



Original Research Paper

GIS-based MCDA for Gully Vulnerability Mapping Using AHP Techniques



Ishaku Yakubu Bashir^{1*}, Rachel Osesienemo Sallau¹, Abubakar Danjuma Sheikh², Zuni Aminu³, Shu'aib Musa Hassan⁴

1. Department of Geography, Faculty of Natural Sciences, Ibrahim Badamasi Babangida University, Lapai, Nigeria.
2. Department of Geography, Usman Danfodio University, Sokoto, Nigeria.
3. Department of Geography, Federal University Birnin Kebbi, Kebbi State, Nigeria.
4. Department of Geography and Environmental Sciences, University of Abuja, Nigeria.

Abstract

This paper explores the potentiality of GIS-based Multi-Criteria Decision Analysis (MCDA) and Analytical Hierarchy Process (AHP) for gully vulnerability mapping. Multilayer information of basin characteristics, such as drainage density, Topographic Wetness Index (TWI), Stream Power Index (SPI), slope aspect and land use land cover (LULC), were used in this study to develop a Gully Vulnerability Index (GVI). A weighted approach was implemented on each criterion relative to their inferred influence on gully vulnerability and validated by determining the Consistency Ratio (CR). Findings show a varying magnitude of gully vulnerability across the study area. The low to medium gully vulnerability class was dominant covering a land area of 6557ha (21.25%), and mostly confined to developed areas. Still, it is noteworthy to observe that the severe gully vulnerability class covers a substantial land area of 5825ha (18.88%), which presents a great risk to infrastructural development and human settlements in the study area. The study has a model predictive capability with accuracy rate of 84.62%. The integration of the MCDA and AHP into GIS workflow is an effective approach critical to minimize the limitations associated with gully occurrence analysis, using a singular basin characteristic. The results obtained in the study will equally be important in determining gully risk zones, circumspect urban development, tracking and proper infrastructure construction plans for long-term gully disaster mitigation.

Article history

Received: 27 August 2020
Revised: 12 October 2020
Accepted: 13 October 2020

Keywords

AHP;
Basin characteristics,
GIS;
Gully Vulnerability
Mapping;
Multilayer;
MCDA.

Editor(s)

M. A. Siddiqui,
Vijay Bhagat

1 INTRODUCTION

Land degradation and erosion have become an ever increasing occurrence as global populations rise and human activities geared towards satisfying social and economic demands. These activities may result in the exposure of land surfaces, thus increasing the vulnerability of land surfaces to water erosion. Water induced soil erosion has been considered as a major cause of loss of land across the global environment (UNCCD, 1994; Valentin *et al.*, 2005; Dreibrodt *et al.*, 2010; Handl, 2012; Ambalam, 2014). Emerging from the soil erosion research in the last few decades, is an attempt to develop different methods and techniques for

effective testing and monitoring of soil erosion and gully occurrence (López-Vicente *et al.*, 2013; Lal, 2017; Arabameri *et al.*, 2018).

A gully may be defined as the expulsion of soils on drainage paths as a result of surface runoff. These soils are transported by the means of head ward or by slumping of the drainage banks (Pokhara, 2008; Araki, 2012; Casali *et al.*, 2015). It occurs as a concentrated movement of water along an eroded channel expunges soils and parent material that may have been too bulky to be destroyed by cultivation practices (Conoscenti *et al.*, 2014; Casali *et al.*, 2015). Gullies appear

* Author's address for correspondence

Department of Geography, Faculty of Natural Sciences, Ibrahim Badamasi Babangida University, Lapai, Nigeria.
Tel.: +234 9060995569

Emails: ishakubashiryakubu@gmail.com (B. Yakubu -Corresponding author), osesie@gmail.com (S. Osesienemo); sheikh.abubakar@udusok.edu.ng (S. Danjuma); aminuzuni@yahoo.com (A. Zuni), shuaibhassan123@gmail.com (H. Musa).

<https://dx.doi.org/10.21523/gcj5.20040201>

© 2020 GATHA COGNITION® All rights reserved.

as one of the most damaging and complex effects of water erosion. It is known to be the major source of sediment load deposition in a reservoir (Mohsen *et al.*, 2018). In recent times, gully erosion has appeared to be responsible for a substantial loss of properties including; buildings, farm lands and other basic infrastructures (Ajaero *et al.*, 2010). The economic worth of these properties is estimated to be well over a million dollars per annum (Ayele *et al.*, 2015; Goudie, 2018; Medvedeva *et al.*, 2018; Peterson *et al.*, 2018).

Alatorre *et al.* (2012), Shit *et al.* (2015), and Wang *et al.* (2016) have documented some of the major expository environmental factors influencing gully development and dynamics. They are related to precipitation in the form of rainfall, soil, topography, soil moisture, soil erosivity factor, lithology and the prevalent land use land cover (LULC) types in a given area. Rainfall and elevation patterns are the most critical factors that influence surface runoff (Shi, *et al.*, 2017; Xiong, *et al.*, 2019; Pei *et al.*, 2020). Rainfall provides the amount of energy required to transport generated sediments down slope; resulting in lateral and vertical erosion between the generated sediment load with the channel wall and bed. Post *et al.* (2017), Abdulazeez *et al.* (2018), Arabameri *et al.* (2018); Mahmud and Umaru (2018), and Frankl *et al.* (2019) have reported the effects of gully formation on the environment, LULC, properties and infrastructure, using ground measurements and space-based data. The finding points to a scientific approach for the integration of multiple datasets towards effective management of gully occurrence. In addition, Arabameri *et al.* (2018) discussed the approaches that can integrate multi-layer information of basin characteristics with high levels of accuracy, in relation to gully expansion and intensity. The stability of a gully depends on the stream erosive process; they include the eroded material from the upstream and any sediment that may grow from the head-cut and channel bottom. Gully occurrences are largely associated with a condition where geomorphic threshold is exceeded due to growth in the inflow of erosive water and sediment erosive capabilities (Huang *et al.*, 2005; Kirkby and Bracken, 2009; Gao *et al.*, 2010; Essien and Okon, 2011; Herzig *et al.*, 2011).

In addition, the nature and distribution of soils and other subsurface materials, the ground steepness, and saturation levels are largely responsible for the circulation of underground hydrology, which provides a suitable drainage controlling factor regime of a location (Kakembo *et al.*, 2009; Daggupati *et al.*, 2013). These conditions are responsible for the regulation of gully morphology amidst the susceptibility of different soil horizons at varied erosive conditions (Conoscenti *et al.*, 2014; Arabameri, *et al.*, 2018). In assessing the contribution of gully occurrence to erosion in a tropical environment, the depth and width characteristics are critical parameters that determine the dynamics of erosion. The interception of a linear infrastructure such as roads and rail lines can form node points where

overland flow converges and focuses on the downstream slope (Svoray and Markovitch, 2009; Svoray and Ben-Said, 2010; Izham *et al.*, 2011; Svoray *et al.*, 2012; Torri and Poesen, 2014; Gudino-Elizondo *et al.*, 2018).

The heterogeneous attributes of gully instability have necessitated the need for modeling of its dynamism (Maquaire *et al.*, 2003; Sidorchuk *et al.*, 2003; Valentin *et al.*, 2005). Studies that have explored this includes: the empirical models (Jetten *et al.*, 2006; Conoscenti *et al.*, 2014; Pourghasemi *et al.*, 2017), the routine for linear gully erosion models (Kheir *et al.*, 2007; Evans and Lindsay, 2010), and lastly gully morphometric analysis which largely utilizes surface drainage data (Gabet and Bookter, 2008; Jha and Kapat, 2009; Vachtman *et al.*, 2013). The primitive assumption of the later model is based on the *insitu* based measurements, where different gully inventory data is generated and evaluated for quantification. The morphometric measurements are based on the use of drainage pattern information which utilizes the nature of sediment load characteristics. Drainage based models for gully related studies require quantitative evaluation of water volumes, passing through the drainage and the composition of the transport sediment load which can vary over time (Vaezi *et al.*, 2017; Chang *et al.*, 2018; Caracciolo, 2020). Detailed knowledge of these parameters can effectively reveal a great deal of information, regarding lateral and vertical erosion which influences gully dynamics. Although, these models have provided an effective frontier for the study of gully erosion, the use of empirical data synonymous to models are often grossly inadequate which affects model generalization. Similarly, the use of surface runoff and sediment load characteristics is often difficult to come by and some of the required data points are difficult to access. Evidence-based models still tend to possess uncertainties such as the potential of bias induced weight and the absence of a spatial scope of the area of interest. These uncertainties have the potential of significantly limiting their application, and in addition they justify the application of a geospatial model which will efficiently handle the local limitations, in the absence of model testing and performance. Lucà *et al.* (2011); Conoscenti *et al.* (2013); Conoscenti *et al.* (2014); Dube *et al.* (2014); Rahmati *et al.* (2016) and Zabihi *et al.* (2018) have presented a wide range of techniques including inferential statistics using bivariate data, that can effectively test the reliability of model parameters. In addition, the developed models allow for the regional analysis of gully trends and susceptibility using multilayer information; regarding the different parameters that may influence gully development, management and control. Although, these models were able to overcome the deficiencies associated with the physical model, and were able to provide a technique for quantitatively evaluating the correlation between gully formation parameters and its dynamics using multilayer information, data integration was not effectively provided.

The difficulties associated with the integration of multiple basin characteristics in the assessment of gully vulnerability informed the techniques that allowed for proportional distribution of parameter weight within a given catchment basin. Kavzoglu *et al.* (2014), Valjarević *et al.* (2015), Arabameri, *et al.* (2018), Arabameri *et al.* (2019), and Vijith and Dodge-Wan (2019) have implemented a GIS-based multi-criteria technique for gully morphometric analysis and assessment by assigning weights to different parameters using the AHP using Saaty (1980) scale. This scale has the advantage of effectively managing the assigned weights to parameters without bias. It determines the consistency ratio (CR) and consistency index (CI) by managing assigned weights through validation. In addition, multiple criteria can be effectively validated with a high degree of reliability and generalization. In terms of model testing, accuracy assessment can be conducted and when applied in modeling, sensitivity analysis can effectively be evaluated to ascertain the level and extent of model reliability. Recent advances in the use of AHP and MCDA based research has focused largely on the management of bias during weight assignment to a parameters. Dashti *et al.*, (2013); Asakereh *et al.*, (2014), Hadji *et al.*, (2017) and Chabok, *et al.*, (2020) employed fuzzy logic in the validation and justification of weight assignment, proving the viability of MCDA and AHP in the evaluation of weights among independent parameters considered to influence the dependent parameter under study.

