Exploration of hydro-geomorphological indices for coastal floodplain characterization in Rivers State, Nigeria

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Abstract

Flood is a reoccurring natural hazard in many parts of Nigeria, and is likely to increase in severity and frequency. Characterization of recently flooded areas was carried out using hydro-morphological indices to identify flood prone areas. In flood risk quantification and identification, hydrodynamic models require vast amounts of data, while contour delineation fails to account for the upstream contribution and accumulation at downstream locations. Data on recently flooded areas and elevation data were collated. Hydro-geomorphometric indices were computed and compared using the Mann-Whitney U test. Across the indices, the terrain roughness indices – vertical roughness measure (VRM) and topographic roughness index (TRI) were found to be significant but weakly correlated (r = 0.455, P<0.05). There was a significantly positive but moderate correlation between topographic wetness index (TWI) and VRM (r=-0.673) and TWI vs TRI (r=0.572). Topographic position index (TPI) displayed a weak but significant relation to VRM, TWI and TRI. Of these four indices, TWI and TRI have standardized test statistics of -6.11 and 10.00 respectively and a significant test value < 0.05. Results show that flooded and non-flooded areas can be distinguished for the study area using these indices. It is recommended that hydro-geomorphometric indices should be used, adding another layer of confidence in the identification of flood prone areas for disaster risk management in data poor environments.

Keywords: Flooding; GIS; Hydrological indices; Geomorphometric indices; Terrain analysis

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Introduction

Flooding occurs as a result of the overflow of rivers, lakes and other water bodies, or the accumulation of rainwater on saturated ground (Dyhouse, Hatchett, Benn, & Totz, 2003). Flood may build up gradually, but flash flood usually occurs very quickly. In other instances, flood could occur on low-lying area with saturated ground where water may not run off or may do so very slowly. The recent flood in Nigeria was reported to have resulted from torrential rains (lasting a few days), the overflowing of River Niger (leading to release of water from Kanji and Shiroro Dams) and the release of water from Lagdo Dam – Cameroun (Sidi, 2012). Apart from the loss of lives and properties, flood can also increase the risk of food insecurity.

Flood is the most important recurring natural hazard in many parts of Nigeria, affecting many people and their livelihood. Farmers and fishers as well as urban dwellers are significantly affected by this phenomenon. With the anticipated changes in climate there is the likelihood of an increase in the incidence and unpredictability of extreme weather events globally (Intergovernmental Panel on Climate Change, 2007). Furthermore, with projected changes in climate, the severity and frequency of floods are likely to increase. It is therefore not far-fetched to conclude that such events would have devastating impacts on vulnerable people and places, especially low lying areas and coastal communities which are more prone to such extreme weather events. Flooding is a major natural disaster, accounting for around 31% of the economic losses (globally) from natural disaster and claiming around 55% of the global causalities from natural disasters (Borrows & de Bruin, 2006).

Urban environments in middle and low income countries are likely to be significantly at risk owing to the increasing rate of urban population in these regions (without people, hazard cannot turn into disaster). The risk is also exacerbated by the increase in surface runoff by a factor of 2 to 6 (in comparison to natural rates) from such urban environments (Douglas et al., 2008). Rivers State (and most especially Port Harcourt) is one of the rapidly urbanizing and densely populated States in Nigeria. The location of settlement is significantly determined by the availability of dry land while the nature of the terrain has led to the low number of large settlements across the Niger Delta region. Big metropolitan areas in mangrove swamps, such as Port Harcourt, developed on islands of dry lands in the interior parts of the Niger Delta with relatively better drainage conditions and accessibility. Dominant ecological zones of the State include Mangrove forest and coastal vegetation, fresh water swamp and lowland rainforest. Silt nourishment, as brought about by floods, plays a significant role in the improvement and maintenance of the soil biota and fertility. The landmass is located on a coastal plain belonging to the Niger Delta sedimentary formation (Short & Stauble, 1967). The terrain is relatively flat (average slope of 3 and 5 degrees), thus impacting on the drainage. With the peculiarity of its terrain, weather and geomorphology, it is particularly vulnerable to the impacts of climate change and global warming. In addition to these, the state also has similar problems as many low and middle income countries – poor urban planning, poor infrastructural investment/development, corruption and poor resource management. All these often result in the development of large populations in high risk or vulnerable places with little or no protection from imminent danger, due to the socioeconomic circumstances (low income, lack of access to assets for risk reduction) of the inhabitants of such places (Lawal & Arokoyu, 2015).

With these problems and concerns, it is therefore pertinent that data and information to support planning and management is at the fingertips of developers, planners and government authorities. To this end, this study examined the potential of hydrological and geomorphometric indices in characterizing recently flooded areas in Rivers State, Nigeria. With this aim, the study (i) examined relationships across various hydro-geomorphometric indices computed for the flooded areas and (ii) compared these indices across flooded and non-flooded areas. This is intended to support planning and development of human habitation in this State, thereby reducing the risk of loss of lives and properties due to flood. This approach was also intended to test the application of hydro-geomorphic indices within a Geographic Information Systems (GIS) environment in the characterization of potentially vulnerable (to flooding) locations across a coastal plain.

Vulnerability could be conceptualized for places and people, thus bringing about the concept of biophysical vulnerability and social vulnerability. Biophysical vulnerability addresses the attributes of the hazard events and physical conditions influencing potential for losses (of lives and properties) and the ability to recover (Lawal & Arokoyu, 2015). The social aspect relates to the attributes of the society or people which make them unable to withstand the negative outcome of hazard events. Both of these aspects contribute to the management and reduction of risk from hazard and disasters. There are wide variations in vulnerability (both physical and social) and consequently resilience across the country, but it is clear that human action or inaction often determines the outcome of disasters (Lawal & Arokoyu, 2015). Therefore, efforts made to improve the socioeconomic circumstances of communities and households could significantly impact on their vulnerability and resilience. Pathways of human activities leading to changes on the planet are often driven by policy/planning, economic rewards and attributes of the place in question. Evidently, such changes are often the result of complex interaction of physical, biological, political, social and economic factors. However, while biological and physical conditions are often difficult (or impossible) to change, political, social and economic factors are amenable to modification. This highlights the importance of policy in building and improving resilience of places and communities to disasters. It is in this light that research and effort must be made to carry out rapid assessments which could support land use planning and address vulnerability to flooding across different parts of the country.

