detachment limited.

The SPI was evaluated and mapped using the model developed by (Moore et al, 1993)

$$SPI = \ln(A_s * \tan \beta) \dots \dots \dots (2)$$

Where A_s = flow accumulation of an upstream catchment area

β = slope gradient in percentage

Multi-temporal sets of the SPI were then generated by integrating with rain-surface raster maps of 1987, 2000 and 2015 to have SPI_87, SPI_2000 and SPI_2015 respectively

Then the SPSI was generated from the geometric mean of the three multi-temporal SPI mapsets.

$$SPSI = \sqrt[3]{SPI_{2000} + SPI_{2000} + SPI_{2015}}$$

Since SPI is directly proportional to erosion potential, areas with high values or magnitude of SPI will have high erosion potential while low SPI value towards zero means low erosivity.

Evaluation and mapping of sediment transportation index (STI) and sensitivity index (STSI)

Land degradation through water erosion is driven by ecogeomorphological processes which may alter transfer paths at the hillslope, the soil-hydraulic conditions of the upper soil layers and the vegetation structure of the hillslope. In semi-arid ecosystems, it is already well established that hydrology, especially soil erosion exerts a profound influence over other abiotic components of the landscape, primarily erosion (Wainwright et al., 2000), and the loss or redistribution of

biogeochemical nutrients (Schlesinger et al., 1999, 2000; Parsons et al., 2003). This can be assessed using the Sediment Transport Index.

This index is derived from unit stream-power theory and is sometimes used in place of the length-slope factor in the revised universal soil loss equation (RUSLE) for slope lengths less than 100 m and slope less than 14 degrees. The index combines upslope contributing area (A_s), under the assumption that contributing area is directly related to discharge, and slope (B).

$$STI = A_s / 22.13^{0.6} * (\sin / 0.0896)^{1.3} \dots \dots \dots (3)$$

Evaluated using the model derived by (Burrough and McDonnell, 1998)

Sediment transport is estimated as

$$ST = \text{erodibility} \times (\text{runoff} \times \text{distance from divide})^2 \times \text{gradient}$$

This is similar to sediment yield

$$SY = \text{erodibility} \times (\text{runoff})^2 \times \text{relief}$$

Multi-temporal sets of the STI were then generated by integrating with rain-surface raster maps of 1987, 2000 and 2015 to have STI_87, STI_2000 and STI_2015 respectively

Then the SPSI was generated from the geometric mean of the three multi-temporal STI mapsets.

$$STSI = \sqrt[3]{STI_{87} + STI_{2000} + STI_{2015}}$$

Evaluation and mapping of Normalised Difference Water Index (NDWI) and sensitivity index (NDWSI)

With the advance in space technology, it is now possible to employ remote sensing techniques for estimating surface and subsurface water over large areas.

$$NDWI = \rho(0.86\mu\text{m}) - \rho(1.24\mu\text{m}) / \rho(0.86\mu\text{m}) + \rho(1.24\mu\text{m})$$

Multi-temporal sets of the NDWI were then generated by integrating with rain-surface raster maps of 1987, 2000 and 2015 to have NDWI_87, NDWI_2000 and NDWI_2015 respectively

Then the SPSI was generated from the geometric mean of the three multi-temporal STI mapsets.

$$NDWSI = \sqrt[3]{NDWI_{87} + NDWI_{2000} + NDWI_{2015}}$$

To Assess the Spatio-temporal Patterns of Aggregated Hydro-geomorphic Sensitivity Index (H_gSI)

This is achieved based on analysis the three sets of multi-temporal topographic indices and their respective sensitivity indices (TWI, SPI, STI and TWSI, SPSI, STSI) maps that were generated in objective 1 and generation of hydro-geomorphic sensitivity index (H_gSI) map using the MEDALUS model approach. The H_gSI map is then reclassified into five (5) hierarchical environmental (hydro-geomorphic landscape) sensitivity areas.