It is against this background that the research explores the potentiality of remote sensing data, physical data, meteorological and pedological information along with other auxiliary data in modeling gully dynamics in Minna, Niger state. This study seeks to develop a MCDA and AHP technique for the integration of bivariate data sets as an accurate and easy to use in modeling. This will provide a logical rationale for the implementation of sustainable environmental management. The principle of MCDA and AHP provides an effect-based evaluation of all critical parameters that influences the gully instability. In addition, the approach provides a methodology of managing the multiple parameters, by reflecting the magnitude of each in the understanding of gully occurrence.

2 STUDY AREA

Minna is located on 09° 33' 00" to 9° 45' 30" N and 6° 27' 00" to 6° 48' 15" E with a total area of 20.44 km² (Figure 1). The study area is circumscribed towards the East by Paidia 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 m above sea level and a steep slopes within the borders East of the study area. The location is characterised by the wet and dry season. During the wet season, precipitation is experienced upto 2003 mm per annum within a period of six months of the average. The dry season is often characterized by an absence of precipitation, fast moving winds with characteristics of dryness and of North Easterlies Origin at the early onset of dryness. Temperature in the study area varies significantly in response to the season. The mean annual temperature is between 28 to 36°C. In terms of slope, the study area is dominated mainly by a gentle slopes.

3 MATERIALS AND METHODS

3.1 Criteria

The flow chart (Figure 2) describes the procedure employed in the research data collection and, data sets used and the analysis techniques. Physical parameters in this study refer to: gully inventory data, elevation, rainfall, topography, drainage network data, soil and LULCT as it relates to socio-economic activities.

3.1.1 Morphometric Characteristics

Gully erosion regimes and behavior occur in response to surface runoff, erodability of the surface/sub-surface cover, coupled with several geo-environmental factors associated with its development. The determination of these behavioral attributes along with other geo-environmental conditions is critical to reliability of any gully dynamic modeling analysis. This study therefore, explored the extensive field survey and other conditioning factors to enable the derivation of the criteria for modeling. To this end, gully points were identified using High Resolution Remote Sensing Imagery (HRRSI) of Minna acquired in 2016 with a spatial resolution of 5 m. Using image analysis techniques sequel to correction and ratification, the identified points were based on inference from the spectral characteristics of the features on the image. Total of 186 gully points was identified, out of which a ground trotting exercise was embarked on to identify the validity of the identified gully potential points, as well as generate gully inventory data. A Garmin Handheld Global Positioning System (GPS) was used in tracking and locating the identified points. A measuring tape was also used in determining the gully morphometric data (length, depth and width) after a series of correction of the tape calibration for accuracy. The generated information was coded and developed into a geo data base. Information related to topography was exploited from contour survey maps of Minna, Niger State on a scale of 1:250,000 and a Digital Elevation Model (DEM) of 20 by 20 cell sizes obtained from the Synthetic Aperture Radar, of the Shuttle Radar Topography Mission (SRTM). These were applied in the process of the extraction of slope degrees, elevation, drainage density and distance from infrastructure which were processed and produced into varieties of maps.

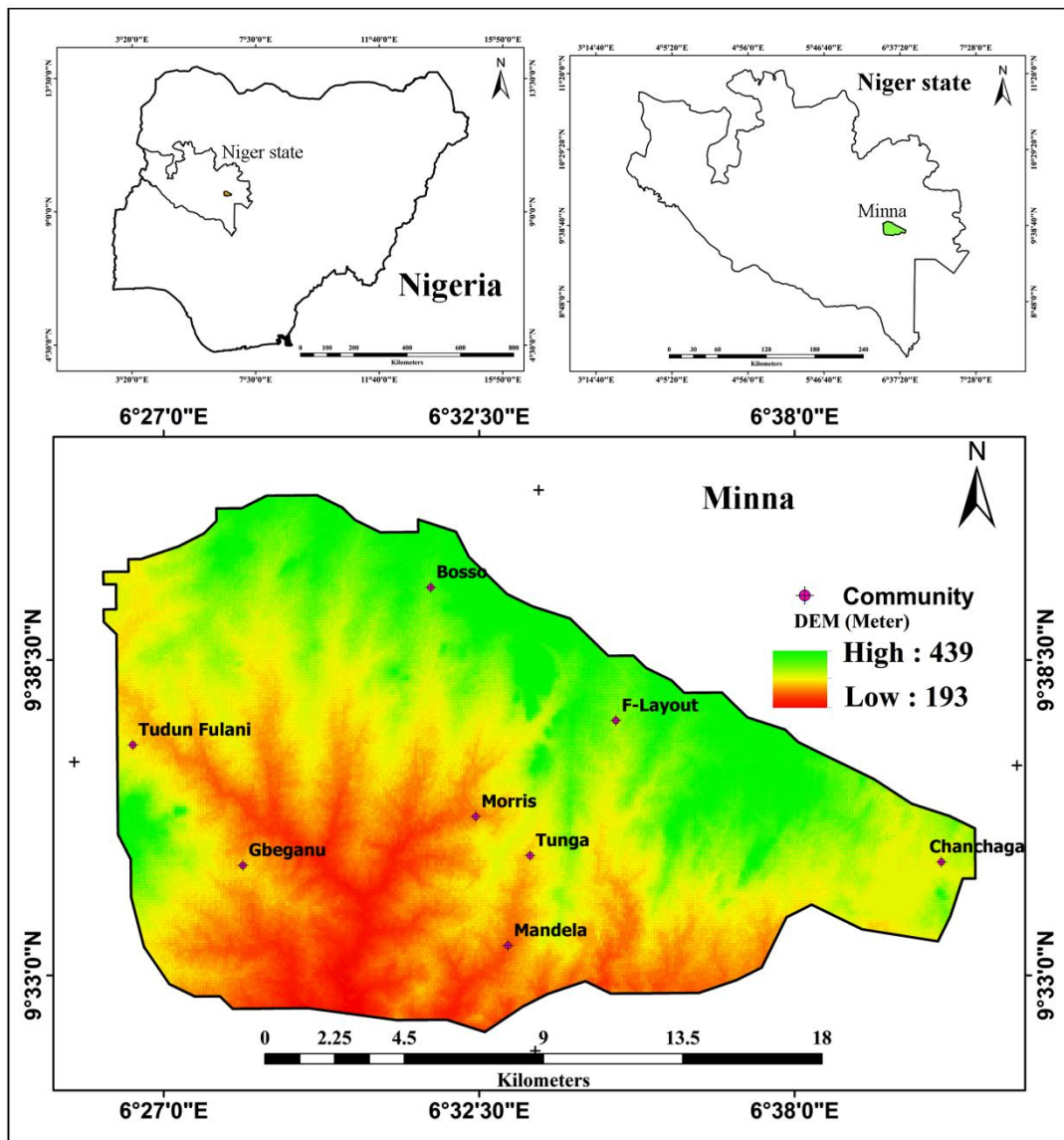


Figure 1. Study area: Minna from Nigeria

3.1.2 Soils

Soil is a critical parameter in the modeling of erosional driven hazards. These properties are associated with the morphological evolution of land features. According to Omid et al. (2016) gullies are dependent on the nature of the prevalent soils and lithology of an area. To explore this further, the soil map of Niger state was collected from the Faculty of Agriculture, Ibrahim Badamasi Babangida University Lapai, Niger State. ArcMap version 10.5 was used to extract the soil map of Minna, Niger State as presented (Figure 3). The processed soil data was validated using other existing pedology data sourced from the State Ministry of Agriculture and Rural Development, along with soil ground control points.

3.1.3 Land Use Land Cover (LULC)

LULC and their management are key components of the hydrological conditioning process of a given location. It is also known to impact on the geomorphological structure instability to gully occurrences (Omid et al., 2016). In general, bare or poorly vegetated surfaces when accompanied by substantial variation in elevation and precipitation are highly vulnerable to erosion. In contrast, densely vegetated surfaces with the same lithological characteristics have vegetation retarding the action of surface flow. This relationship sequence indicates that a negative to low correlation may exist between a densely vegetated surface and erosion, while a positive correlation exists between bared and poorly vegetated surfaces to erosion (Lucà et al., 2011; Sougnez et al., 2011). The acquired satellite data used in this study are presented in Table 1. They are Landsat-7

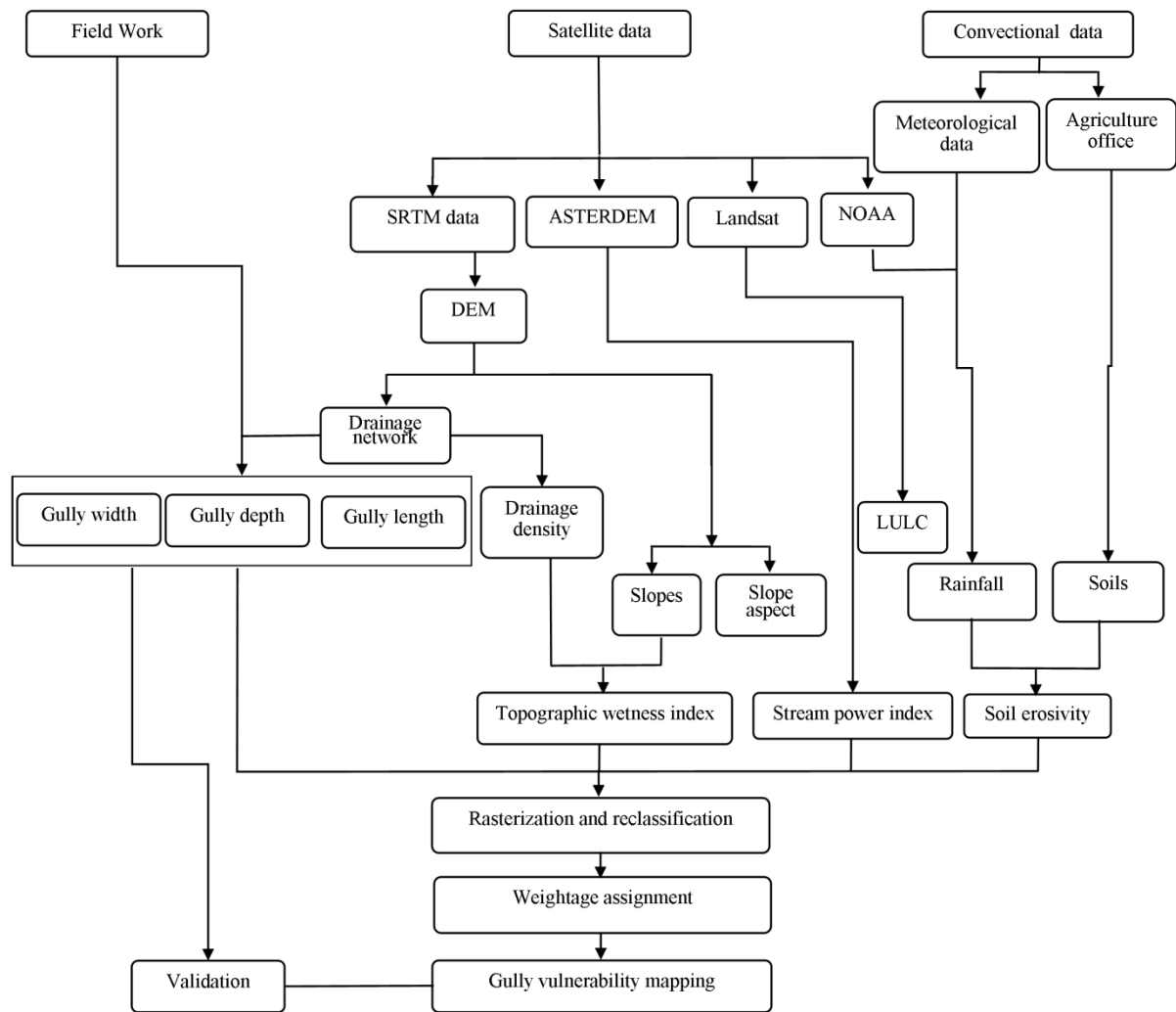


Figure 2. Methodology

Enhanced Thematic Mapper Plus (ETM+) and Landsat-8 Operational Land Imager/Thermal Infrared Sensor (OLI)/TIRS images, in C1 level-1. The satellite data was collected for years of 2017 and 2018 in band 7 and 11, respectively.