Disasters will not simply go away, but how we deal with them can significantly change how they impact on people and the environment. Within the sphere of disaster risk management, vulnerability could be referred to as the potential for loss to life or properties from disaster or hazard events (Lawal & Arokoyu, 2015). In the light of this, places as well as people could be vulnerable. Another aspect to vulnerability is the internal dimension which has been referred to as coping capacity, capacity for response or adaptive capacity (Gallopín, 2006). It is a component of vulnerability and Gallopín (2006) defines it as "the ability of the systems to adjust to disturbance, moderate potential damage, take advantage of opportunities and cope with subsequent transformation that occurs". This definition also shows a linkage with resilience which is another trait of the Socioecological system (SES) and according to Van der Leeuw (2001) they can only be clearly understood in relation to one another. According to Folke (2006), the resilience perspective originated from various studies in ecology in the 1960s and early 1970s, and it has also found application in social systems and SES.

Hydrological (hydrodynamic) models and the traditional method (contours delineation) are widespread in flood risk mapping. However, hydrodynamic models (e.g. Soil and Water Assessment Tools –SWAT and Better Assessment Science Integrating Point and Nonpoint Sources -BASINS) require a vast amount of information and at scales which are often not available in many developing economies. Furthermore, the use of elevation/contours fails to account for the level variability as a result of upstream contribution to water movement and accumulation at downstream locations. Thus, there is a need for a method which takes into consideration these peculiarities and challenges while creating a useful and rapid assessment framework for flood risk mapping that is useful for land use planning by local authorities.

Geomorphometry is very important in understanding many earth processes, hydrology, natural hazard, landscape evolution, river basin morphology, topography and in flood related studies (Bishop, James, Shroder Jr, & Walsh, 2012). Geomorphometric and hydrological indices have found extensive use in understanding land based processes and hazards. Cavalli, Trevisani, Comiti, and Marchi (2013) examined erosion and sediment delivery across two alpine catchments in Italy. Using a high resolution digital elevation model, they derived a geomorphometric index which could be used to characterize sediment connectivity across the catchment with good performance when compared to ground truth data. Sediment connectivity is the degree of linkage which controls sediment fluxes across any landscape (relationship between upstream sediment sources and downstream areas) and sediment transfer processes (Cavalli et al., 2013). This is very important in understanding which part of the catchment is contributing most to sediment yield and thus planning for proper measures to control it. Korup (2004) examined landslide dams' stability by using geomorphometric variables. These dams are formed by the blockage of river channels by mass movement from hill slopes, and they represent a significant hazard in case of a failure of such natural water features (Korup, 2004). The study concluded that Backstow, basin and relief indices; land slide-dammed lake volume; contributing area; and upstream relief can provide means for the derivation of a critical threshold for the formation of a persistent landslide dam.

Ozdemir and Bird (2008) investigated morphometric parameters across two drainage networks to characterize their influence on flooding. Their study identified the most important sub-basins (morphometrically) with the greatest infleunce for flooding in the Havran River basin (Turkey) and opined that analysis of morphometric parameters within GIS provided an added value to the understanding of basin drainage charatersitics in flood management. They concluded that to understand the infleunce of sub-basins on main channel flooding, morphometric and hydrological parameters need to be considered.

Study Area

Rivers State is located within the Niger Delta region of Nigeria (Figure 1). It has three ecological zones – mangrove forest and coastal vegetation; fresh water swamp; and lowland rainforest (Niger Delta Development Commission, 2006). Geologically, the State is situated within a coastal plain belonging to the Niger Delta sedimentary formation (Short & Stauble, 1967). In terms of surface morphology, slopes across the study area range between an average of 3 and 5 degrees in a NW-SE direction. It is poorly drained as a result of the low relief and gentle slopes.

