



Study of Flood Prone Sites in Minna Metropolitan City, Niger State, Nigeria

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ABSTRACT

The frequent incidence of high surface runoff generation over urban terrain, accurate mapping of susceptibility areas ushers a new nexus in urban stormwater management for flood mitigation and protection. This research is aim at developing spatially distributed surface runoff scenario indexes using Evidential Weight approach. The specific objectives are to: identify the surface runoff induced factors; assign weight to each of the identified factors and obtain normalized weight of the identified factors using Analytical Hierarchy Process (AHP) and Multi-Criteria Decision Analysis (MCDA) to produce surface runoff index map of Minna. The generated susceptibility index map uses GIS-based MCDA along with AHP methods to delineate and quantify optimal criterial weights that contributes more to surface runoff scenario. The result of the surface runoff map generates five (5) scenarios: very low, low, medium, high and very high susceptibility indexes, after overlay of slope degree; precipitation; elevation; Land Use Land Cover (LULC) information; soil types and drainage density map. The result of the study provides city planners and policy makers with critical information required for effective decision making in understanding runoff susceptibility zones for flood mitigation and protection.

Keywords: Flood, Surface runoff, Analytical Hierarchy Process, Multi-Criteria Decision Analysis

INTRODUCTION

In recent years, there have been continue concerned to the devastating effects of flood to human environment, property and infrastructures amidst increase in global climate change scenario. Evidences has linked the incessant flood events as a result of increase in urban storm water flow system to climate change scenario resulting to increase in rainfall events for extended duration with high intensity. Thus, increasing the accumulation of rainwater beyond what the surface can absorb, transmit and transport as a surface runoff. Surface runoff events and its destructive magnitude has become worrisome among policy makers, environmentalist and other stake holders in view of its effects on soil erosion, degradation of water quality in many rivers, agricultural security and deterioration of environmental quality. Large scale runoff events often result to flash flood which has struck many communities in Nigeria, causing damage estimated to be well over a billion of naira to properties and farmlands and has continue to increase in frequency.

The implementation of Geographical Information System (GIS) in runoff related studies has favor rapid expansion in the scope of flood generated risk research on a regional scale and has also benefited the expansion in soil-water related simulation (Izham *et al.*, 2011). In addition, GIS has enabled the spatial representation of riparian measurements on a theory-based models thus, providing a robust technique for effective event validation on a regional scale. The implementation of these GIS based model provide a platform to professional ends users (i.e., civil engineers in urban water channel design, environmentalist and geologist) to effectively utilizes spatial information including infiltration, floodplain analysis and channelization (Johnson, 2014; Kokas, 2017; Yusoff *et al.*, 2010). Surface runoff events occur when soil has attained it maximum water holding capacity and continues addition of water from precipitation and irrigation to the surface will results to runoff (M. Izham *et al.*, 2011). Soil physical and structural conditions including

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bulk density, structure, texture, hydrogeological and surface heterogeneity conditions can immensely favor the development of a unique water movement that can generate favorable overland flow events at a varying scale or magnitude (Miall, 2014; Walliss & Rahmann, 2016). Two major conditions are necessary for runoff occurrence; the infiltration inform of Infiltration Excess Overland Flow (IEOF) which is described as the downward movement of surface water towards the baseline formation (Y. M. Izham *et al.*; Singhal & Gupta, 2010; Williamson *et al.*, 2019) and saturated condition known as Saturated Excess Overland Flow (SEOF) which occur when a geological medium has attained the maximum water holding capacity thus, allowing for a surface runoff condition along with contribution from the adjacent areas (Campling *et al.*, 2002; Ferreira *et al.*, 2015; Gülbaz *et al.*, 2020; Yang & Chu, 2015).