The processed images were subjected to radiometric and geometric correction to minimize cloud, smoke and dust haze that cause misclassification. The corrected images were then classified using supervised classifications. The result revealed seven (7) major kinds of LULC (Figure 3) in the study area as: built up, vegetation, farmland, water body, outcrop, bare and impervious surfaces. Based on this classification, substantial parts of farm lands tend to be highly gully vulnerable areas, while the built up areas which were the most dominant land use type possessed moderate gully points. Preliminary change detection matrix of the LULC changes is in agreement with the findings of Bashir et al., 2018. They show an increase in urbanization and agricultural land use in the study area; while both activities are found to be encroaching into natural vegetation and some isolated forests.

3.1.4 Topography

Topographical variables are driving parameters of gully erosion; they enhance the development of fissures; which could be used to envisage gully sidewall instability (Shit et al., 2015). Topographic factors refer to the product of slope length and steepness gradient. Slope refers to the distance from the originating point of overland flow to the point where gradient decline substantially retards erosion and increases deposition (Wischmeier and Smith, 1978). In addition, slope was considered in this study to allow for the inference of soil loss volume from a given length of slope over land of a known elevation. For this analysis, a 10 m Digital Elevation Model (DEM) obtained from the Shuttle Radar Topographic Mission (SRTM) was used to derive slope data. The state ministry of lands and housing provided the topographical map of the study area; and this was used to extract the contour information which has great potential in understanding terrain condition. The derived slope distribution information was reclassified into four classes for weighting and rating based on MCDA and AHP.

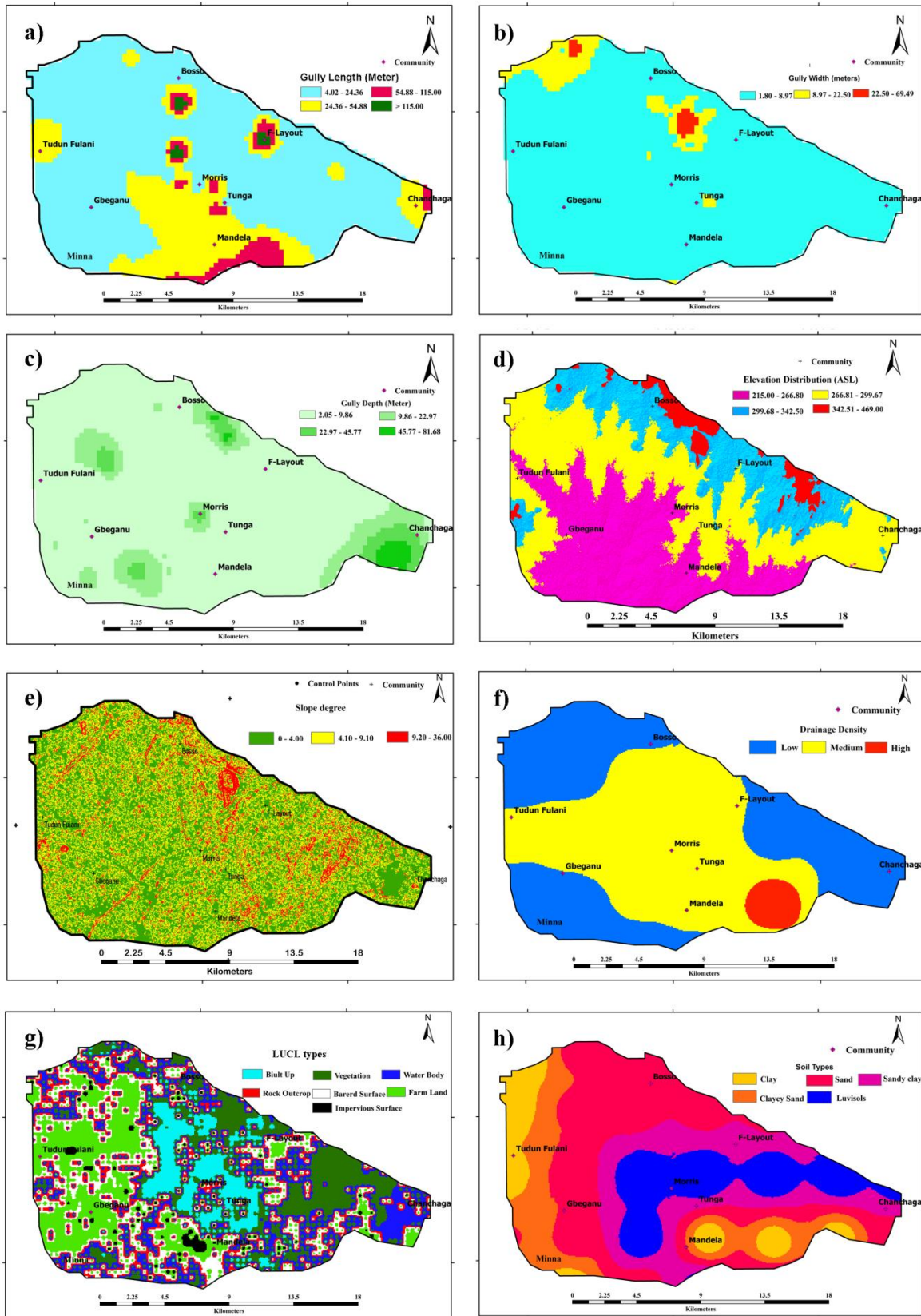


Figure 3. (a) Gully length, (b) Gully width, (c) Gully depth, (d) Elevation, (e) Slope, (f) Drainage density, (g) LULC, (h) Soil types

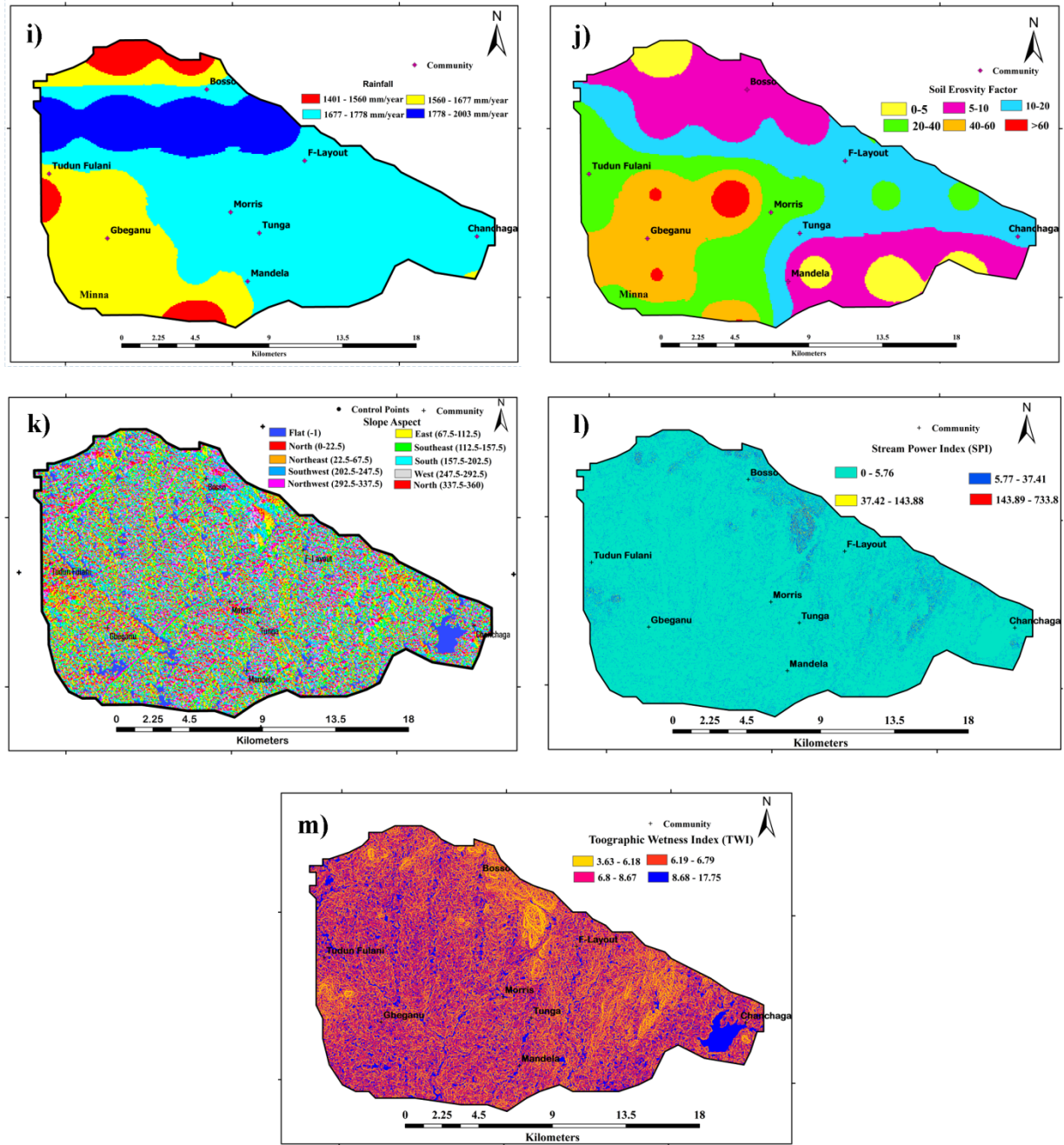


Figure 3. (i) Rainfall distribution, (j) Soil erosivity factor, (k) Slope aspects, (l) Stream power index, and (m) Topographic wetness index