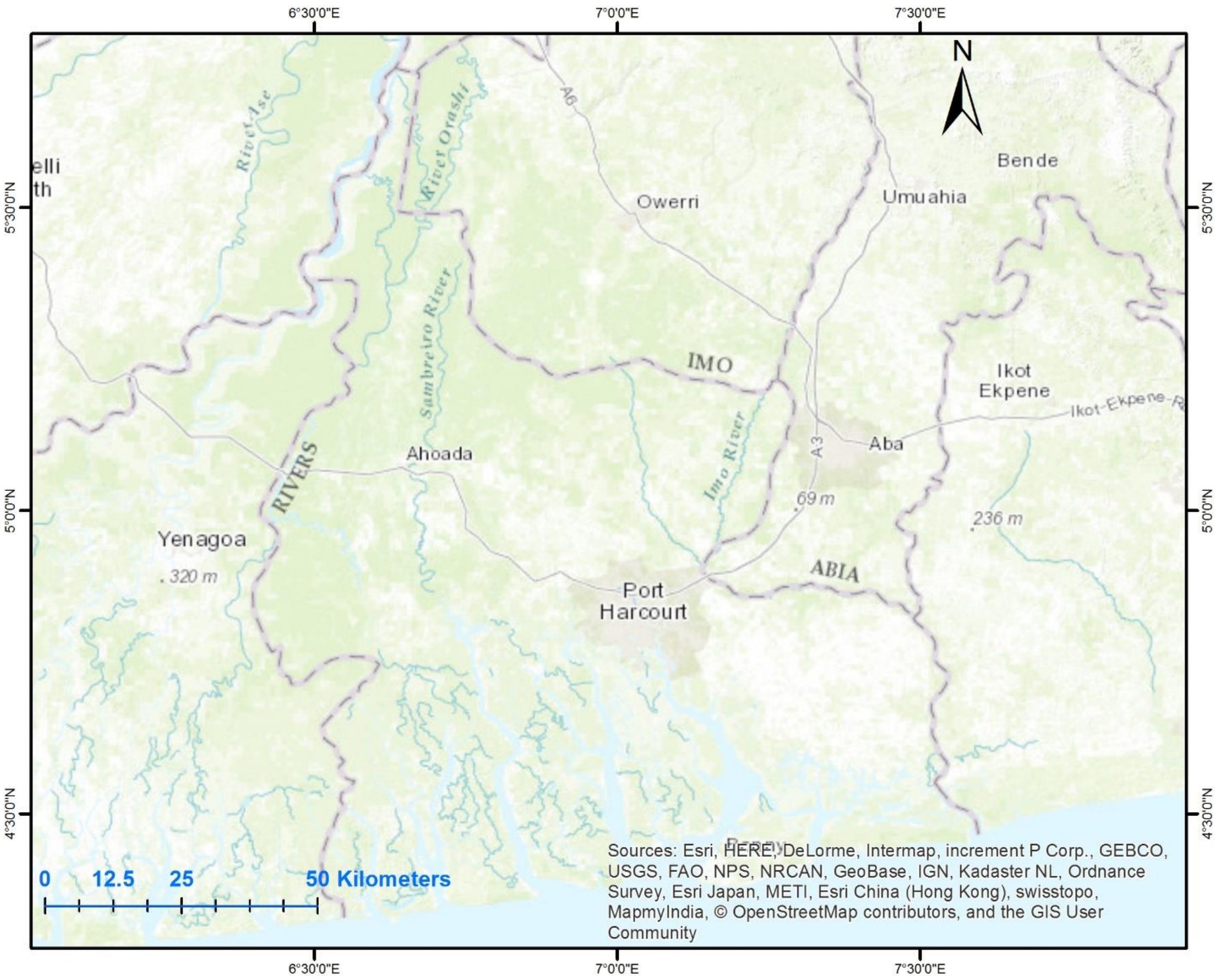

Figure 1: Rivers State topography and drainage networks

The Niger Delta development Commission (2006) provides an extensive detail of the region's land and the people. Availability of dry land dictates the pattern of settlement, in that swampy terrain limits the number of large settlements across the region. A large city like Port Harcourt was formed on the dry islands in the mangrove swamp in the interior parts of the Delta due to relatively better drainage conditions and accessibility. Over 60% of the top soils of Rivers State are of low fertility. Furthermore, silt nourishment as a result of floods plays a significant role in the improvement and maintenance of the soil biota and soil fertility.

In terms of climate, the study area belongs to the Tropical Monsoonal type (Rubel & Kottek, 2010), characterized by a short dry season and a pronounced wet season which starts around March and lasts till October with a break, usually around August. Temperatures are fairly constant throughout the year, ranging between a maximum of 28ºC and 33ºC to a minimum of 21ºC – 23ºC. Agriculture and industries are dominant and across many rural communities, fishing and subsistence farming are commonplace. Industries such as food manufacturing, oil servicing, oil and gas, construction and marine industries are also common.

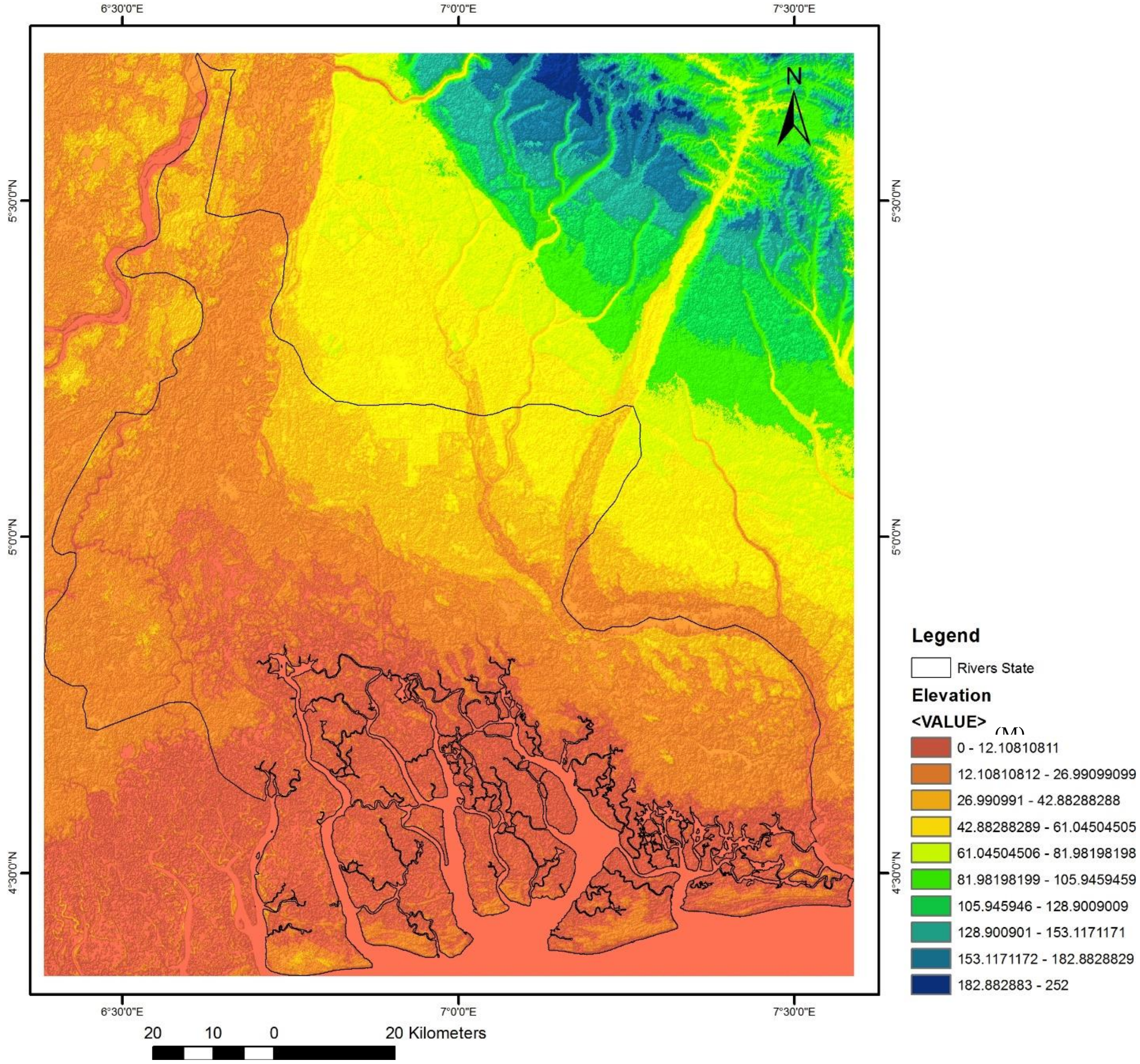

Figure 2: Elevation data (in meters) for Rivers State with hillshade effect

The elevation data was extracted from the Shuttle Radar Topographic Mission (SRTM) 30m resolution dataset from the U.S. Geological Survey (Figure 2). The data were extracted in the Georeferenced Tagged Image File Format (GeoTIFF); the horizontal datum is the World Geodetic System 1984 (WGS84 – Geographic) while the vertical datum is the Earth Gravitational Model 1996 (EGM 96) ellipsoid; and the vertical unit is meters (USGS, 2016). The data for the study area was downloaded from the Earth Explorer website (http://earthexplorer.usgs.gov/).