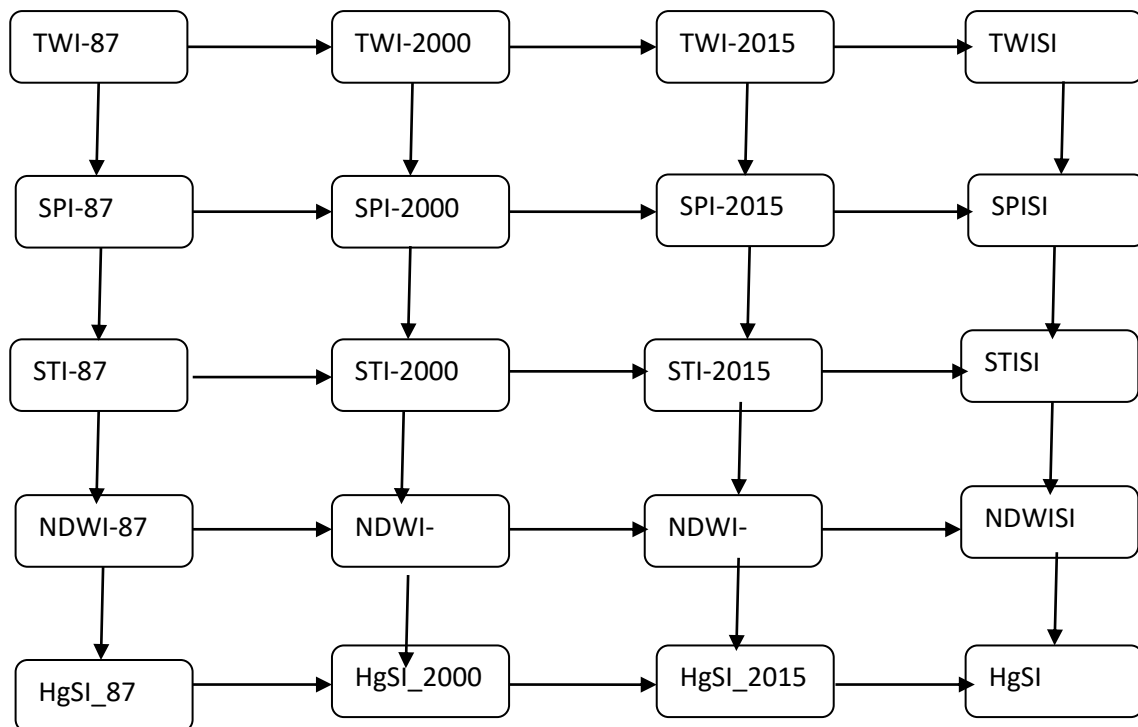


Fig B: Flow Chart of the Assessment of the Spatio-temporal Patterns of Hydro-geomorphic Sensitivity Index The horizontal dimensional analysis algorithm:

$$TWSI = \sum(TWI_{87} + TWI_{2000} + TWI_{2015})^{1/3}$$

$$SPSI = \sum(SPI_{2000} + SPI_{2000} + SPI_{2015})^{1/3}$$

$$STSI = \sum(STI_{87} + STI_{2000} + STI_{2015})^{1/3}$$

$$NDWSI = \sum(NDWI_{87} + NDWI_{2000} + NDWI_{2015})^{1/3}$$

$$HgSI_1 = \sum(TWSI + SPSI + STSI + NDWSI)^{1/4}$$

The vertical dimensional analysis algorithm:

$$HgSI_{87} = \sum(TWI_{87} + SPI_{87} + STI_{87} + NDWI_{87})^{1/4}$$

$$HgSI_{2000} = \sum(TWI_{87} + SPI_{2000} + STI_{2000} + NDWI_{2000})^{1/4}$$

$$HgSI_{2015} = \sum(TWI_{2015} + SPI_{2015} + STI_{2015} + NDWI_{2015})^{1/3}$$

$$HgSI_2 = \sum(HgSI_{87} + HgSI_{2000} + HgSI_{2015})^{1/3}$$

$$HgSI = (HgSI_1 + HgSI_2)^{1/2}$$

Where;

$HgSI$ = Hydro-geomorphic Sensitivity Index

$TWSI$ = Topographic Wetness Sensitivity Index

$SPSI$ = Stream power Sensitivity Index

$STSI$ = Sediment Transport Sensitivity Index

$NDWSI$ = Normalised Difference Water Sensitivity Index

Results and Discussion

Topographic Wetness Index and Sensitivity Areas:

The presence of saturation excess overland flow areas also indicates areas favors ephemeral gully formation. High values represent high moisture content or saturation excess runoff and low values low for zones that dry up easily or dry soil conditions/areas. Hence, the areas with high TWI will have more risk of gully erosion than areas with low TWI value and vice versa. High TWI values also signify areas where saturated surface soil loses its strength and then slump when seepage occurs leading gullying. The slumped soil is carried away by overland flow (rainfall excess plus saturation excess) that further scour the bed and wall of the channel causing gullies to deepen and widen. High values also signify low or flat terrain while low values represent fair to steep relief or slopes.