Table 1. Landsat metadata

Sensor	Landsat-7 ETM+	Landsat-8 OLI/TIRS
Landsat product identifier	LE07_L1TP_189053_20171020_20171115_01_T1	LC08_L1TP_189053_20180116_20180120_01_T1
Landsat scene identifier	LE71890532017293SG100	LC81890532018016LGN00
Sensor identifier	ETM	OLI_TIRS
Acquisition date	2017/10/20	2018/01/16
Path and row	89/053	189/053
Spatial resolution	30 X 30m	30 X 30m

3.1.5 Drainage System

The drainage information used in this study was generated using GIS-based watershed analysis techniques. The study area was delineated and drainage networks were extracted using two major data sets: The DEM and Landsat 7 ETM. The data was subjected to analysis using HEC-GeoHMS tool and the delineated drainages were dissolved into a single data set. A drainage density network analysis was derived from equation 1. Each drainage path was considered and reconditioned into a known cell size within a given grid. The center of the grid approach has the advantage of ease of tracing stream erosion capabilities and thus, enables the linking of erosive power to a cell within the area (Baker et al., 2018; Warren et al., 2019; Garlin et al., 2019). Although the work of Mohsen et al. (2018) indicated the possibilities of using pixels rather than center of a grid in evidential layers, this approach becomes highly degraded due to the inability of the approach to manage slight variation in information flow between two cells. In addition, while the evidential base is capable of managing boundary issues in data flow, the pixel approach makes ambiguous generalizations across all pixels within the area of interest.

$$\text{Drainage density } (\rho) = \frac{\sum l}{A} \quad (1)$$

Where, l = total length of stream in (km), and A = cross sectional area (km²)

3.1.6 Universal Soil Loss Equation (USLE)

The precipitation data used in this work comprises of rainfall data sets which were obtained from three Nigerian Meteorological Agency (NIMET) stations viz.: Minna airport, Bida and Abuja. Other rainfall data used to supplement the NIMET data were obtained from (1) The Department of Geography, Ibrahim Badamasi Babangida University Lapai weather station. (2) The Agricultural Development Program Observatory Station. (3) The Niger State Ministry of Water Resources Observatory. Furthermore, due to the scanty nature of the obtained rainfall data, remotely sensed data from the National Oceanic and Atmospheric Administration (NOAA) was processed for a 5 year period. The mean annual rainfall for the period under review was then integrated into the grids, which was converted into rainfall density maps using attribute tools in the GIS environment.

The soil information was used with rainfall data for the estimation of the rainfall erosive factor for the USLE in equation 2 to produce a map of erosive factor in Figure 3.

$$EI_{ix} = (KE \times I_x)/100 \quad (2)$$

Where, KE = Kinetic energy of rainfall is expressed as $KE = 210.3 + 89 \log I$, I = Rainfall volume in (cm³), I_x = Maximum volume of the rainfall event and x = Rainfall duration in minutes.

3.1.7 Topographic Wetness Index (TWI) and Stream Power Index (SPI)

TWI is the spatial distribution showing the zone of saturation and the points of surface runoff generation. Utilization of TWI and SPI provide a viable indicator to understand areas of ephemeral gullies in a watershed. Thus, an area with larger upslope drainage and a shallow slope will produce higher TWI values. This is indicative of a more likely tendency for runoff. TWI value distribution can be used to identify the relative runoff potential zones and catchment (Ågren et al., 2014; Koriche and Rientjes, 2016; Raduła et al., 2018). This model performs optimally when integrated with soil maps to overcome the deficiency of low performance over poorly drained soils (Kakembo et al., 2009; Daggupati et al., 2013). The TWI of the study area was computed using equation 3 and the result generated is presented in Figure 3. The result reveals varying degrees of wetness across the study area with the largest proportion dominated by a wetness index of 6.80 to 17.56. The low index value was prevalent in some isolated elevated areas and among the exposed rock outcrops in the study area indicating low wetness.

Stream Power Index (SPI) on the other hand, measures the erosive power of a surface runoff based on the hypothesis that the discharge rate is proportionate to the basin. SPI provides an insight regarding net erosion in a catchment basin and the peripheral convexity with net deposition in locations of profile concavity (Pourghasemi et al., 2013). It is the major erosion dominating factor in varying slope areas and a hypothesis for the indication of available potential energy to retain sediments (Dube et al., 2014). This study therefore implemented GIS based determination of SPI using the ASTERDEM (Advanced Space-borne Thermal Emission and Reflection Radiometer Digital Elevation Map) of 30 m as found in equation 4. A cell size of 0.001 and a pixel of 30 were used based on Moore et al. (1991) approach. The result obtained was effectively mapped into different SPI values of the study area as seen shown in Figure 3.

$$TWI = \frac{\ln \alpha}{\tan \beta + c} \quad (3)$$

where, α = Cumulative upslope drainage area per unit contour length, β = Surface slope or gradient of the area and c = Cell size (0.001).

$$SPI = \alpha \times \tan \beta \quad (4)$$

3.1.8 Slope Aspect

The slope aspect map in this study was produced to demonstrate the relationship between gully occurrence and the slope orientation within the study location. Nine (9) thematic layers were derived from the slope aspect as shown in figure 3. About 9 classes correspond to: Flat (-1), North (337.5-360)°, North West (292.5-337.5)°, North East (22.5-67.5)°, South (157.5-202.5)°, South West (202.5-247.5)°, South East (112.5-157.5)°, West (247.5-292.5)° and East (67.5-112.5)°.

3.2 MCDA Weight Determination Using AHP

AHP as developed by Saaty (1980) was used to determine the weight of each factor. The relative weight of the pair wise comparison valued on scales 1-9 is shown in Table 2 and this is used to determine the scores. These scores are assigned based on ranking of contribution to the gully vulnerability index. Due to the subjective nature of criteria weights judgments, there exists a high potentiality of bias resulting in some degree of inconsistency in the assigned weights. Hence, the need for the revalidation of judgments by evaluating the logical consistency of the pair wise comparison matrix (equation 5). Normalized pair wise evaluation matrices of the allotted weights to the specific features were used to derive the Eigen vector as shown in Table 2. Matlab (2010) was used to deduce the Eigen vector values (equation 6) for each of the map themes. The relative importance of the factors under study was shown in the pair wise comparison.

$$\begin{bmatrix} 1 & x_{12} & x_{13} & \dots & x_{1n} \\ 1/x_{21} & 1 & 1/x_{23} & \dots & x_{2n} \\ 1/x_{31} & 1/x_{32} & 1 & \dots & x_{3n} \\ \vdots & \vdots & \vdots & \dots & \vdots \\ 1/x_{n1} & 1/x_{n2} & 1/x_{n3} & \dots & 1 \end{bmatrix} \begin{bmatrix} W_1 \\ W_2 \\ W_3 \\ \vdots \\ W_n \end{bmatrix} \quad (5)$$

and the Eigen value was obtained as follows:

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^n \left(\frac{\sum_{i=1}^n \text{row entry of } AW}{i\text{th entry of row}} \right) \quad (6)$$

The consistency index (CI) refers to the measure of consistency. This was derived using the equation 7 (Saaty, 1980).

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (7)$$

Where, n= Number of factors, λ_{max} = Eigen value.

Therefore, if the CI value is less than 0.1, the judgments are said to be consistent and there will be no need for re-evaluation. Thus, the result obtained from this step was used since they were consistent.

The consistency ratio (CR) was determined using the relation:

$$CR = \frac{CI}{RI} \quad (8)$$

Where, CI represents the consistency index, RI represents the random consistency index with a value of 0.58, for n = 3 (Saaty, 1980).

Each of the parameters were weighted and scored using the rating 1-6, accordingly. The rating R was assigned and validated using expert vetting according to the order of priority of influence on gully events and dynamics.

3.3 Estimation of Gully Vulnerability Index

The final map was developed using:

$$GVI = \sum W_i R_i \quad (9)$$

Where, W_i refers to the weight of the gully in parameter i and R_i refers to the score rating of parameter i .

The estimation of the Gully Vulnerability Index (GVI) was developed using a weighted linear combination in equation 9. The normalized weighting of each of the selected criteria and the potentiality parameters relative to each of the selected criteria, was then calculated to obtain the total weights of the different factors (Figure 3) using weighted linear combination approach in equation 10 and presented in Table 3.

$$GV = E_{NW}E_i + S_{NW}S_i + RF_{NW}RF_i + SL_{NW}SL_i + LULC_{NW}LULC_i + DD_{NW}DD_i + GC_{NW}GC_i + SA_{NW}SA_i + SPI_{NW}SPI_i + EF_{NW}EF_i + TWI_{NW}TWI_i \quad (10)$$

where, GV is Gully Vulnerability, E is Elevation, S is soil, RF is Rainfall, SL is slope, LULC is the Land Use Land Cover Type, DD is the Drainage Density, GC is the Gully Characteristics, SA is the Slope Aspect, SPI is the Stream Power Index, EF is the Erosivity Factor, TWI is the Topographic Wetness Index, NW is the Normalized Weight and i is the weight of individual factor.

Table 2. Saaty scale of weight assignment

Less important		Equally important					More important	
Extremely	Very strongly	Strongly	Moderately	Equal importance	Moderately	Strongly	Very strongly	Extremely
1/9	1/7	1/5	1/3	1	3	5	7	9

4 RESULT AND DISCUSSION

4.1 Criteria Conditioning

The gully dynamic factors and criteria rating of different classes show the importance of the different classes of the eleven factors. It can be observed from Table 3, that the minimum elevation has a value of 215 m from ASL with the lowest weight of 1. The maximum elevation distribution in the study area was 469 m with the highest weight of 4. Inference from these ratings indicates a strong positive correlation between elevation values and surface erosion. This phenomenon when related to gully occurrence will increase as a result of an increment in elevation and decline in response to a reduction in elevation. The nature of sub-surface lithology/soil is critical to the formation of gully conditions which is often initiated by sheet erosion. The presence of luvisols is a major lithology that is highly susceptible to gully occurrences. Thus, luvisols soil type was scored the highest weight of 6 and sandy clay had a score weight of 4. The most stable soil type that is least susceptible to gully occurrence is clay. Clayey soils have tighter pore spaces that make them resistant to lateral collapse and they are redundant to corrosion, due to movement of lateral particles. Artificially, natural mineral can be combined with organic substances for soil stabilization and enhanced physical and mechanical properties (Gholamiderami et al., 2020). Precipitation inform of rainfall is a major factor and the most active agent of soil erosion in the tropical region (Mancino et al., 2016; Gaubi et al., 2017). It becomes more active when accompanied by highly unstable soil and rapidly changing elevation. Soil types are key determinants of gully conditioning; as they provide erosive surfaces and topographic wetness factors which are necessary for lateral erosion. Slope classes of 9.20-36.00 degrees have the highest weight of 5 and the lowest value of 1. Slope values of 9.20 to 36 degrees, indicate that an increase in slope gradient to a certain value will increase the chances of gully occurrence; and upon reaching a peak value, decreases. The gully points in the study area appear as a linear feature adjoining many of the drainages, except for some few isolated cases around the developed or built-up areas. The gully morphometric parameter of the highest weight (5) is the width. A gully width is likely to expand rapidly thus, destroying any structure along its path and result in increased damage. The capability of LU types in influencing the erosion process is more significant on bare and sparsely vegetated surfaces thus, experiencing rapid erosion, as compared to densely vegetated areas with reduced infiltration and low erosion occurrences (Lucà et al., 2011). Farmland in LULCT was scored 6 and indicative of the maximum weight of criteria in this group. Farmlands are often associated with most favorable conditions of soil degradation due to the destruction of soil particles which make it more vulnerable to erosion.