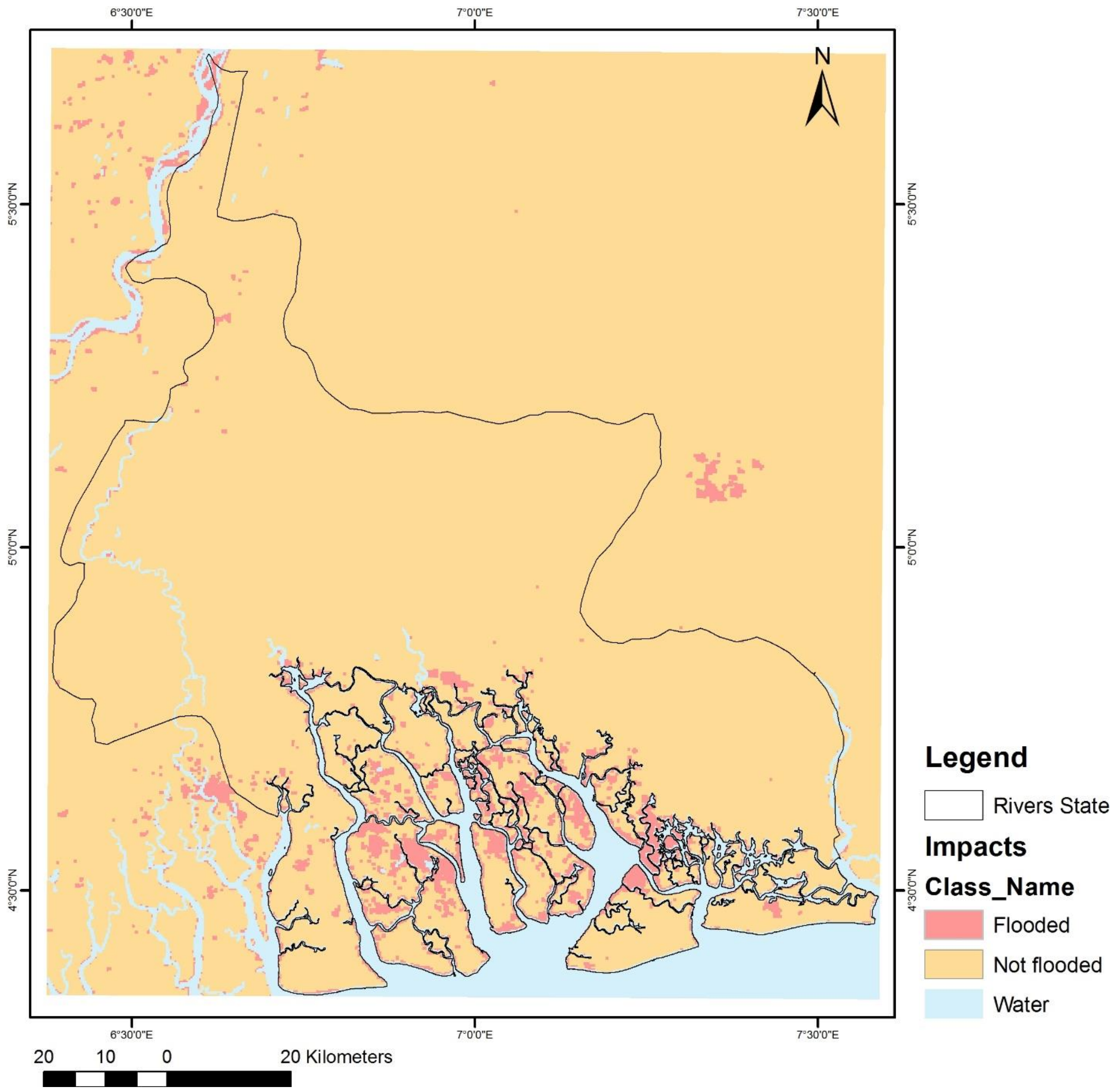

Figure 3: Rivers State and historical extent of flooded area

Data on flooded area from 2000 to date (Figure 3) was sourced from the Dartmouth Flood Observatory (Brakenridge & Kettner, 2016). The dataset was produced using remotely sensed data to create a surface water record of satellite observed changes in surface water during recent as well as historical floods from the year 2000. The Moderate Resolution Imaging Spectro-radiometer (MODIS) instrument (aboard the Terra and Aqua satellites) provides the basis for the creation of this dataset, with each one of the satellites covering the entire earth's surface in 1 to 2 days. This coverage provides a huge dataset which enriches our understanding of various processes on and over the surface of the planet.

Methods

Hydrological and terrain indices were computed with the Quantum GIS (QGIS) open source GIS software (Version 2.14.0). The combined use of the hydrological and geomorphometric indices is termed the hydro-geomorphometric method in this study. These indices were then used in the characterization of flooded and non-flooded areas.