From both Fig 1 and Table1 below it shows the mean extents of the various topographic wetness sensitivity areas and desertification status for the period (1987-2015) for the total study area of 30373 km² from largest to least is as follows; Very High, 18090 km² (59.56%), High, 5116 km² (16.84%), Moderate, 4239 km² (13.96%), Low, 1918 km² (6.31%) and Very Low, 1007 km² (3.32%) respectively. Three of the classes; Very High, High and Very Low showed increasing trend at annual rate of 0.73, 0.73 and 0.68 km²; change intensity for the period of 0.268, 0.268 and 0.198%; dynamic rate of 0.017, 0.060 and 0.237% respectively. The other two classes Moderate and Low showed declining trend at annual rate of 0.81 and 0.75 km²; change intensity for the period of 0.421 and 0.2% and dynamic rate of change for the period of 0.113 and 0.180% respectively. From Fig 2 and Table2 it

shows the mean extents of the various sediment transport sensitivity areas for the period (1987-2015) for the total study area of 30373 km² from largest to least as follows; Very High, 11756 km² (38.71%), High, 7677 km² (25.28%), Moderate, 5034 km² (16.57%), Low, 4096 km² (13.49%) and Very Low, 1810 km² (5.96%) respectively. Both Very High and Moderate classes showed increasing extent at annual rate

of , 1.31 and 0.42 km²; change intensity for the period of 8.264, 0.040% and dynamic rate of 0.910, and 0.009% respectively. The other three classes High, Low and Very Low on the other hand showed declining trend at annual rate of 1.15, 0.84 and 0.21 km²; change intensity for the period of 6.753, 0.948 and 0.603% and dynamic rate of change for the period of 0.912, 0.62 1 and 0.374% respectively.

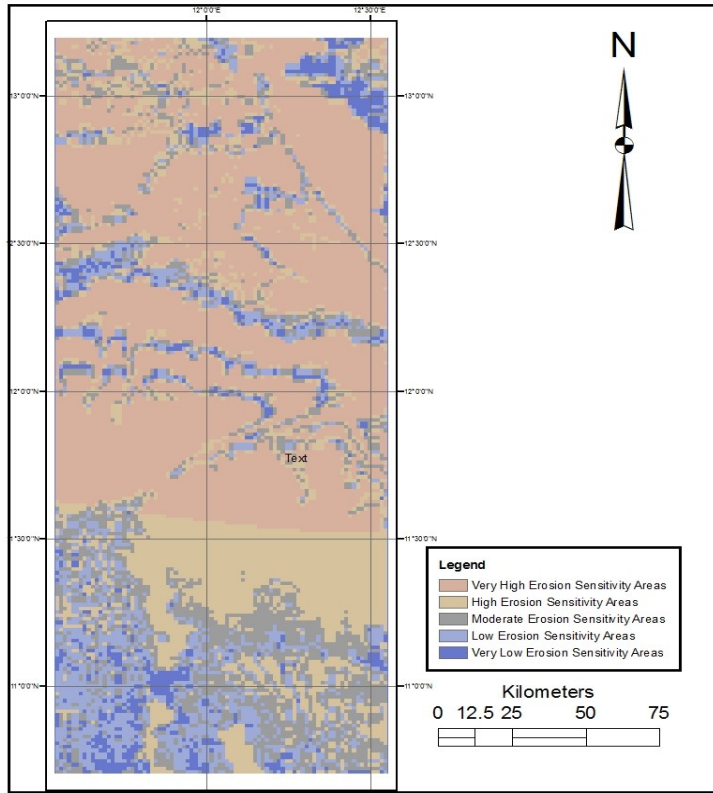


Fig 2: Spatial Patterns of Sediment Transport/Erosion Sensitivity Areas in the Borno-Yobe Part of the Semi-arid Zone of Nigeria
Source: Ndabula, 2015