A high-density (length per unit square area) class was weighted as score 5; marking the highest amongst weights in this category. Higher drainage densities were linked with more vulnerability to gully erosion due to the creation of a favorable wetness necessary for the formation of underground drainages, and the provision of strong erosive (both lateral and horizontal) capability of the adjoining contributions. In SPI, the highest weight of 4 was assigned to the maximum index of 143.88-733.80, representing a peak region of runoff into drainages. The SPI of drainage indicates it erosive power, this is a requisite condition for the formation of gullies especially in a high slope degree with poor soil structure and precipitation. It is expected that the higher the SPI, the more rapid the gully formation will be, especially when the gullies are adjunct to drainages as evident in the study area. In the study area, a TWI of class >8.67 has the highest score of 4, demonstrating a greater likelihood of gully incidence within the study area. In general, a higher TWI is an indication of a higher infiltration rate (Mousavi et al., 2017). This also has potential of facilitating the formation of piping and roof collapse (Mohsen et al., 2018) as a result of a close depression, sink holes, blind gullies. In the TWI scenario, the relationship between gully occurrence, and slopes of >36 degrees, soil and SPI of >140 largely reflect a strong positive magnitude of susceptibility in the study area. In addition, an elevation along with the TWI at a reliable class can also create an enabling environment for a rapid expansion in gully width, especially when these gullies are adjunct to an existing network of streams. In this study, the classes of Soil Erosive Power (SEP) varies from slightly above 0 to a class of 60. The highest criteria weight of sixty indicates a high potentiality of gully widening as the SEP value increases. Lucà et al. (2011); Ganasri and Ramesh (2016) and Gaubi et al. (2017) observed a similar relationship between the severity of a gully occurrence in length, width and depth as SEP increases. Usually, the intensity of gully destruction is largely due to its ability to widen as a result of wind and other forms of erosion such as sheet and rill. Their development may create a sub-surface gully which might sprout up to the surface; consequent to the creation of a large void below the structure or along its path especially in karst regions. Slope aspect is a description of slope inclination orientation. It influences rainfalls, wind Coriolis effects and surface exposure to agents of denudation (Yalcin and Bulut, 2007; and Wang et al., 2015). The slope aspects of the North and North-West were rated as 4 and 3, while the remainder were rated 2; with an exception one which was considered negligible and rated 1. In the study area, the nature of the surfaces along with the soil and climatologically variables make it suitable for the dominance of North and North West; as the slope aspect with the highest erosive power.

Table 3. Criteria and weights

Criteria	Sub-criteria	PIGOD	Rating	NW (%)
Elevation (MSL)	215.00-266.80	Low	1	7.16
	266.81-299.67	Medium	2	
	299.68-342.50	Medium-High	3	
	342.51-469.00	High	4	
Soil	Clay	Very low	1	10.12
	Clayey Sand	Low	1	
	Sand	High	4	
	Sandy clay	Medium	5	
	Luvisols	High	6	
Rainfall (mm)	1401-1560	Low-Medium	1	8.30
	1560-1677	Medium	2	
	1677-1778	Medium-High	3	
	1778-2003	High	4	
Slope (Degree)	0.00-04.00	Relatively flat (Very high)	5	8.56
	4.10-9.10	Gentle slope (low)	1	
	9.20-36.00	High slope (medium)	1	
LULCT	Built-up	Low	4	10.12
	Bared surface	Medium	5	
	Farm land	Medium to high	6	
	Rocky outcrop	Very low	1	
	Vegetation	Low	2	
	Water body	Low to Medium	3	
Drainage Density	Low	Moderate	3	9.31
	Medium	Medium-High	2	
	High	High	5	
Gully Morphology (m)	Length	Medium	2	9.86
	Width	Medium - High	3	
	Depth	High	4	
Stream Power Index	0-5.78	Low	1	5.62
	5.79-37.42	Medium	3	
	37.42-143.88	Medium-High	2	
	143.88-733.80	High	4	
Topographic Wetness Index	3.63-6.18	Low	1	6.01
	6.18-6.79	Low-Medium	2	
	6.79-8.67	Medium-High	3	
	8.67-17.76	High	4	
Soil Erosivity Factor	0-5	Slight	1	7.79
	5-10	Moderate	2	
	10-20	High	3	
	20-40	Very high	4	
	40-60	Severe	5	
	>60	Very severe	6	
Slope Aspect (degrees)	Flat	Negligible	1	3.15
	Northeast	Low	2	
	Southeast	Low	2	

Southwest	Low	2
Northwest	Medium	3
North	High	4
South	Low	2
West	Low	2
East	Medium	3

Note- PIGOD: Potential influence on gully occurrences and dynamics; **NW:** Normalized weights

4.2 Gully Vulnerability Mapping

The implemented method provides us with a technique to generate a gully susceptibility rate on a spatial scale in Minna, Niger State Nigeria. The intricate relationship among gully influencing factors and environmental attributes were adequately accessed using the MCDA and AHP technique by evaluating the different criteria. The consistency ratio and the gully vulnerability index were used to validate the inferential weights assigned to different maps. The spatial distribution of gullies was produced using a substantial number of input variables. For enhanced visual interpretation of the classified gully vulnerability classes, the data was reclassified into a unique thematic map layer using ARCGIS 10.5. Each of the thematic layers was grouped into a class of six representing low, low-medium, medium, medium-high, high and severe vulnerability as depicted in Figure 4.

The low and low to medium vulnerability areas extends from Bosso community to some parts of Gbeganu area of Minna. This region is mostly confined to developed areas. These areas are often characterized by low vegetation, poor water infiltration and low soil erosive factor due to the predominance of impervious surfaces which according to Patil (2018) it significantly retard soil degradation. In addition, the prevalence of clay and clayey sandy soil is most likely to be responsible for the low gully events in the area, due to tighter pore spaces between soil particles which can influence permeability and the subsequent erosion potential of an area (Marot et al., 2016 and Sajedi-Hosseini et al., 2018). The major gully driving factor of the medium vulnerability zone is the nature of the soil which has direct correlation with the soil erosivity factor and slope (Conoscenti et al., 2014 and Zabihi et al., 2019). This result is in conformity with the soil, rainfall and erosion relationship documented in the work of Kirkby and Bracken, 2009; Conoscenti et al., 2014; Aminu and Jaiyeoba, 2016 and Teng et al., 2016. Slope orientation, soil and land surface conditions are intricate but interrelated factors influencing gully development especially in the context of lateral erosion and energy required to transport the generated sediment load along the gully path. The amount and rate of erosion is inversely proportional to gravity which is driven by slope. A higher slope value accompanied by luvisols is highly vulnerable to erosion due to the low particle cohesion. Slopes provide the maximum gravitational force required to transport sediment load either in

suspension or solution along the gully banks by changing from potential energy to kinetic energy.

Medium to high gully vulnerability regions majorly correspond with locations that are well-planned layouts characterized by either poor drainage design or complete absence of drainages. The poor drainage condition accompanied by poor soil particle cohesion provides suitable surfaces for maximum erosion since runoff from buildings are not properly coordinated and controlled along in a designed channel for urban storm water management (Izham et al., 2011). Further, examination of LULCT by this study, revealed dominance of farmland and some isolated cases of built-up areas especially behind army barracks Minna and Mandela compared to the city center. The destruction of the soil structure and texture associated with the clearing of vegetation cover, and poor agrarian practices (Souchere et al., 2003 and Gordon et al., 2008), might have create a conducive condition for the development of gully erosion which often begins in form of sheet or rill erosion; and finally captures the available drainage network in the area. In addition, the constant exposure of the soil to the direct impact of rainfall can further exacerbate the process of soil erosion. The process of erosion and transportation will further result in the widening of gullies, when the floor of the created gully canal collapses. The dominance of lateral erosion and poor soil particle cohesion is largely responsible for the expansion of the gully depth and creating instability in its dynamics.

4.3 Gully Distribution and Vulnerability

The spatial analysis of the output performed in this study, shows a varying magnitude of vulnerability of gullies across the study area as presented in Table 4. The result shows 8.67% of the study area showing low vulnerability, low to medium vulnerability (21.25%), medium vulnerability (13.68%), and medium to high vulnerability (19.47%), high vulnerability (18.06%), and severe vulnerability (18.88%), respectively. The overall analysis shows the dominance of low-medium gully vulnerability area of up to 21.25%. The result of this study by implication, suggests that a substantial level of gully erosion covers the study area, which if not checked might hamper infrastructural development and human settlement in the study area. The narrow margin between the high and severe vulnerability of 18.06% and 18.88% is a clear indication of a similarity in gully occurrence conditions. This condition might have arisen from the homogeneity in precipitation which provides a

similar surface runoff denudation across the similar soil formations.

4.4 Predictive Accuracy and Performance of the Model

In this study, a visual predictive check approach was employed in assessing the accuracy of the developed model's predictive capability. To this end, a total of 60 training samples representing 33% of 180 points were selected for validation. The results obtained are presented in Table 3. The result shows that out of the total of 13 control points where training samples were selected, only three (3) representing 15.38% failed to compared to the obtained model vulnerability prediction results. In addition, ten (10) representing 84.62% were consistent with the map prediction. The high success rate of the predictive capability of the model is an indication of the excellent capability of the developed model in assessing the gully vulnerability in the study area. The accuracy of 84.62% of the predictive capability of the model revealed that GIS-Based MCDA and AHP has an excellent performance value and thus, suitable for gully erosion vulnerability mapping. Further statistical evaluation of the model performance accuracy (Table 4) from a regression plot graph (Figure 5), shows

a high R-square value indicating that, the predicted map and training sample used in developing the model are well fitted. This further indicates that the employed MCDA and AHP demonstrate a high efficacy in gully prediction by integrating a multilayer data set.

5 CONCLUSIONS

This study adds to the academic literature which supports the validity of employing the MCDA and AHP approaches in the understanding of gully occurrence and vulnerability. It further demonstrates the efficacy of evaluating multiple criteria influences (by assigning weights based on ranked importance) on gully development. The findings show an accuracy of 96% (Figure 5), thereby demonstrating the viability of this approach in the integration of physical, lithological and precipitation data, along with drainage characteristics in the understanding of gully vulnerability classes. Even though the low to medium gully vulnerability class (21.25%) was dominant in the study area, it is also important to note that the severe vulnerability gully class covers a substantial area of 18.88%. This has affected the buffer zones in the study area and could create risks to urban growth.