Although several studies including: forecasting (Chau *et al.*, 2005; Cloke & Pappenberger, 2009; Hapuarachchi *et al.*, 2011; Jain *et al.*, 2018), runoff flood extend assessment (Jain *et al.*, 2018; Yusoff *et al.*, 2010) and modelling (Y. M. Izham *et al.*; Konadu & Fosu, 2009; Samanta & Koloa, 2014), were able to map different runoff indexes with some degree of reliability. GIS practitioners need to understand the heterogeneity of urban surfaces, in view of many intricate factors that come to play in initiating runoff occurrence conditions, if sustainable flood mitigation is to be incorporated into urban planning and development. Several methods and tools were developed toward mitigating the effect of flood events on a spatiotemporal scale. This advances were favored by rapid development in computer technology, which provide a platform for the processing and storage of large volume of data from multiple sources that may be considered as reciprocal relationship with an event or scenario. To this end, the full potential of GIS has been explored along with different data sets in a dynamic modelling including flooding, fire and other environmental unstable conditions. Emergence from the numerous techniques and approach to runoff studies, GIS has appeared to be most reliable tool for modelling of such unstable condition. The caveat attributes of GIS were largely favored its ability to integrate multiple layer information along with many susceptibility tools that allow for regional decision making.

For example, the rate of IEOF is largely influenced by the topographic nature of the environment along with the prevalent geological conditions that are dependent on amount of rainfall inputs. The conventional approach of runoff conceptualization cannot effectively represent the heterogeneity and complexity of hydrological processes leading to surface runoff generation. In overcoming the uncertainty associated with the conventional approach, incorporating the role of landscape factors such as; terrain conditions like soil, and vegetation are critical for runoff generation. In addition, topography, geology, drainage condition and nature of the environment provides a complex system affecting modelling of flood onset and magnitude in an environment. In addition, the application of flood occurrence from surface runoff arises from the contribution from adjacent cells commonly in many GIS based flood studies may be difficult to obtain in reality owing to the variation in the nature and types of surface condition. The heterogeneity experienced in many of the urban environments due to the complex nature of prevalent surfaces that obstruct surface water draining condition are also critical factors that have affected the accuracy of any runoff models. From the foregoing, it is evident that heterogeneity in surface condition along with multiple parameters can influence flood occurrences and the inability to incorporate these constructs can significantly influence modelling output or performances. Since these parameters are closely interconnected with geographical boundaries, their variation in a geographical space can also influence water movement across the surface to generate SEOF conditions that are necessary for runoff conditions that could favor flood occurrence with high-risk impact. SEOF is one of the most outstanding flood generation processes on a watershed and on different surfaces with varying water saturation behavior. The effectiveness of SEOF process in area volume modelling is outlined by (Izham *et al.*, 2011) demonstrated in many hydrological and water shade management in a GIS environment including; Soil Moisture Routine Model (SMRM), Hydro-geomorphic Steady State Model (HGSS), and Kinematic Runoff And Erosion Model (KINEROS).

This approach however, is often difficult to implement especially in an urban environment where the surfaces are completely

heterogeneous and flow accumulation from adjacent cells becomes compromised as well as lack of uniformity in IEOF and SEOF across the urban surfaces. Also, in many regions, runoff is often generated across a small portion of landscape which are easily susceptible to become completely saturated thus, affecting the efficacy of the model in urban environment. In view of this limitations of flood modelling in an urban environment, the development of a robust methodology that can effectively manage the heterogeneity of urban environment can effectively provide highly promising and reliable approach for cost-effective flood risk assessment and vulnerability mapping for sustainable development. Currently, IEOF model has been explored extensively in many scientific investigations. This type of model is effective and accurate to meet prediction requirements (Yusoff *et al.*, 2009).

Urban storm water informs of surface runoff using GIS-based multi-criteria analysis is a nexus in the integration of multiple factors that help in effective flood control. Scanty literature has demonstrated the viability of this approach in groundwater potential mapping (Jhariya *et al.*, 2016; Rahmati *et al.*, 2015), flood risk mapping (Yeganeh & Sabri, 2014), land suitability for agricultural mapping (Mendas & Delali, 2012; Musakwa, 2018; Paul *et al.*, 2020) among several others. Thus, use of GIS-MCDA in surface runoff modelling for sustainable urban flood management becomes necessary in view of the complexities of the urban surface heterogeneity.

This research therefore, aim to develop spatially distributed flood scenario simulation using Evidential Weight Approach in Minna Niger State. The specific objectives of the research include: (i) to identify the surface runoff induced factors (ii) to determine the consistency of the identified Surface runoff induced factors using MCDA in AHP, (iii) to developed GIS-Based surface runoff susceptibility map indexes by overlaying the normalized weight of the evaluated criteria.