Prior to the computation of the hydro-geomorphic indices, sinks within the Digital Elevation Model (DEM) were filled using the Wang and Liu (2006) method. In order to capture the hydrological characteristics, the TWI was computed using the modified catchment area calculation - System for Automated Geoscientific Analyses (SAGA) wetness Index, as suggested by Böhner et al. (2001). TWI helps quantify the control of topography over hydrological processes and it was developed by Beven and Kirkby (1979). As topography influences spatial distribution of soil moisture and groundwater flow (Rodhe & Seibert, 1999; Zinko, Seibert, Dynesius, & Nilsson, 2005), it has been shown that TWI has a high correlation with Species richness, pH, groundwater, soil moisture and wetness degree (Sørensen, Zinko, & Seibert, 2006). Furthermore, Famiglietti and Wood (1991) used TWI in creating a land surface hydrology parameterization for global circulation models while Zinko et al. (2005) relate TWI to vegetation pattern. In addition, in characterizing the flow paths for geochemical modelling, Robson, Beven, and Neal (1992) also used TWI, similarly for modelling net primary production (White & Running, 1994), saturated area (Güntner, Seibert, & Uhlenbrook, 2004) and wildfire potential risk (Lein & Stump, 2009). In the computation of TWI, three different methods of type of area (absolute catchment area, square root of catchment area and specific catchment area) were used in combination with two types of slope computation (local slope and catchment slope). This resulted in six different TWI maps for the study area. The designations of the TWI computed are highlighted in table 1.

Table 1: Methods used for TWI computation

Contributing Area computation	Absolute Catchment		Square Root of Catchment		Specific Catchment Area	
Slope Computation	Local Slope	Catchment Slope	Local Slope	Catchment Slope	Local Slope	Catchment Slope
TW_1	✓					
TW_2		✓				
TW_3			✓			
TW_4				✓		
TW_5					✓	
TW_6						✓

In relation to Morphometric or Terrain Analysis, three indices were selected: TPI, TRI and VRM. TPI was calculated using the method proposed by Guisan, Weiss, and Weiss (1999), TRI was computed as suggested by Riley, Degloria, and Elliot (1999) and VRM was calculated using the method proposed by Sappington, Longshore, and Thompson (2007). VRM is different from TRI in the sense that it decoupled slope from the indices better than TRI (Sappington et al., 2007). Both indices measure how rough a location is, taking into account the changes in elevation for a point and the areas surrounding it (central point and the 8 cells surrounding it). It is clear that physical and biological processes are often influenced by topographic position, and these measures could be used in creating a better understanding of erosion, deposition, hydrological characteristics, and wind exposure, and as such they can influence biophysical activities across a landscape (Weiss, 2001).

In the computation of VRM and TRI, four different distance weighting methods were considered:

1. No distance weighting,
2. Inverse distance weighting,
3. Exponential distance weighting, and
4. Gaussian distance weighting.

This resulted in four different maps for VRM and TRI, while TPI has one map (using the Geospatial Data Abstraction Library [GDAL] module in QGIS). This amounts to a total of 15 maps of hydrological and geomorphometric indices. The flood extent map was converted to point data and the hydrological and geomorphometric data was extracted for these points using the bilinear interpolation within ArcGIS (ESRI, 2015). Spearman Rank Correlation analysis was carried out to examine the relationship among the indices computed. This correlation analysis was carried out using the IBM Statistical Package for Social Scientists – SPSS (Version 23). Details of the computation, power and efficiency of Spearman Rank correlation can be found in the works of Gibbons and Chakraborti (2014) and Siegel and Castellan (1988).

In order to find out if there is a difference between the area flooded and otherwise, based on the indices computed, the Mann-Whitney U Test was applied (within SPSS). The Mann-Whitney U test is an alternative to the parametric t-test analysis for independent samples which allows one to test whether there are differences between two groups without the normality assumption. Comparatively, it is more sensitive than the Wald-Wolfowitz runs test and the Kolmogorov-Smirnov two-sample test (StataCorp, 2011).

Results and Discussion

Examination of relationship among indices

Correlation analyses carried out revealed that all the indices used for TRI and VRM are perfectly correlated. This shows that similar values were arrived at irrespective of the methods used for computation. Essentially, the methods used captured and presented the same information for this area under investigation. This could be attributed to the topography and the resolution of the elevation data used. Since the area under investigation is a coastal plain, there is not much variation in the elevation data to bring about any great difference in the values.

Values for VRM range between 0 and 1 (Figure 4) with a mean of 0.462 and a standard deviation of 0.255 (Table 2). The mean value gave an indication that the terrain is relatively flat (0 implies central point is not different from surrounding 8 pixels – no terrain variation; higher VRM means higher variation). The TRIs show variation across the different methods of computation. However, the correlation analysis shows that there is a significantly strong positive correlation among the different methods, i.e., locations designated as undulating or rough (or flat) are similarly designated across the different methods.