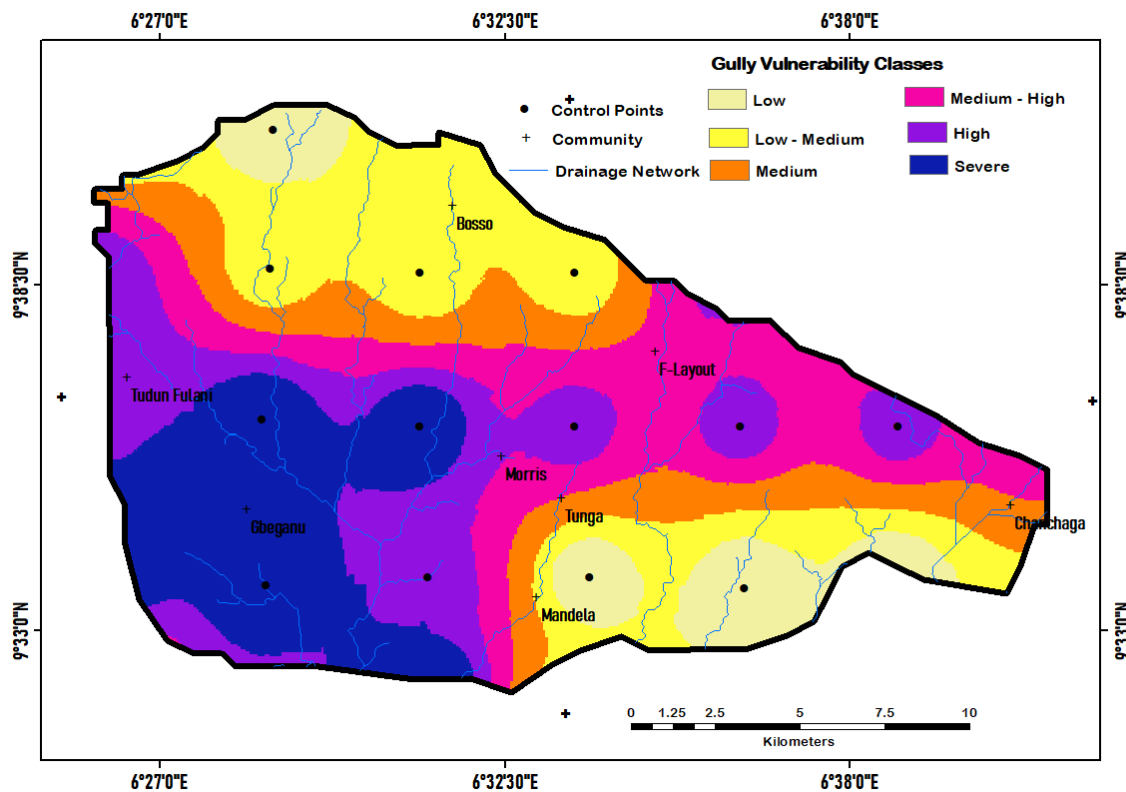


Figure 4. Gully vulnerability

Table 4. Spatial distribution of gully vulnerability

Gully Vulnerability Classes	Number of Pixel	Area (Ha)	Percentage (%)
Low	5173	2674	8.67
Low - Medium	12684	6557	21.25
Medium	8163	4220	13.68
Medium - High	11624	6009	19.47
High	10778	5571	18.06
Severe	11269	5825	18.88
Total			100

Table 5. Validation of predicted gully map

Control Points		Expected Vulnerability	Obtained Vulnerability	Inference	Remarks
Northing	Easting	Value	Value		
9° 40' 58.80"	6° 28' 48.00"	Low	Low	True	Coincide
9° 38' 42.00"	6° 33' 36.00"	Low-Medium	Low-Medium	True	Coincide
9° 38' 42.00"	6° 31' 8.40"	Low-Medium	Low-Medium	True	Coincide
9° 38' 45.60"	6° 28' 44.40"	Low-Medium	Low-Medium	False	Failed
9° 36' 21.60"	6° 28' 37.20"	Severe	Severe	True	Coincide
9° 36' 14.40"	6° 31' 8.40"	High	Severe	False	Failed
9° 36' 14.40"	6° 33' 36.00"	High	High	True	Coincide
9° 36' 14.40"	6° 36' 14.40"	High	High	True	Coincide
9° 36' 14.40"	6° 38' 45.60"	High	High	True	Coincide
9° 33' 39.60"	6° 36' 18.00"	Low	Low	True	Coincide
9° 33' 50.40"	6° 33' 50.40"	Low-Medium	Low	False	Failed
9° 33' 50.40"	6° 31' 15.60"	High	High	True	Coincide
6° 28' 40.80"	6° 28' 40.80"	Severe	Severe	True	Coincide
				Coincided	84.62 %

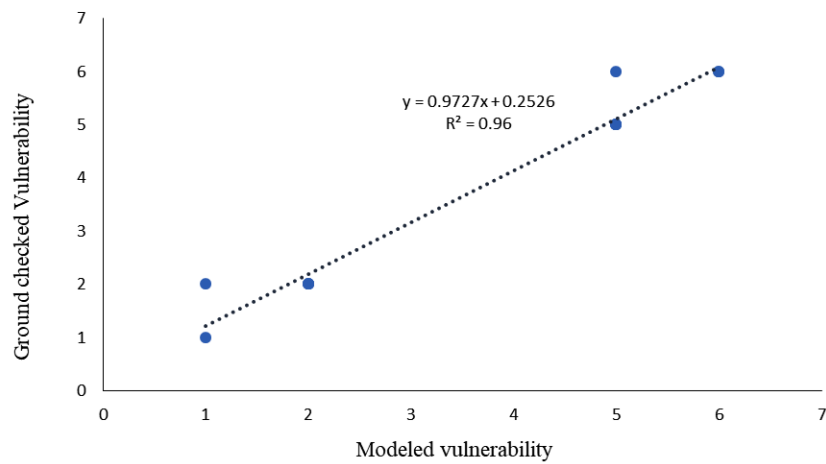


Figure 5. Ground checked and modeled vulnerability

The integration of the MCDA and the AHP into GIS workflow provides an effective approach critical to minimizing the limitations associated with gully occurrence analysis, using a singular basin characteristic; as evidenced in the existing erosion studies. The findings of this study provide an effective model for estimating gully vulnerability; which is critical to the understanding of soil erosion. The results obtained will be equally important to the fields of civil/water engineering, urban planning and government agencies such as the environmental protection agency. This will be pertinent in determining gully risk zones, circumspect urban development, tracking and proper infrastructure construction plans for long-term gully disaster mitigation. The methods and techniques employed in this study can be applied in regions with similar physical, lithology, climate and hydrogeological conditions.

ACKNOWLEDGMENTS

The authors will like to sincerely acknowledge the Tertiary Education Trust Fund (TET Fund) for funding this research under the Institutional Based Research (IBR) 2017. The Geographical Information System Laboratory, Ibrahim Badamasi Babangida University, Lapai is also appreciated for their provision of both soft copy and hardware copy material used in this research. The authors will like to sincerely acknowledge the two anonymous reviewers for the constructive critics to improve the manuscript quality. We also acknowledge the effort of Mr. Madaki Mohamed from the Department of English, School of Preliminary and Remedial Studies Agaie of Ibrahim Badamasi Babangida University Lapai for grammatical editing of the manuscript.

FUNDING AGENCY

This research is funded by Tertiary Education Trust Fund (TET Fund) as Institutional Based Research Grant (IBR) 2017.

ABBREVIATIONS

AHP: Analytical Hierarchy Process; **C:** Celsius; **CI:** Consistency Index; **CR:** Consistency Ratio; **DEM:** Digital Elevation Model; **GIS:** Geographic Information System; **Ha:** Hectare; **LULC:** Land Use Land Cover; **MCDA:** Multi-Criteria Decision Analysis; **NOAA:** National Oceanic and Atmospheric Administration; **OLR:** Outgoing Long-wave Radiation; **TM:** Thematic Mapper; **UNEP:** United Nations Environment Program.

CONFLICT OF INTEREST

The authors hereby declare that there is no conflict of interest. In addition, this publication has strictly adhered to ethical guidelines and is thus devoid of plagiarism, data fabrication, double publication/submission, and redundancy.

REFERENCES

- Abdulazeez, A., Sani, F. K., and Labaran, H. B., 2018. A spatial assessment for the extent and severity of gully erosion in Dawakin-Tofa LGA, Kano State. *International Journal of Geography and Environ. Management*, 4(2), 25-38.
- Adiat, K. A. N., Nawawi, M. N. M., and Abdullah, K., 2013. Application of multi-criteria decision analysis to geoelectric and geologic parameters for spatial prediction of groundwater resources potential and aquifer evaluation. *Pure and Applied Geophysics*, 170(3), 453-471. DOI: <https://doi.org/10.1007/s00024-012-0501-9>
- Ågren, A. M., Lidberg, W., Strömberg, M., Ogilvie, J., and Arp, P. A., 2014. Evaluating digital terrain indices for soil wetness mapping—a Swedish case study. *Hydrol. and Earth Syst. Sci.*, 18(9), 3623-3634. DOI: <https://doi.org/10.5194/hess-18-3623-2014>
- Ajaero, C. K., and Mozie, A. T., 2010. The Agulu-Nanka Gully Erosion Menace In Nigeria: What Does the Future Hold for the Population at Risk? *Climate Change and Migr: Rethinking Policies for Adapt. and Disaster Risk Red.*, 74-81.
- Alatorre, L. C., Beguería, S., Lana-Renault, N. N. A, and García-Ruiz, J. M., 2012. Soil erosion and sediment delivery in a mountain catchment under scenarios of land use change using a spatially distributed numerical model. *Hydrol. and Earth Syst. Sci.*, 16(5), 1321-1334. DOI: <https://doi.org/10.5194/hess-16-1321-2012>
- Ambalam, K., 2014. Challenges of compliance with multilateral environmental agreements: The case of the United Nations Convention to Combat Desertification in Africa. *J. of Sustainable Devt. Studies*, 5(2), 145-168.
- Aminu, Z., and Jaiyeoba, I. A., 2016. An assessment of soil degradation in Zaria Area, Kaduna State, Nigeria. *IFE Research Publications in Geography*, 13(1), 27-37.
- Arabameri, A., Pradhan, B., Rezaei, K., and Conoscenti, C., 2019. Gully erosion susceptibility mapping using GIS-based multi-criteria decision analysis techniques. *Catena*, 180, 282-297. DOI: <https://doi.org/10.1016/j.catena.2019.04.032>
- Arabameri, A., Pradhan, B., Rezaei, K., Yamani, M., Pourghasemi, H. R., and Lombardo, L., 2018. Spatial modelling of gully erosion using evidential belief function, logistic regression, and a new ensemble of evidential belief function–logistic regression algorithm. *Land degradation and devt.*, 29(11), 4035-4049. <https://doi.org/10.1002/ldr.3151>
- Arabameri, A., Rezaei, K., Pourghasemi, H. R., Lee, S., and Yamani, M., 2018a. GIS-based gully erosion susceptibility mapping: A comparison among three data-driven models and AHP knowledge-based technique. *Environ. earth sci.*, 77(17), 628. DOI: <https://doi.org/10.1007/s12665-018-7808-5>
- Araki, S., 2012. Morphology and Formation of Gully Features on Mars Using Mars Reconnaissance Orbiter Context Images. (Master of Scienc), University of Illinois at Chicago, Chicago, Illinois.
- Asakereh, A., Omid, M., Alimardani, R., and Sarmadian, F., 2014. Developing a GIS-based fuzzy AHP model for selecting solar energy sites in Shodirwan region in Iran. *International Journal of Advanced Science and Technology*, 68, 37-48. DOI: <http://dx.doi.org/10.14257/ijast.2014.68.04>