METHODOLOGY

Three major data were sourced for the purpose of this research; the physical data, remote sensing data and precipitation data. The physical data includes: topographic, soil (Figure 2c), digital elevation model (DEM) and drainage

information. The remote sensing data was used to extract the Land Use Land Cover (LULC) map of Minna Niger state. Information regarding amount of rainfall received over a given period of time was extracted from the four (4) meteorological observatory (Nigerian Meteorological agency, Nigerian Agricultural Development Agency, Federal University of Technology Bosso Campus Observatory and Ibrahim Badamasi Babangida University weather observatory station.

Data set used for the research

DEM

Topography of an area play an important role in the hydrographic processes. The circulation of water over a given surface to near surface is largely an interplay of topography and runoff driven by nature and types of soil medium over which the water accumulates and flow. The topography condition region of flow concentration and subsequently generate flood. To this end, ASTER-DEM of 30m and SRTM DEM of 90m were resolution was downloaded and geometrically ortho-corrected for higher elevation precision (Rajasekhar *et al.*, 2018; Tampubolon *et al.*, 2021). The DEM was process to produce slope map (Figure 2d) of the study area (Figure 1).

Drainage Morphometric Information

The number of prevalent networks of stream plays critical role in defining flood prone areas. Proximity to river is mostly likely to be more vulnerable to flooding compared to a more distant area. The drainage data of the study area was delineated from DEM and stream network information available on the topographic sheet map of Minna. The extracted drainage network information was process and converted into portable GIS data format, delineated into drainage density thematic layers (Figure 2f) using ArcGIS 10.5. The thematic layers were then assigned a weight of 4 and 1, for areas with high and low drainage density respectively.

Precipitation Data

Amount of rainfall received over a given period of time is the major cause of surface runoff and consequently, river flooding when both the stream and surface can no longer evacuates excess water. Since runoff has direct correlation with precipitation amount, increase in precipitation will implies higher amount of surface runoff leading to flooding. Diurnal precipitation data were converted into mean

monthly and mean annual from 2010-2020. Each of the stations within the study area and outside the gauge were coded and their precipitation data interpolated using Kriging technique in ArcGIS environment to produced precipitation map (Figure 2a). The precipitation map was then reclassify as assigned weight between 1-4 representing low and high values.

LULC Data

To map the LULC types of the study area, remote sensing data from landsat 8 OLI/TIR was sourced from USGS using 189/059 path and rows for 26th October, 2020. The imagery was subject to radiometric correction to remove dust haze and geometric correction to convert the geospatial attributes of the imagery into local value of Minna zone 31N. The corrected imagery was enhanced using Normalized Vegetation Index (NDVI) prior to the selection of training sample. A total of 150 training samples were then selected for each of the classes identify and used to trained the entire image using interactive maximum likelihood classification technique. A total of 7 different LULC (Figure 2e) were identify as; developed area, agricultural land, barren land, water body, non-pervious surface, vegetation and outcrop. Weights between 1-7 were then assigned to each of the LULC types as low to high surface runoff (Table 1).

Saaty scale of weight assignment to parameter under study

less importance		equally important			more important			
Extremely	Very strongly	Strongly	moderately	equal importance	moderate	strongly	very strongly	extremely
1/9	1/7	1/5	1/3	1	3	5	7	9

The consistency index (CI) defined as the measure of consistency was determined using The equation (i) (Thomas, 1980).

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{i}$$

Where n=number of factors, λmax = consistency refer to as Eigen value in some literature.

The consistency ratio (CR) was determined using the relation

$$CR = \frac{CI}{RI} \tag{ii}$$

Where CI is the consistency index, RI is the random consistency index defined by a value 0.58 for n=3

Mapping of flood vulnerable areas

The flood risk mapping produced as the final result of this research was a composite product of hazards risk influencing factors and vulnerability weight of the vulnerability that

AHP implementation approach

Analytical Hierarchy Process (AHP) utilizes hierarchical weight of evidence as a representation of problem as a function of multiple variables that are inferred to exert influence on the dynamics of occurrences. the approach then developed alternative of priority based on the judgmental and subjectivity of the user (Thomas, 1980) based on the pairwise comparative evaluation of criteria. The determination of criteria weight is based on their order of importance..