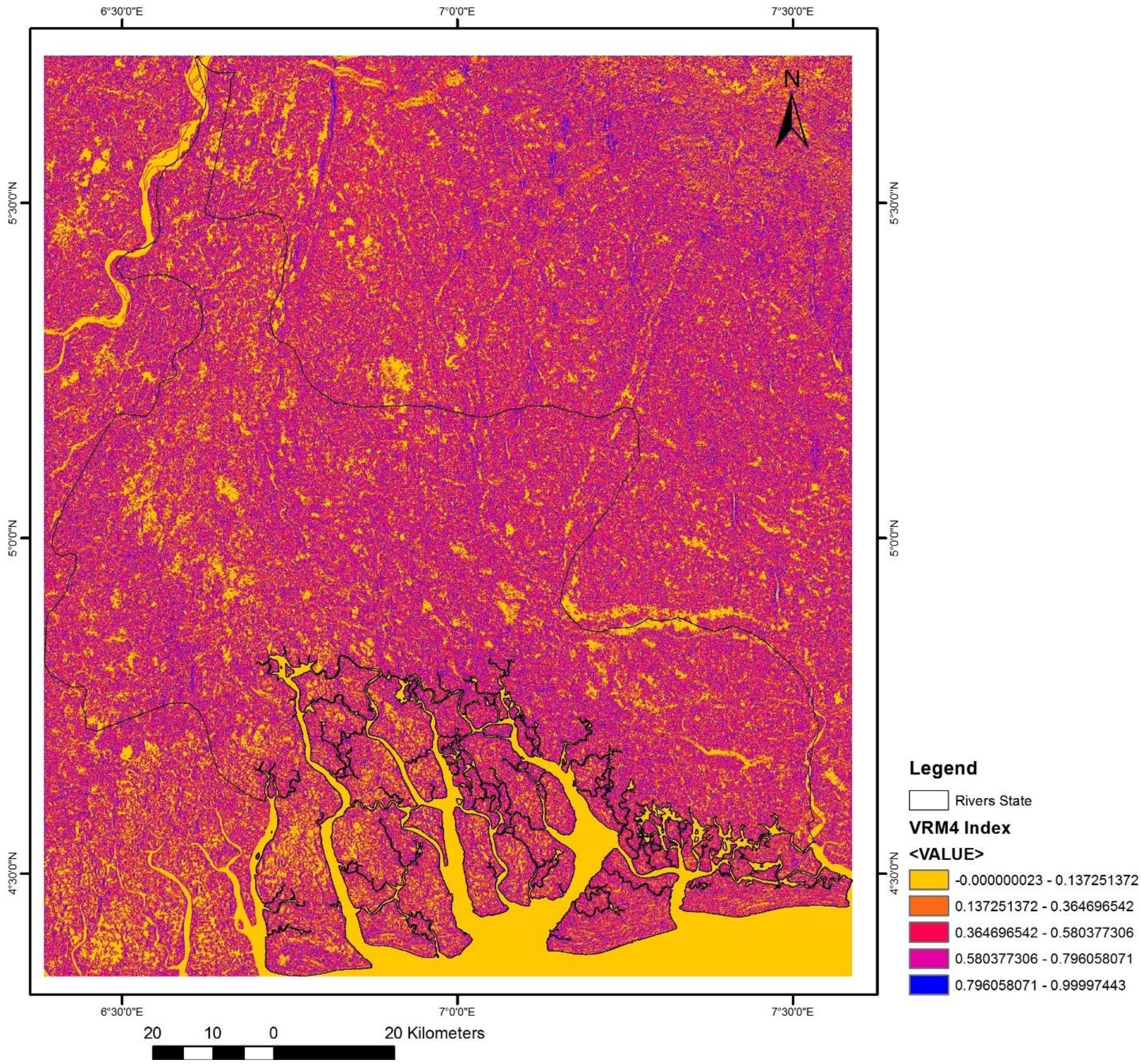

Figure 4: Vector Roughness Index (VRM4) across Rivers State

The TRIs have values ranging between 0 and 13.220 with this maximum recorded for the TRI1 (No distance weighting), the maximum of 8.018 was recorded for TRI_3 (Exponential distance weighting) – lowest maximum TRI value (Figure 5).

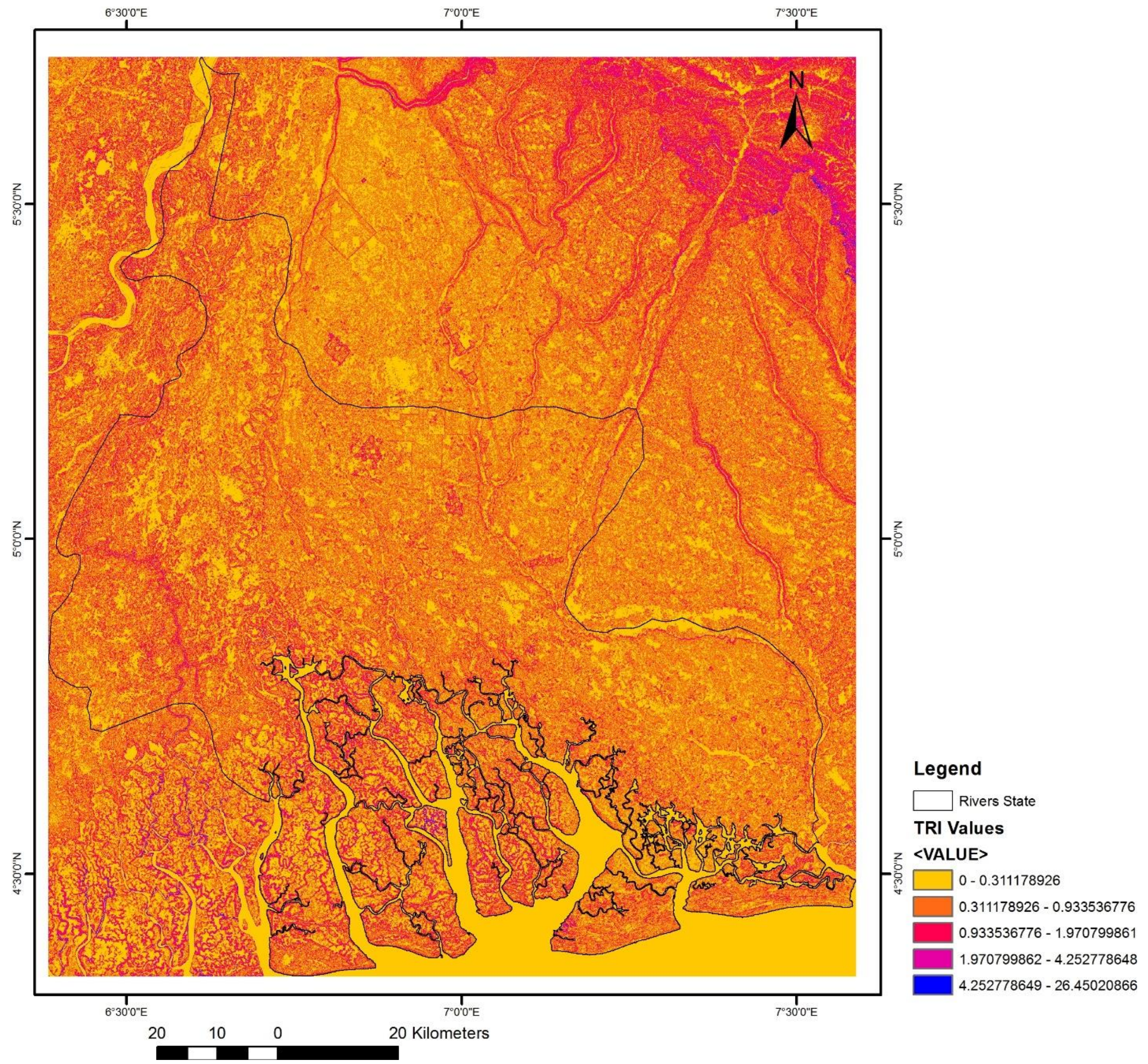

Figure 5: Terrain Roughness Index (TRI_3) values for Rivers State

Across the TRI the mean values range between 0.548 (TRI_3) and 0.903 (TRI_1), while the standard deviation ranges between 0.475 and 0.783. These gave an indication that there is very little variation in the terrain across the study area. The combination of the two indices of terrain roughness (TRI and VRM) shows that the study area is relatively flat.