- Ayele, G. K., Gessess, A. A., Addisie, M. B., Tilahun, S. A., Tenessa, D. B. L., Eddy J., Steenhuis, T. S., and Nicholson, C. F., 2015. The economic cost of upland and gully erosion on subsistence agriculture for a watershed in the Ethiopian highlands. *African J. of Agricultural and Res. Economics*, 10(2), 265-278.
- Baker, M., Saavedra, D., and Norton, M., 2018. Methodology for developing high-resolution stream and waterbody datasets for the Chesapeake Bay watershed.
- Bashir, I. Y., Shua'ib M. H., and Sallau, R. O., 2018. An assessment of spatial variation of land surface characteristics of Minna, Niger state Nigeria for sustainable urbanization using geospatial techniques. *Geosfera Indonesia*, 3(2), 27-51. DOI: <https://doi.org/10.19184/geosi.v3i2.7934>
- Caracciolo, L., 2020. Sediment generation and sediment routing systems from a quantitative provenance analysis perspective: Review, application and future development. *Earth-Sci. Reviews*, 103226. DOI: <https://doi.org/10.1016/j.earscirev.2020.103226>
- Casali, J., Giménez, R., and Campo-Bescós, M. A., 2015. Gully geometry: What are we measuring?, *Soil*, 1, 509-513. DOI: <https://doi.org/10.5194/soil-1-509-2015>
- Castellanos, A. E. A., and Van Westen, C. J., 2007. Qualitative landslide susceptibility assessment by multicriteria analysis: A case study from San Antonio del Sur, Guantánamo, Cuba. *Geomorphology*, 94 (3-4), 453-466. DOI: <https://doi.org/10.1016/j.geomorph.2006.10.038>
- Chabok, M., Asakereh, A., Bahrami, H., and Jaafarzadeh, N. O., 2020. Selection of MSW landfill site by fuzzy-AHP approach combined with GIS: Case study in Ahvaz, Iran. *Environmental Monitoring and Assessment*, 192(7), 1-15. DOI: <https://doi.org/10.1007/s10661-020-08395-y>
- Chang, T. J., Wang, C. H., Chen, A. S., and Djordjević, S., 2018. The effect of inclusion of inlets in dual drainage modelling. *J. of Hydrol.*, 559, 541-555. DOI: <https://doi.org/10.1016/j.jhydrol.2018.01.066>
- Conoscenti, C., Agnesi, V., Angileri, S., Cappadonia, C., Rotigliano, E., and Märker, M., 2013. A GIS-based approach for gully erosion susceptibility modelling: A test in Sicily, Italy. *Environmental earth sci.*, 70(3), 1179-1195. DOI: <https://doi.org/10.1007/s12665-012-2205-y>
- Conoscenti, C., Angileri, S., Cappadonia, C., Rotigliano, E., Agnesi, V., and Märker, M., 2014. Gully erosion susceptibility assessment by means of GIS-based logistic regression: A case of Sicily (Italy). *Geomorphology*, 204, 399-411. DOI: <https://doi.org/10.1016/j.geomorph.2013.08.021>
- Daggupati, P., Douglas-Mankin, K. R., and Sheshukov, A. Y., 2013. Predicting ephemeral gully location and length using topographic index models. *Transactions of the ASABE*, 56(4), 1427-1440. DOI: <http://dx.doi.org/10.13031/trans.56.10087>
- Dashti, S., Monavari, S. M., Hosseini, S. M., Riazi, B., and Momeni, M., 2013. Application of GIS, AHP, Fuzzy and WLC in island ecotourism development (Case study of Qeshm Island, Iran). *Life Science Journal*, 10(1), 1274-1282.
- Dreibrodt, S., Lubos, C., Terhorst, B., Damm, B., and Bork, H. R., 2010. Historical soil erosion by water in Germany: scales and archives, chronology, research perspectives. *Quaternary International*, 222(1-2), 80-95. DOI: <https://doi.org/10.1016/j.quaint.2009.06.014>
- Dube, F., Nhapi, I., Murwira, A., Gumindoga, W., Goldin, J., and Mashauri, D. A., 2014. Potential of weight of evidence modelling for gully erosion hazard assessment in Mbire District-Zimbabwe. *Physics and Chemistry of the Earth, Parts A/B/C*, 67, 145-152. DOI: <https://doi.org/10.1016/j.pce.2014.02.002>
- Essien, O. E., and Okon, E. G., 2011. Rainfall characteristics, runoff rate and traffic flow on gully morphometric parameter growth and soil loss in sand-mined peri-urban, Uyo, Nigeria. *Journal of Geology and mining research*, 3(7), 180-187. DOI: <https://doi.org/10.5897/JGMR.9000065>
- Evans, M., and Lindsay, J., 2010. High resolution quantification of gully erosion in upland peatlands at the landscape scale. *Earth Surface Processes and Landforms*, 35(8), 876-886. DOI: <https://doi.org/10.1002/esp.1918>
- Frankl, A., Guyassa, E., Poesen, J., and Nyssen, J., 2019. Gully erosion and control in the Tembien highlands. In *Geo-trekking in Ethiopia's Tropical Mountains* 333-343. Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-04955-3_22
- Gabet, E. J., and Bookter, A., 2008. A morphometric analysis of gullies scoured by post-fire progressively bulked debris flows in southwest Montana, USA. *Geomorphology*, 96(3-4), 298-309. DOI: <https://doi.org/10.1016/j.geomorph.2007.03.016>
- Galin, E., Guérin, E., Peytavie, A., Cordonnier, G., Cani, M. P., Benes, B., and Gain, J., 2019. A review of digital terrain modeling. In *Computer Graphics Forum* 38(2), 553-577. DOI: <https://doi.org/10.1111/cgf.13657>
- Ganasri, B.P., and Ramesh, H., 2016. Assessment of soil erosion by RUSLE model using remote sensing and GIS- A case study of Nethravathi Basin. *Geoscience Frontiers*, 7(6), 953-961. DOI: <https://doi.org/10.1016/j.gsf.2015.10.007>
- Gao, Q., Kang, M., Xu, H., Jiang, Y., and Yang, J., 2010. Optimization of land use structure and spatial pattern for the semi-arid loess hilly-gully region in China. *Catena*, 81(3), 196-202. DOI: <https://doi.org/10.1016/j.catena.2010.03.002>
- Gaub, I., Chaabani, A., Mammou, A. B., and Hamza, M. H., 2017. A GIS-based soil erosion prediction using the revised universal soil loss equation (RUSLE)(Lebna watershed, Cap Bon, Tunisia). *Nat. hazards*, 86(1), 219-239. DOI: <https://doi.org/10.1007/s11069-016-2684-3>
- Gholamiderami, P., Lahooti, P., and Darbam, H., 2020. The effect of mulch on properties of erosion sensitive soil using a wind tunnel. *Global J. of Environmental Sci. and Management*, 6(4), 537-552. DOI: <https://doi.org/10.22034/GJESM.2020.04.09>
- Gordon, L. M., Bennett, S. J., Alonso, C. V., and Bingner, R. L., 2008. Modeling long-term soil losses on agricultural fields due to ephemeral gully erosion. *Journal of soil and water conservation*, 63(4), 173-181. DOI: <https://doi.org/10.2489/jswc.63.4.173>
- Goudie, A. S., 2018. *Human impact on the natural environment*: John Wiley and Sons.
- Gudino-Elizondo, N., Biggs, T. W., Castillo, C., Bingner, R. L., Langendoen, E. J., Taniguchi, K. T., Kretschmar, T., Yuan, Y., and Liden, D., 2018. Measuring ephemeral gully erosion rates and topographical thresholds in an urban watershed using unmanned aerial systems and structure from motion photogrammetric techniques. *Land degradation and development*, 29(6), 1896-1905. DOI: <https://doi.org/10.1002/ldr.2976>