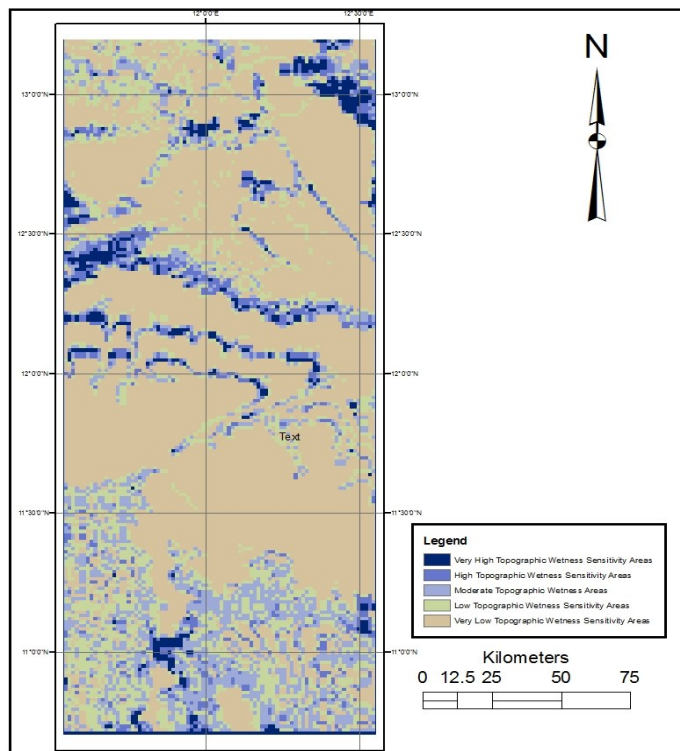


Fig 1: Spatial Patterns of Topographic Wetness Sensitivity Areas in the Borno-Yobe Part of the Semi-arid Zone of Nigeria
Source: Ndabula, 2015

Table1: Spatio-temporal Patterns of Topographic Wetness Sensitivity Areas and Desertification Status (Based on TWI)

Sensitivity Area (SA)	Extent of i^{th} class of SA in km^2 1987 (U_{ai})	Extent of i^{th} class of SA in Km^2 2000	Extent of i^{th} class of SA in Km^2 :2015 (C_{ext})	Mean extent of i^{th} class of SA in Km^2 based on TWSI (U_{bi})	Change in extent of i^{th} SA in Km^2 for study period ($U_{bi}-U_{ai}$)	Annual Rate of change of i^{th} SA in Km^2 (Li)	Change intensity index for i^{th} class of SA in % for the study period (Ti)	Dynamic index for i^{th} class of SA in % for the study period (Ki)
1-VeryHigh	17927	17976	18007	18090	80	0.73	0.268	0.017
2- High	5170	5109	5250	5116	80	0.73	0.268	0.060
3- Moderate	4374	4346	4246	4239	-128	-0.81	-0.421	-0.113
4- Low	1944	1916	1853	1918	-91	-0.75	-0.300	-0.180
5- Very low	957	1025	1016	1007	59	0.68	0.194	0.237

Table2: Spatio-temporal Patterns of Sediment Transportation/Erosion Sensitivity Areas and Desertification Status (Based on STI)

Class of Sensitivity Area (SA)	Extent of i^{th} class of SA in km^2 1987 (U_{ai})	Extent of i^{th} class of SA in Km^2 2000	Extent of i^{th} class of SA in Km^2 :2015 (C_{ext})	Mean extent of i^{th} class of SA in Km^2 based on STSI (U_{bi})	Change in extent of i^{th} SA in Km^2 for study period ($U_{bi}-U_{ai}$)	Annual Rate of change of i^{th} SA in Km^2 (Li)	Change intensity index for i^{th} class of SA in % for the study period (Ti)	Dynamic index for i^{th} class of SA in % for the study period (Ki)
1-VeryHigh	7289	6272	8955	4919	1666	1.173	5.485	0.879
2- High	11060	13163	14243	10312	3183	1.347	10.480	1.107
3- Moderate	7303	8311	6183	9315	-1120	1.173	-3.687	-0.590
4- Low	2650	2187	668	3281	-1982	1.268	-6.526	-2.877
5- Very low	2072	439	323	2546	-1749	1.247	-5.758	-3.247

From Fig 3 and Table 3 below it shows the mean extents of the various surface run-off erosivity sensitivity areas for the period (1987-20130) for the total study area of 30373 km² from largest to least as follows; Very High, 17778 km² (58.53%), Moderate, 4575 km² (15.06%), High, 4543 km² (14.96%), Low, 2362 km² (7.78%) and Very Low, 1114 km² (3.68%) respectively. Three of the classes; Very High, High and Very Low showed decreasing trend at annual rate of 0.58, 0.52 and 0.37 km²; change intensity for the period of 0.105, 0.076 and 0.030%; dynamic rate of 0.007, 0.019 and 0.0317% respectively. The other two classes Moderate and Low showed increasing trend at annual rate of 0.18 and 0.68 km²; change intensity for the period of 0.010 and 0.194% and dynamic rate of change for the period of 0.003 and 0.099% respectively.