Weight Assignment and Calculation of Comparison Consistency

The weight of each factor was determine using AHP developed by (Saaty, 1980). The scores were based on the relative weight of pair wise comparison rated between scales of 1-9 in Table 1 in order of relative importance role contributing to flood generation. Pair wise comparison matrices of the assigned weights of the map themes along with the individual features were normalized to obtain the Eingen vector. The Eigen vector values for each of the map themes were determine using Matlab 2010a. The pair wise comparison represents relative importance of the factors under study.

produces the normalized weight of the judgmental value of each of the criteria. This approach is identified to be suitable for natural hazards mapping. The geospatial analysis procedure is presented in the equation (iv). The vulnerability map was then obtained by combining elevation, land use, precipitation, drainage density, slope and soil. The result of the flooding vulnerability map defines 5 level of vulnerability, low, medium, high, very high and risky vulnerability.

$$Vulnerability = Hazard\ index\ Vulnerability\ weight \tag{iv}$$

Location of Minna Niger State

Minna the study area, is located on 09°33'00" to 9°45'30"N and 6°27'00" to 6°48'15"E east with a total area of 20.44km² as presented in Fig. 1.

The physical tarring of study area is circumscribed towards the east by Paida slope extending eastwards in the direction of Maitumbi. The vegetation comprises of open savanna and is very favorable for cultivation. The open savanna is strengthened by the Fadama resulting from the large waterways, alongside intermittent streams laden with thick riparian woodlands. The geography of the study area displays a variation in elevation rising gently from 153 to 436 meters above sea level and a steep slope within the borders east of the study area. The location is characterized by the wet and dry season. During the wet season, precipitation is experienced up to 1660.72mm per annum with a duration of six months on the average. The maximum amount of rainfall is

recorded during the month of August through September. Temperature in the study area varies significantly in response to the season. As precipitation amount, intensity and duration declined, temperature value increases steadily until the peak of harmattan where morning temperature degree reach it minimum level. The mean annual temperature is between 28 to 36°C. Slope id the rate of change between high and low depression. This differences in slope are in response to undulating geomorphic which creates intercalation of low and high lands. In terms of slope, the study area is dominated mainly by a gentle slope of 51.92–106.40 and a few isolated high slopes of 158.42-268.83 degrees.