Hydrological characteristics as captured by TWI, computed using 6 different methods, show that there is a significant strong positive correlation among the six methods (Table 3). Some of the TWI methods were found to be perfectly correlated - TWI_2 vs TWI_6; TWI_1 vs TWI_5; TWI_3 vs TWI_5 and TWI_1 vs TWI_3.

Table 2: Summary of Descriptive statistics of roughness indices

	N	Minimum	Maximum	Mean	Std. Deviation
VRM_4	143441	0.000	1.000	0.462	0.255
TRI_4	143441	0.000	10.296	0.703	0.610
TRI_3	143441	0.000	8.018	0.548	0.475
TRI_2	143441	0.000	9.348	0.639	0.554
TRI_1	143441	0.000	13.220	0.903	0.783

Source: Computed from collated data

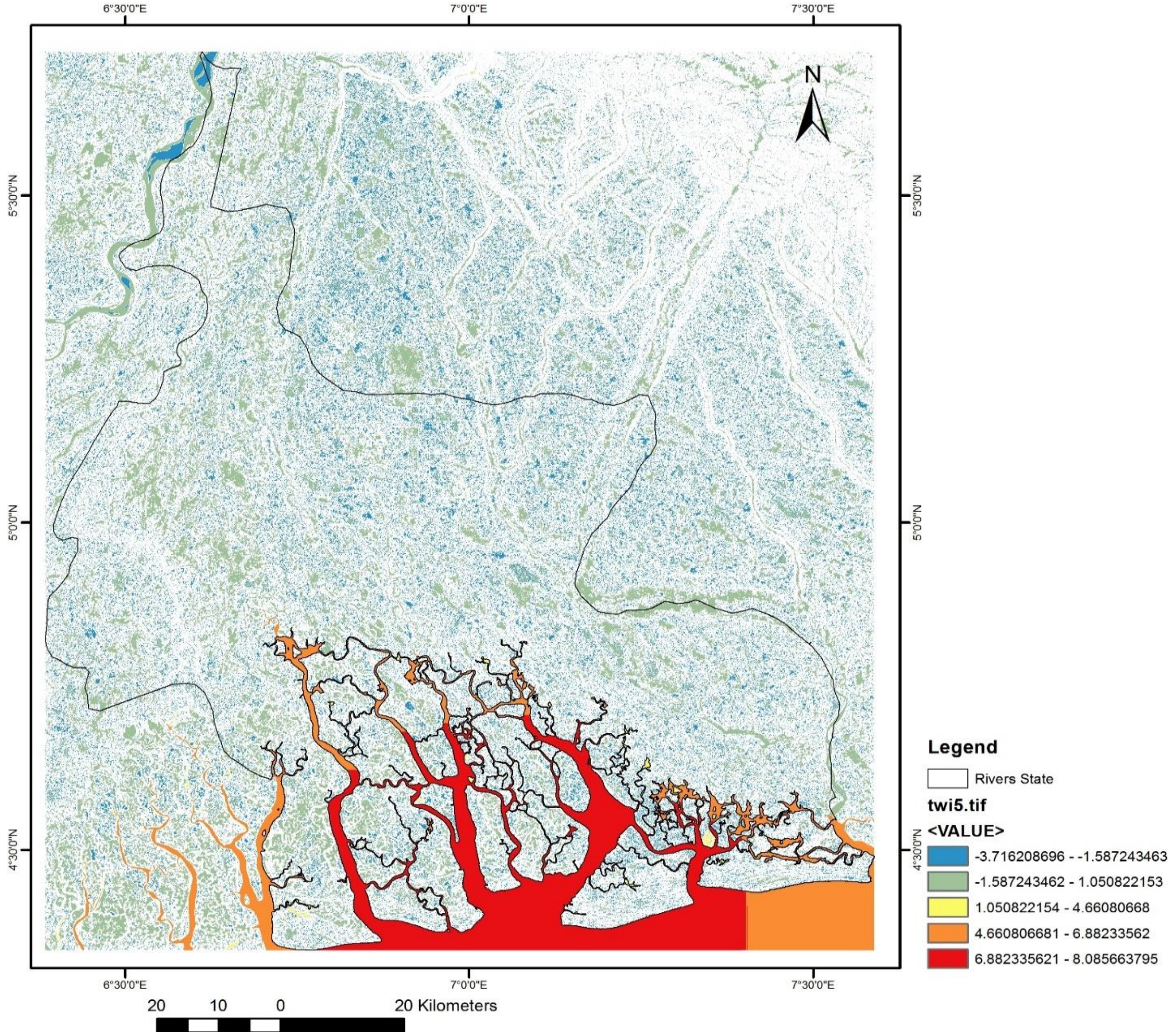

Figure 6: Topographic wetness index (TWI_5) for Rivers States

NB. White cells indicate no data (no values)

This index is a function of upstream contribution area (computed using three different approaches) and slope (computed using two different approaches); in essence, higher values indicate areas with depression (dips and hollow) where water accumulates for a longer period of time (higher flow accumulation), while lower values identify areas with higher elevation such as ridges and crests. An examination of the TWI values shows that there is a preponderance of negative values (Figure 6 and Table 4). This could be attributed to the exceedingly high slopes as captured by the resolution of the elevation data (30m).

Table 3: Correlation among TWI computed using different methods

	TWI_6	TWI_5	TWI_4	TWI_3	TWI_2	TWI_1
TWI_6	1.000					
TWI_5	0.782	1.000				
TWI_4	0.998	0.742	1.000			
TWI_3	0.783	1.000	0.742	1.000		
TWI_2	1.000	0.782	0.998	0.783	1.000	
TWI_1	0.782	1.000	0.742	1.000	0.782	1.000

All are significant at 5% probability

Across the six methods, TWI_5 (specific catchment area and local slope) performed better for the study area, having a minimum value of -3.518 and a maximum of 4.737 (Figure 6). This is desirable, as the minimum is closer to zero than any other of the methods used in computing the catchment area and slope. With this understanding, TWI_5 was used for subsequent analysis.