From Fig 4 and Table 4 below it shows the mean extents of the various surface water sensitivity areas for the period (1987-20130) for the total study area of 30373 km² from largest to least as follows; Very High, 11756 km² (38.71%), High, 7677 km² (25.28%), Moderate, 5034 km² (16.57%), Low, 4096 km² (13.49%) and Very Low, 1810 km² (6.00%) respectively. Three of the classes; Very High, High and Very Low showed decreasing trend at annual rate of 0.58, 0.52 and 0.37 km²; change intensity for the period of 0.105, 0.076 and 0.030%; dynamic rate of 0.007, 0.019 and 0.0317% respectively. The other two classes Moderate and Low showed increasing trend at annual rate of 0.18 and 0.68 km²; change intensity for the period of 0.010 and 0.194% and dynamic rate of change for the period of 0.003 and 0.099% respectively.

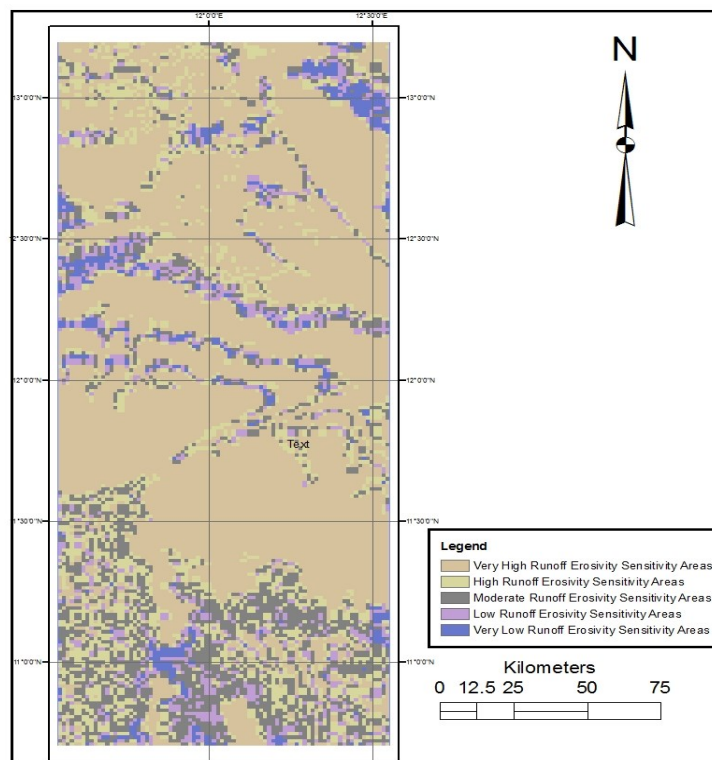


Fig 3: Spatial Patterns of Runoff Erosivity Sensitivity Areas in the Borgu-Yobe Part of the Semi-arid Zone of Nigeria
Source: Ndabula, 2015