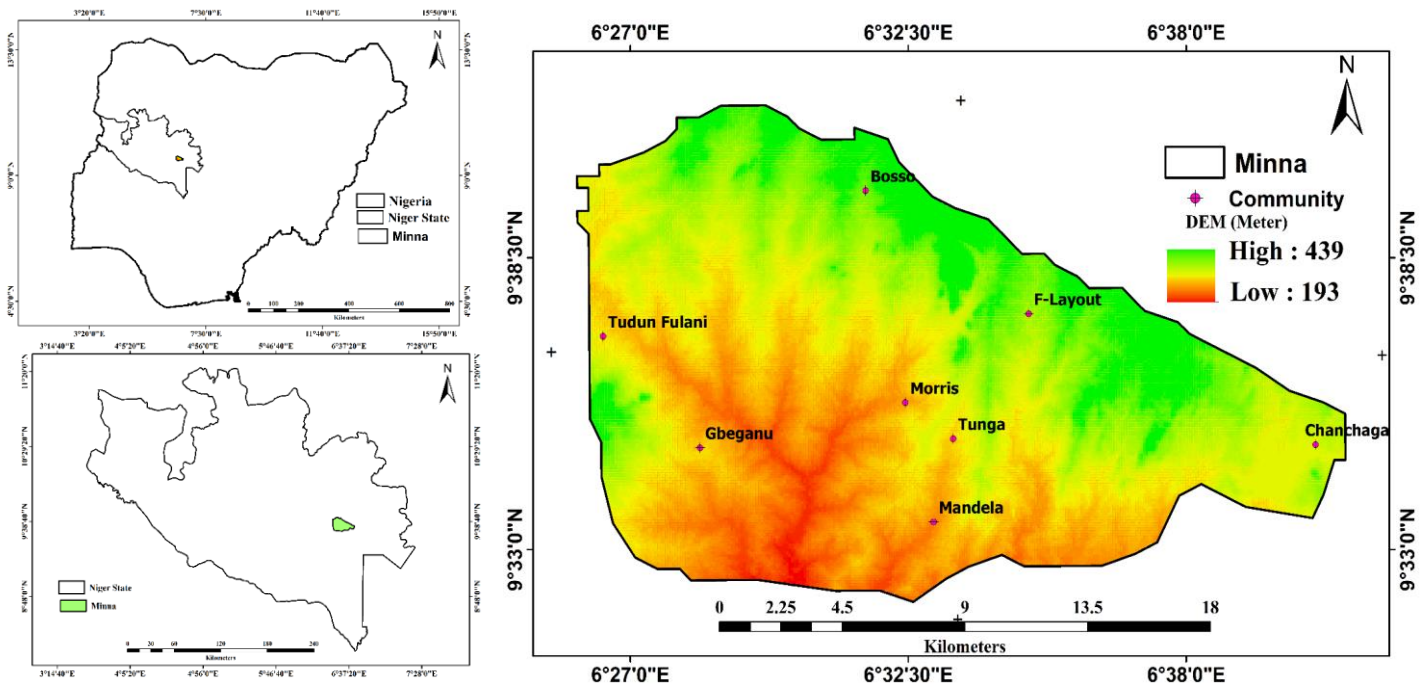


Figure 1: Map of Nigeria inset Niger state and study area

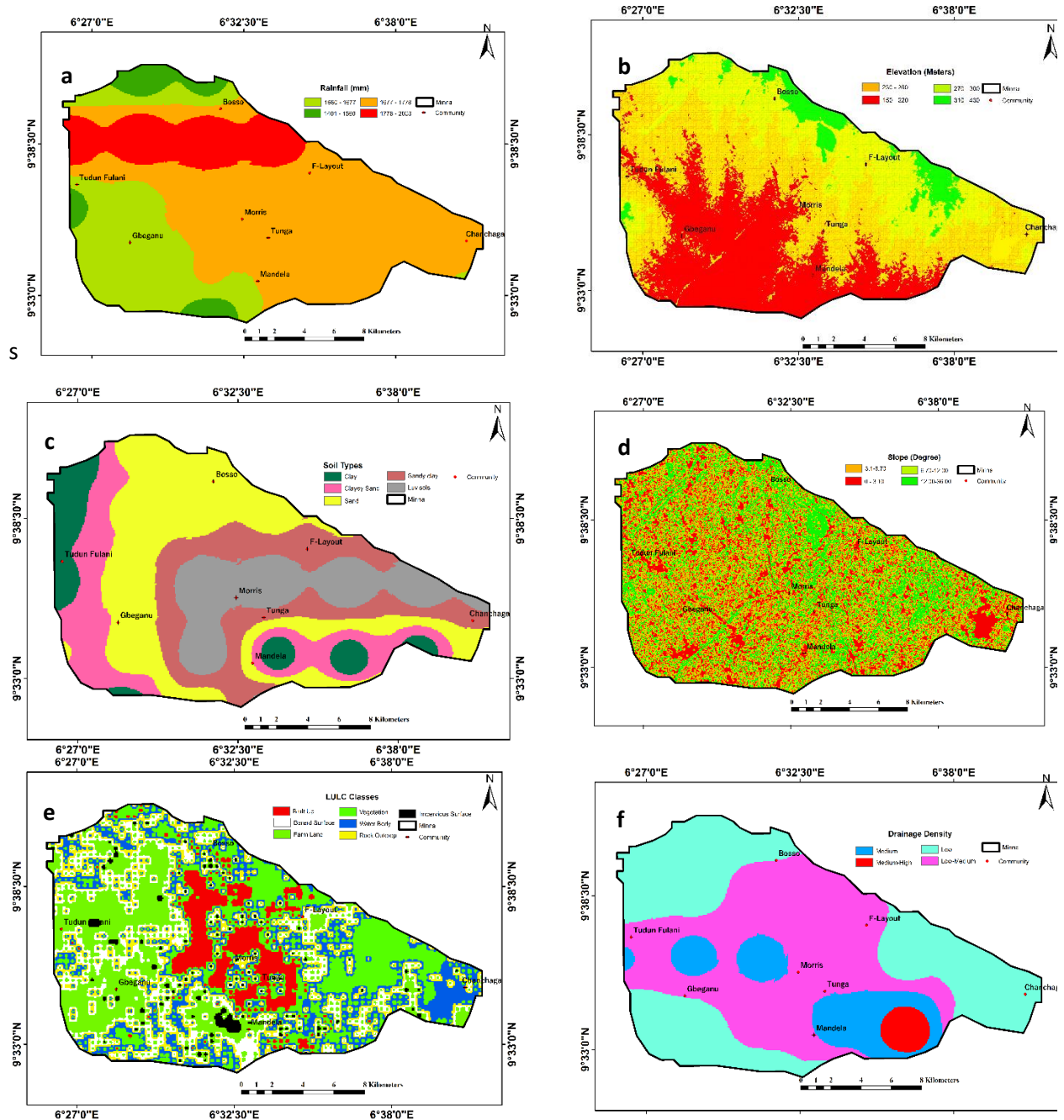


Figure 2: Surface runoff generation criteria map; (a) rainfall; (b) elevation; (c) soil types; (d) slope; (e) LULC and (f) drainage density map