TPI also captured an aspect of the geomorphology of the terrain – measure of relative elevation of a point to the elevation of its surrounding. For this index, areas that are flat have values close to zero, while positive values give an indication that the area has an elevation greater than the surrounding areas. In addition, the index could also have negative values; large negative values give an indication of valley or depression.

Table 4: Summary of descriptive statistics for hydrological indices

	N	Minimum	Maximum	Mean	Std. Deviation
TWI_6	61239	-19.624	4.254	-6.041	4.440
TWI_5	40230	-3.518	4.737	-1.553	0.750
TWI_4	61239	-19.922	.309	-6.928	4.164
TWI_3	40230	-3.574	.554	-2.591	0.375
TWI_2	61239	-27.813	-3.935	-14.229	4.440
TWI_1	40230	-11.706	-3.451	-9.741	0.750

The result from the descriptive analysis shows that TPI values range between -4.965 and 11.363; the mean for the study area stands at 0.002 with a standard deviation of 0.565. This result gave an indication that the area under this study is mostly flat (TPI is zero or near zero). This is in agreement with the results from VRM and TRI presented earlier.

From the correlation analysis between the TPI and the other indices, it is evident that the TPI captured a different dimension not captured by the other indices. There is a weak but significant positive correlation between TPI and VRM_4; TWI_5; and TRI_3 (Table 5). Moreover, VRM vs TWI and TRI vs TWI shows a medium but significant negative correlation, while TRI vs VRM shows a positive but weak significant correlation.

Table 5: Correlation between TPI and other geomorphometric and hydrologic indices

	VRM_4	TWI_5	TRI_3
TWI_5	-0.673		
TRI_3	0.455	-0.572	
TPI	0.060	0.329	0.115

All are significant at 5% probability

Comparison of Indices between flooded and Non-flooded Areas

With the elimination of redundant indices, the remaining indices were used to find out if there are statistically significant differences between flooded and non-flooded areas. A Mann-Whitney U test was carried out for the 4 remaining indices (Table 6).

Table 6: Independent Samples Mann-Whitney U Test Results

Indices	Mean Rank		Standardized	Asymptotic Sig.
	Not Flooded	Flooded	Test Statistics	(2-Sided test)
VRM_4	71,673.88	72,414.12	1.65	0.09
TWI_5	20,205.09	18.718.79	-6.11	0.00
TRI_3	71,436.28	75,909.45	10.00	0.00
TPI	71.709.49	71.890.37	0.40	0.69

Source: Computed from collated data

Results from Table 6 show that out of the 4 remaining indices, only two have values which can differentiate flooded and non-flooded locations within the study area. TWI_5 and TRI_3 values were significantly different ($P<0.05$) for flooded and non-flooded areas. TWI captures the influence of topography over hydrological processes –soil moisture, groundwater flow, wetness degree etc. The method using specific catchment area (Contributing area computation) and local slope (Slope computation) thereby highlights the importance of the consideration of macro and macro scales in the identification of flood prone areas. TRI also captured the roughness of an area in relation to the elevation of its surroundings. From these results it is evident that the roughness plays a role in determining whether an area is prone to flooding or not.

These results give a clear indication that the wetness index and the roughness index can be used for rapid assessment of potential vulnerability to flooding in the study area. The result is in agreement with recent findings (Manfreda, Di-Leo, & Sole, 2011; Pourali, Arrowsmith, Chrisman, Matkan, & Mitchell, 2014) that while hydrodynamic modelling is extremely valuable for flood risk assessment, hydrological and geomorphometric indices are tools for rapid assessment of flood prone areas. This therefore, could help in many parts of the world where data and details required for efficient and accurate hydrodynamic modelling are limited. Identification and delineation of such areas could support land development planning as well as flood mitigation initiatives which can help communities build resilience across the Niger Delta region.

Summary and Conclusions

Analyses of geomorphometric and hydrological indices have been used in the characterization of spatial processes. Spatially, flooding is a major natural disaster across the world as well as in Nigeria, based on its inherent catastrophic impacts on people, property and the environment. In the light of this, it is very important that efforts be made to identify and delineate areas at risk of inundation. This study examined the distinctions between flooded and non-flooded areas in relation to geomorphometric and hydrological indices.

Different methods of computation of VRM, TRI and TWI were compared. From the results, it is possible to conclude that methods for computing VRM and TRI are not statistically different from one another, using the same resolution of elevation data. Thus, any of the methods could be used. This lack of difference could also be attributed to the type of terrain under investigation. Similarly, TWI methods were also found to be strongly and positively correlated, leading to the conclusion that irrespective of the method used, there is no significant difference in the output. Across the indices, TWI was found to be significantly correlated (negatively and moderately) with TRI and VRM, while TPI was weakly and positively correlated with TRI and TWI. In essence, the roughness of the terrain (TRI and VRM) negatively impacts saturation across the landscape. In addition, the recorded level of association (weak) between TPI and the roughness and saturation indices shows that either the relationship is not linear or there are other dimensions in the landscape not captured by just one individual index. Therefore, it is possible to conclude that a mixture of indices should be used when characterizing landscape in this environment.

A comparison of the flooded and non-flooded areas based on hydrological (TWI_5) and geomorphometric (VRM_4, TRI_3 and TPI) indices shows that these two locations only differ based on TWI and TRI in the area under this investigation. Therefore, it is evident that while computation of the indices may be problematic on a fairly flat terrain, there is still a possibility of distinguishing between flooded and non-flooded areas. The results also highlight why it is impossible to do away with hydrodynamic models in delineating flood prone areas. However, in a situation where rapid assessment is required, or there is a problem of incomplete data (spatial or temporal details), or regional assessment is required, it is recommended that this approach be adopted to identify areas potentially vulnerable to flood. This could add another layer of confidence to the conventional contour delineation.

In the light of the current study, there is the need to develop a new approach for characterizing wetness index in lowlands, one which takes into account the peculiarity of this landscape. This is because of the many missing values (no data cells) in the computation of the TWI due to the flatness of the terrain. Furthermore, due to the problem of steep slopes along the edges of the drainage network, a lot of negative TWI values were generated, thus showing that the quality of the elevation data significantly influences the computation of hydro-geomorphometric indices.

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