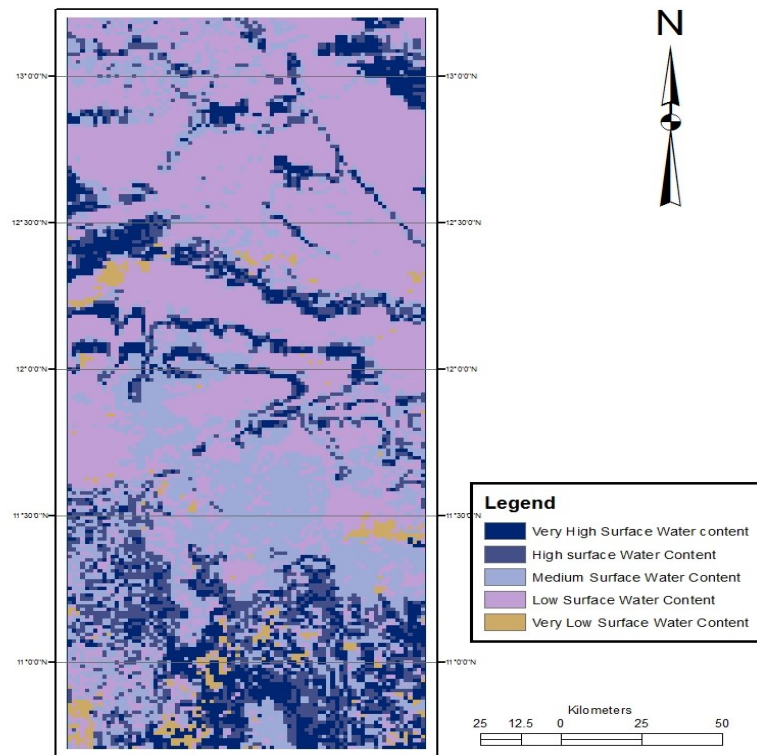


Fig 4: Spatial Patterns of Surface Water Distribution in the Borno-Yobe Semi-arid Zone of Nigeria

Source: Ndabula 2015

Table3: Spatio-temporal Patterns of Stream/Surface-runoff Erosivity Sensitivity Areas and Desertification Status (based on SPI)

Class of Sensitivity Area (SA)	Extent of i^{th} class of SA in km^2 1987 (U_{ai})	Extent of i^{th} class of SA in Km^2 2000	Extent of i^{th} class of SA in Km^2 :2015 (C_{ext})	Mean extent of i^{th} class of SA in Km^2 based on SPSI	Change in extent of i^{th} SA in Km^2 for study period ($C_{ext}-U_{ai}$)	Annual Rate of change of i^{th} SA in Km^2 (Li)	Change intensity index for i^{th} class of SA in % for the study period (Ti)	Dynamic index for i^{th} class of SA in % for the study period (Ki)
1-VeryHigh	17730	17733	17698	17778	-32	-0.58	-0.105	-0.007
2- High	4693	4583	4670	4543	-23	-0.52	-0.076	-0.019
3- Moderate	4566	4581	4569	4575	3	0.18	0.010	0.003
4- Low	2283	2331	2342	2362	59	0.68	0.194	0.099
5- Very low	1100	1137	1091	1114	-9	-0.37	-0.030	-0.031

Table4: Spatio-temporal Patterns of Surface water Sensitivity Areas and Desertification Status (Based on NDWSI)

Class of Sensitivity Area (SA)	Extent of i^{th} class of SA in km^2 1987 (U_{ai})	Extent of i^{th} class of SA in Km^2 2000	Extent of i^{th} class of SA in Km^2 :2015 (C_{ext})	Mean extent of i^{th} class of SA in Km^2 based on NDWSI (U_{bi})	Change in extent of i^{th} SA in Km^2 for study period ($U_{bi}-U_{ai}$)	Annual Rate of change of i^{th} SA in Km^2 (Li)	Change intensity index for i^{th} class of SA in % for the study period (Ti)	Dynamic index for i^{th} class of SA in % for the study period (Ki)
1-VeryHigh	10608	11932	13118	11756	2510	1.31	8.264	0.910
2- High	8650	7764	6599	7677	-2051	-1.15	-6.753	-0.912
3- Moderate	4985	4875	4997	5034	12	0.42	0.040	0.009
4- Low	4248	4031	3960	4096	-288	-0.84	-0.948	-0.261
5- Very low	1881	1769	1698	1810	-183	-0.71	-0.603	-0.374

From Fig 5 and Table 5 shows the mean extents of the various hydro-geomorphic sensitivity areas for the period (1987-20130) for the total study area of 30373 km² from largest to least as follows; Very High, 6532 km² (21.51%), High, 11521 km² (37.93%), Moderate, 5643 km² (16.73%), Low, 4563 km² (15.02%) and Very Low, 2114 km² (6.96%) respectively. Three of the classes; Very High, High and Very Low revealed a trend of increasing extent at an annual rate of 1.20, 0.95 and 0.74 km²; change intensity for the period of 4.441, 0.991 and 0.277%; dynamic rate of 0.493, 0.122 and 1.363% respectively. The other two classes Moderate and Low showed declining trend at annual rate of 0.52 and 1.24 km²; change intensity for the period of 0.076 and 5.627% and dynamic rate of change for the period of 0.014 and 1.762% respectively. The hydro-geomorphic sensitivity areas experiencing increasing trend represent increasing soil erosion susceptibility to desertification which may be attributed to degradation of vegetation cover and increasing rainfall intensities as reported by Ati (2006).

Generally the results showed that annual rate, change intensity and dynamic rate of change of hydro-geomorphic degradation and desertification are either increasing or declining at very slow rates and varies across space.