RESULTS AND DISCUSSION

Six major factors were identified as the main contribution to the process of runoff generation process in urban environment; Elevation, slope degree, precipitation, LULC, soil and drainage density. The weights of evidence were then assigned to the identified factors as explain in Table 1 to the corresponding factors. A pairwise comparison was calculated for the assigned weights and normalized weight (Equation i and ii) of each of the factors was then determined

and used in the overlay process in ArcGIS environment. Finally, the total runoff vulnerabilities indexes were determined for the overall study area as presented in Figure 3. The overall vulnerability was derived from the combination of the multiple criteria, by applying the normalized weights. Precipitation appears to have the highest normalized weight of 28% follow by elevation and soil of 17% respectively. drainage density has a normalized

weight of 13% while slope degree produced the lowest normalized weight of 10%. Evaluation from the normalized weights shows precipitation to have the maximum impact on urban surface runoff process of the total vulnerability while slope has lesser impact on surface runoff occurrences. The lower normalized weights over slope degree can be related to precipitation and soil and nature of the urban surface that are required for runoff generation process (Yusoff *et al.*, 2009).

Precipitation is a critical element in urban runoff generation especially where there exist a high concentration of buildings and impervious surfaces. The amount of precipitation although does not show equal distribution over space but provides information critical to support decision making in designing of drainages to reduce runoff concentration. Areas with poor drainage system including Tunga farm center, Sauka Kahuta and Kpagungu community are often faced with challenges of high runoff generation with annual occurrence in the month of August to September due to prolonged high intensity and long duration of precipitation. This disaster when occur, often result to the submergence of large expense of land with huge cost implication to lives and properties. Extended rainfall duration with poor drainage condition that can evacuate runoff contribution from buildings, roads and other artificial impervious surfaces will lead to rise in the level of water accumulated. This becomes more devastating when there are absent of evacuation channels causing saturation of soil from water infiltration and accumulation of silt characterize by poor network of void that are necessary for effective infiltration of water. Increase in impervious surfaces creates a huge land transformation from high infiltration capabilities to a poor city incapacitated percolation type. The incessant poor drainage blockages, lack of artificial lake capacity to serve as temporary storm water storage, refuse

dump in the few existing drains, dumping of refuse and sewage and obstruction of sewage from cabling and water distribution system are among many of the numerous challenges affecting effective drainage water evacuation capacity. The erosive capability resulting to the collapsing of road into river was also observed as a common phenomenon. Noticeable is the correlation of higher runoff in a sloppy ground with under drainage capacity and availability of impervious surfaces.

Figure 3 is the runoff susceptibility index map produced for the study area shows the present of five (5) classes of susceptibility; the very low; low; medium and high vulnerability area. Region of very low surface runoff susceptibility cut across some part of Tudun Fulani, Gbegenu and Timber market in Mandela community. The low vulnerability at these communities are related to isolated impervious surfaces, low drainage network and low level of buildup concentration which create an effective infiltration of surface water during precipitation events. The low susceptibility region shares similar lithological, physical characteristics with slight difference in the concentration of building and *caluvas* which provides a conveyor belt during which excess water can be evacuated from the surface. The medium and vulnerability coincides with areas with large concentration of buildup as: residential, commercial, government buildings and worship centers. The surfaces of this region are characterized by well concrete surfaces that hinder infiltration and evacuation of surface area. It is worthy to note that the existing large artificial drainage at the city and some part of Bosso draining through FUT Minna, and Keteren Gwari community help in the evacuation of large surface runoff. However, the development at the upstream region with high contribution to runoff has greatly degraded the runoff evacuation capability of the existing drainage network.