Correlation analysis of annual rate of desertification across the hydro-geomorphic sensitivity areas showed that both the very high and high hydro-geomorphic sensitivity hierarchies have strong annual rate relationship and the very low hierarchy. Also both high and very high are strongly related in terms of annual changes. Correlation of change intensity for the period (1987-2015) across the sensitivity areas revealed general low relationships except for the moderate and low. This means the actual change intensity over the period is the shift from low to the moderate sensitivity areas. This was the same with the dynamic rate of desertification.

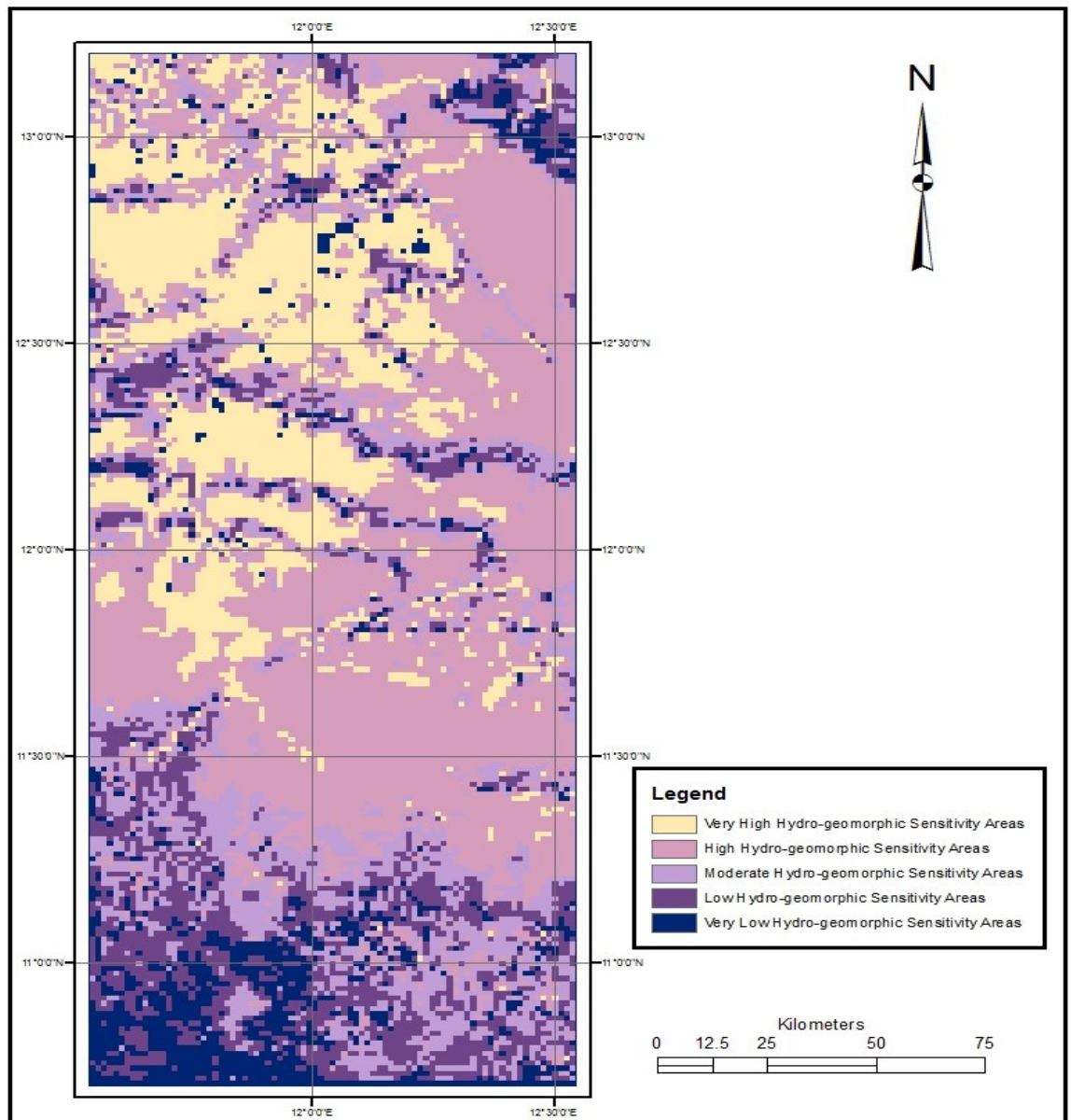


Fig 5: Spatial Patterns of Hydro-geomorphic Sensitivity Areas in a Part of the Borno-Tobe Semi-arid Zone of Nigeria

Source: Ndabula, 2015

Table5: Spatio-temporal Patterns of Hydro-geomorphic Sensitivity Areas and Desertification Status (Based on H_gSI)

	HgSI			HgSI-1	HgSI-2	HgSI_1:2avg				
Class	Extent of i th class in Km ² 1987 (U _{ai})	Extent in i th class Km ² 2000	Extent in i th class Km ² :2015 (C _{ext})	Extent in i th class Km ²	Extent in i th class Km ²	Average extent (A _{ext}) in i th class Km ²	Change in extent in Km ² : (C _{ext} -U _{ai})	Rate of growth in Km ² for i th class (Li)	Desertification Change intensity index for i th class (Ti)	Desertification dynamic index for i th class (Ki)
1-VeryHigh	10531	11967	11880	11290	11290	6532	1349	1.20	4.441	0.493
2- High	9504	11597	9805	9285	9285	11521	301	0.95	0.991	0.122
3- Moderate	6368	6370	6345	6710	6710	5643	-23	-0.52	-0.076	-0.014
4- Low	3731	121	2022	2770	2770	4563	-1709	-1.24	-5.627	-1.762
5- Very low	237	317	321	317	317	2114	84	0.74	0.277	1.363

Table5a: Post Analysis Field Description of Hydro-geomorphic Sensitivity Areas (Based on HgSI)

S/N	Class type	Location	GPS coordinates	Description of hydro-geomorphic unit
1	Very high	Gumsa Margawa	12o31'54"N; 11o42'40"E 12o58'40"N; 12o15'150"E	Direct surface water eg rivers and reservoir. Upslope catchment areas , Bare sandy soil with sparseshrubs and widely spaced trees
2	High	Geidam NW Busari	13o7'33"N; 11o35'58"E 11o0'22"N; 11o33'19"E	Sandy-loamy landscapeUpslopecatchment areas, sandy soil withmoderate shrubs and scattered trees
3	Moderate	Yunusari Buni	13o7'33"N; 11o35'58"E 11o0'22"N; 11o33'19"E	Upslope catchment areas, dominant shrubs and woody tree savanna
4	Low	Gullamoran Dabalam	12o32'11"N; 11o37'28"E 12o8'56"N; 11o32'59"E	Floodplain with alluvial and well drained soils. Down slope catchment areasincluding wetlands, floodplain and riparian vegetation
5	Very low	Garigari Magarwa	11o14'49"N; 11o39'44"E 13o9'35"N; 12o7'42"E	Wetland with poorly drained hydromorphic soils. Down slope catchment areas including broad river channels, water bodies and dense vegetation.

Conclusion

The general performance of hydro-geomorphic sensitivity analysis revealed that the Borno-Yobe semi arid zone of Nigeria can generally be described as hydro-geomorphologically very sensitive to desertification. Although this sensitivity varies both in space and time. The temporal variations are strongly correlated to climatic variations. The spatial variations were observed in this study in terms of average extents of respective sensitivity areas and their corresponding annual rate, dynamic rate and change in intensity for the period 1987-2015. The upslope catchment with sparse shrubs and dense shrub constitute the Very High and High hydro-geomorphic sensitivity land units or landscapes and occupies 18053km² (59%) out of the total land area of 30373km². The areas relative considered to be low and very low hydro-geomorphic sensitivity areas are large water bodies (reservoirs), Oases, broad rivers, wetlands and areas under moderate to dense woody vegetation. These categories occupy a total of 6677 km² (21.98%) of the studied area.

Therefore eco-remediation, rehabilitation and restoration can be targeted at hydro-geomorphic sensitivity levels based on sensitivity areas or based on improving the respective indicators such as soil moisture, soil erosion and surface water. This can be achieved through soil conservation measures which can be achieved through appropriate land management practices to mitigate the flow acceleration, runoff erosive force and hence controlling erosion. Also construction of Dams in the area and intensification of afforestation will increase the areas that are hydro-geomorphologically more resilient or less sensitive to desertification. Proactive management actions should be targeted at the moderate sensitive areas which are transitory zones to slow the extension of the northern most highly sensitive areas from encroaching southward and thus exacerbating desertification. All stakeholders should converge their concerted efforts to rehabilitate, remediate, or restore the various hydro-geomorphic sensitivity areas by redeploying specific and actions that best fit the respective classes.

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