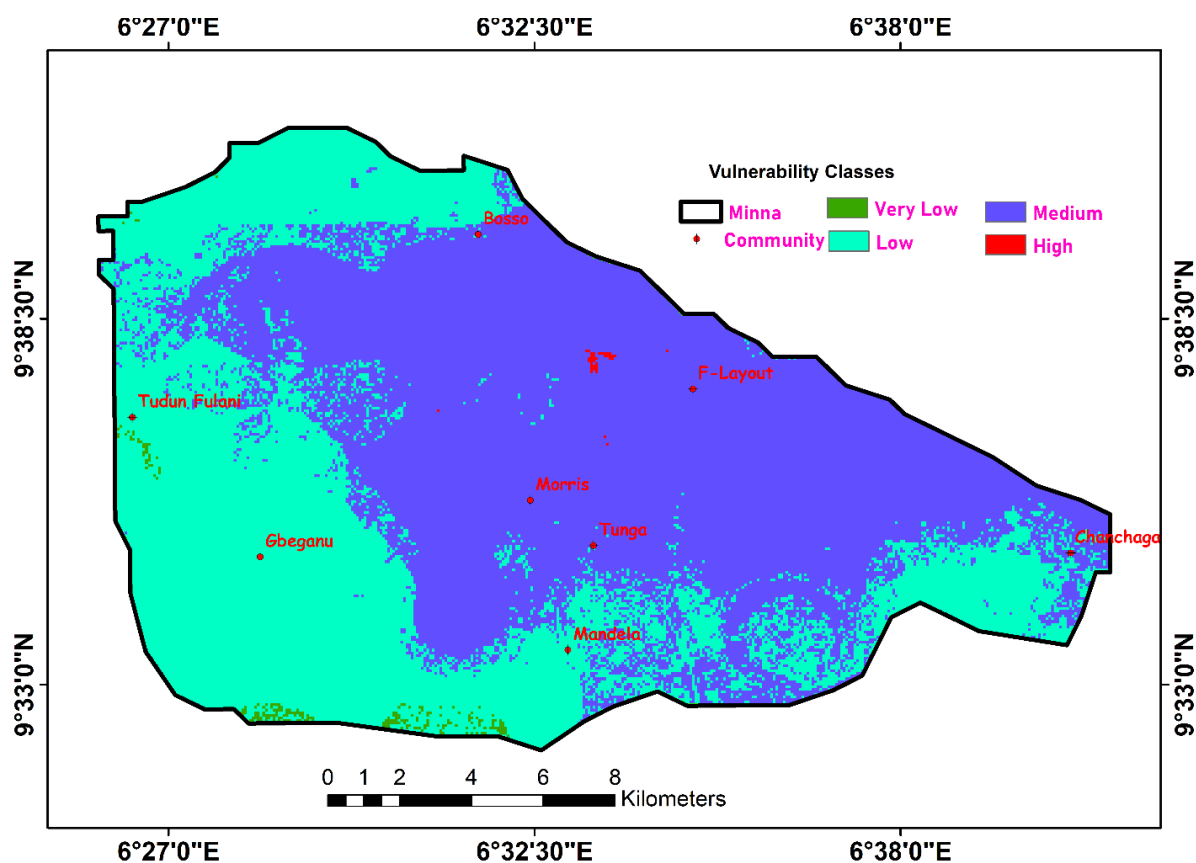


Figure 3: Surface runoff susceptibility map for the study area.

Conclusion

GIS-based MCDA surface runoff susceptibility mapping within an urban area provides a hybrid approach for the estimation of high runoff prone area, thus, providing a framework that help town planners and decision makers to focus in the highly vulnerable areas for detail assessments. The used of this approach provides a highly efficient, reliable, cost-effective and relatively accurate methodology to effectively reduce cost demands for sustainable urban storm water management. Heavy precipitation over a short period of time with poor drain capabilities provide a favorable ground for faster runoff in urban environment. The result of the study show that high urban surface runoff region correlates strongly with impervious areas. Moreover, substantial region of the study area falls into areas of high runoff vulnerability while only few isolated communities fall within the high susceptibility class. The methodology implemented shows that understanding of surface runoff susceptibility mapping from precipitation, criteria of stream density, slope, LULC types, elevation, soil types and

precipitation are adequate in delineating reliable surface runoff areas. However, precipitation is most critical among these criteria that influences surfaces runoff.

Conflict of interest

This research did not report any conflict of interest

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