- Hadji, R., Achour, Y., and Hamed, Y., 2017. Using GIS and RS for slope movement susceptibility mapping: comparing AHP, LI and LR methods for the Oued Mellah Basin, NE Algeria. In *Euro-Mediterranean Conference for Environmental*, 1853-1856. Springer, Cham. DOI: https://doi.org/10.1007/978-3-319-70548-4_536
- Handl, G., 2012. Declaration of the United Nations conference on the human environment (Stockholm Declaration), 1972 and the Rio Declaration on Environment and Development, 1992. *United Nations Audiovisual Library of International Law*, 11.
- Herzig, A., Dymond, J. R., and Marden, M., 2011. A gully-complex model for assessing gully stabilisation strategies. *Geomorphology*, 133(1-2), 23-33. DOI: <https://doi.org/10.1016/j.geomorph.2011.06.012>
- Huang, Y. L., Chen, L. D., Fu, B. J., and Wang, Y. L., 2005. Spatial pattern of soil water and its influencing factors in a gully catchment of the Loess Plateau. *Journal of Natural Resources*, 20(4), 483-492.
- Izham, M. Y., Uznir, U. M., Alias, A. R., Ayob, K., and Ruslan, I. W., 2011. Influence of georeference for saturated excess overland flow modelling using 3D volumetric soft geo-objects. *Computers and geosciences*, 37(4), 598-609. DOI: <https://doi.org/10.1016/j.cageo.2010.05.013>
- Jetten, V., Poesen, J., Nachtergaele, J., and Van de Vlag, D., 2006. Spatial Modelling of Ephemeral Gully Incision: Physical Approach. Soil erosion and sediment redistribution in river catchments: Measurement, modelling and management, 195.
- Jha, V. C., and Kapat, S., 2009. Rill and gully erosion risk of lateritic terrain in South-Western Birbhum District, West Bengal, India. *Sociedade and Natureza*, 21(2), 141-158. DOI: <https://doi.org/10.1590/S1982-45132009000200010>
- Kakembo, V., Xanga, W. W., and Rowntree, K., 2009. Topographic thresholds in gully development on the hillslopes of communal areas in Ngqushwa Local Municipality, Eastern Cape, South Africa. *Geomorphology*, 110(3-4), 188-194. DOI: <https://doi.org/10.1016/j.geomorph.2009.04.006>
- Kavzoglu, T., Sahin, E. K., and Colkesen, I., 2014. Landslide susceptibility mapping using GIS-based multi-criteria decision analysis, support vector machines, and logistic regression. *Landslides*, 11(3), 425-439. DOI: <https://doi.org/10.1007/s10346-013-0391-7>
- Kheir, R., Wilson, J., and Deng, Y., 2007. Use of terrain variables for mapping gully erosion susceptibility in Lebanon. *Earth Surface Processes and Landforms. The J. of the British Geomorphological Research Group*, 32(12), 1770-1782. DOI: <https://doi.org/10.1002/esp.1501>
- Kirkby, M. J., and Bracken, L. J., 2009. Gully processes and gully dynamics. *Earth Surface Processes and Landforms. The J. of the British Geomorphological Research Group*, 34(14), 1841-1851. DOI: <https://doi.org/10.1002/esp.1866>
- Koriche, S. A., and Rientjes, T. H., 2016. Application of satellite products and hydrological modelling for flood early warning. *Physics and Chemistry of the Earth, Parts A/B/C*, 93, 12-23. DOI: <https://doi.org/10.1016/j.pce.2016.03.007>
- Lal, R., 2017. Soil erosion by wind and water: problems and prospects. In *Soil erosion research methods*, 1-10. Routledge.
- López-Vicente, M., Poesen, J., Navas, A., and Gaspar, L., 2013. Predicting runoff and sediment connectivity and soil erosion by water for different land use scenarios in the Spanish Pre-Pyrenees. *Catena*, 102, 62-73. DOI: <https://doi.org/10.1016/j.catena.2011.01.001>
- Lucà, F., Conforti, M., and Robustelli, G., 2011. Comparison of GIS-based gullying susceptibility mapping using bivariate and multivariate statistics: Northern Calabria, South Italy. *Geomorphology*, 134(3-4), 297-308. DOI: <https://doi.org/10.1016/j.geomorph.2011.07.006>
- Mahmud, H. L., and Umaru, E. T., 2018. Impact of gully erosion on landuse/land cover in Bida Town Niger State, Nigeria. *Intl. J. of Geography and Environmental Management*, 4(2), 7-15.
- Mancino, G., Nolè, A., Salvati, L., and Ferrara, A., 2016. In-between forest expansion and cropland decline: A revised USLE model for soil erosion risk under land-use change in a Mediterranean region. *Ecological Indicators*, 71, 544-550. DOI: <https://doi.org/10.1016/j.ecolind.2016.07.040>
- Maquaire, O., Malet, J. P., Remaitre, A., Locat, J., Klotz, S., and Guillon, J., 2003. Instability conditions of marly hillslopes: Towards landsliding or gullying? The case of the Barcelonnette Basin, South East France. *Engineering Geology*, 70(1-2), 109-130. DOI: [https://doi.org/10.1016/S0013-7952\(03\)00086-3](https://doi.org/10.1016/S0013-7952(03)00086-3)
- Marot, D., Rochim, A., Nguyen, H., Bendahmane, F., and Sibille, L., 2016. Assessing the susceptibility of gap-graded soils to internal erosion: Proposition of a new experimental methodology. *Natl Hazards*, 83(1), 365-388. DOI: <https://doi.org/10.1007/s11069-016-2319-8>
- Matlab, V., 2010. *The MathWorks Inc.*, Natick, Massachusetts.
- Medvedeva, R. A., Golosov, V. N., and Ermolaev, O. P., 2018. Spatio-temporal assessment of gully erosion in the Zone of Intensive Agriculture in the European Part of Russia. *Geogr. Nat. Resour*, 39(3), 204-211. DOI: <https://doi.org/10.1134/S1875372818030034>
- Mohsen, Z., Fahimeh, M., Alizera, M., Abdulvahed, K. D., Hamid, R. P., Mohamad, A. Z., and Fatimeh, S., 2018. Spatial modelling of gully in Mazandaran Province, northern Iran. *Catena*, 161, 1-13. DOI: <https://doi.org/10.1016/j.catena.2017.10.010>
- Moore, I. D., Grayson, R. B., and Ladson, A. R., 1991. Digital terrain modelling: A review of hydrological, geomorphological, and biological applications. *Hydrological processes*, 5(1), 3-30. DOI: <https://doi.org/10.1002/hyp.3360050103>
- Mousavi, S. M., Golkarian, A., Naghibi, S. A., Kalantar, B., and Pradhan, B., 2017. GIS-based groundwater spring potential mapping using data mining boosted regression tree and probabilistic frequency ratio models in Iran. *Aims Geosci*, 3(1), 91-115. DOI: <https://doi.org/10.3934/geosci.2017.1.91>
- Omid, R., Ali, H., Hamid, R. P., and Farhad, N., 2016. Gully erosion susceptibility mapping: The role of GIS-based Bivariate Statistical Models and their Comparison. *Natl hazards*, 82, 1231-1258. DOI: <https://doi.org/10.1007/s11069-016-2239-7>
- Patil, R. J., 2018. *Spatial Techniques for Soil Erosion Estimation: Remote Sensing and GIS Approach*. Springer.
- Pei, P., Zhao, Y., Ni, P., and Mei, G., 2020. A protective measure for expansive soil slopes based on moisture content control. *Engineering Geology*, 269, 105527. DOI: <https://doi.org/10.1016/j.enggeo.2020.105527>
- Peterson, R. B., Kapiyo, R. A., Campbell, E. M., and Nyabua, P. O., 2018. Gully rehabilitation trusts: Fighting soil

- erosion through community participation in western Kenya. *J. of Rural Studies*, 58, 67-81. DOI: <https://doi.org/10.1016/j.jrurstud.2017.12.028>
- Pokhara, S., 2008. Conservation of Phewa Lake of Pokhara, Nepal. *NLCDC, Ministry of Culture, Tourism and Civil Aviation*.
- Post, J. A. B., Langeveld, J. G., and Clemens, F. H. L. R., 2017. Quantifying the effect of proactive management strategies on the serviceability of gully pots and lateral sewer connections. *Structure and Infrastructure Engineering*, 13(9), 1230-1238. DOI: <https://doi.org/10.1080/15732479.2016.1260602>
- Pourghasemi, H. R., Pradhan, B., Gokceoglu, C., and Moezzi, K. D., 2013. A comparative assessment of prediction capabilities of Dempster-Shafer and weights-of-evidence models in landslide susceptibility mapping using GIS. *Geomatics, Natl Hazards and Risk*, 4(2), 93-118. DOI: <https://doi.org/10.1080/19475705.2012.662915>
- Pourghasemi, H. R., Yousefi, S., Kornejady, A., and Cerdà, A., 2017. Performance assessment of individual and ensemble data-mining techniques for gully erosion modeling. *Sci. of the Total Environment*, 609, 764-775. DOI: <https://doi.org/10.1016/j.scitotenv.2017.07.198>
- Raduła, M. W., Szymura, T. H., and Szymura, M., 2018. Topographic wetness index explains soil moisture better than bioindication with Ellenberg's indicator values. *Ecological Indicators*, 85, 172-179. DOI: <https://doi.org/10.1016/j.ecolind.2017.10.011>
- Rahmati, O., Haghizadeh, A., Pourghasemi, H. R., and Noormohamadi, F., 2016. Gully erosion susceptibility mapping: The role of GIS-based bivariate statistical models and their comparison. *Natl Hazards*, 82(2), 1231-1258. DOI: <https://doi.org/10.1007/s11069-016-2239-7>
- Saaty, T. L., 1980. *The analytic hierarchy process: planning, priority setting, resources allocation*. McGraw-Hill.
- Sajedi-H., Farzaneh, C., Bahram, S., Karim, Cerdà, A., and Kavian, A., 2018. Spatial prediction of soil erosion susceptibility using a fuzzy analytical network process: Application of the fuzzy decision-making trial and evaluation laboratory approach. *Land degradation and development*, 29(9), 3092-3103. DOI: <https://doi.org/10.1002/ldr.3058>
- Shi, P., Arter, C., Liu, X., Keller, M., and Schulin, R., 2017. Soil aggregate stability and size-selective sediment transport with surface runoff as affected by organic residue amendment. *Sci. of the Total Environment*, 607, 95-102. DOI: <https://doi.org/10.1016/j.scitotenv.2017.07.008>
- Shit, P. K., Paira, R., Bhunia, G. S., and Maiti, R., 2015. Modeling of potential gully erosion hazard using geo-spatial technology at Garbheta block, West Bengal in India. *Modeling Earth Systems and Environment*, 1(1-2), 2. DOI: <https://doi.org/10.1007/s40808-015-0001-x>
- Sidorchuk, A., Märker, M., Moretti, S., and Rodolfi, G., 2003. Gully erosion modelling and landscape response in the Mbuluzi River catchment of Swaziland. *Catena*, 50(2-4), 507-525. DOI: [https://doi.org/10.1016/S0341-8162\(02\)00123-6](https://doi.org/10.1016/S0341-8162(02)00123-6)
- Souchere, V., Cerdan, O., Ludwig, B., Le Bissonnais, Y., Couturier, A., and Papy, F., 2003. Modelling ephemeral gully erosion in small cultivated catchments. *Catena*, 50(2-4), 489-505. DOI: [https://doi.org/10.1016/S0341-8162\(02\)00124-8](https://doi.org/10.1016/S0341-8162(02)00124-8)
- Sougnéz, N., Van-Wesemael, B., and Vanacker, V., 2011. Low erosion rates measured for steep, sparsely vegetated catchments in southeast Spain. *Catena*, 84(1-2), 1-11. DOI: <https://doi.org/10.1016/j.catena.2010.08.010>
- Svoray, T., and Ben-Said, S., 2010. Soil loss, water ponding and sediment deposition variations as a consequence of rainfall intensity and land use: A multi-criteria analysis. *Earth Surface Processes and Landforms. The J. of the British Geomorphological Research Group*, 35(2), 202-216. DOI: <https://doi.org/10.1002/esp.1901>
- Svoray, T., and Markovitch, H., 2009. Catchment scale analysis of the effect of topography, tillage direction and unpaved roads on ephemeral gully incision. *Earth Surface Processes and Landforms. The J. of the British Geomorphological Research Group*, 34(14), 1970-1984. DOI: <https://doi.org/10.1002/esp.1873>
- Svoray, T., Michailov, E., Cohen, A., Rokah, L., and Sturm, A., 2012. Predicting gully initiation: Comparing data mining techniques, analytical hierarchy processes and the topographic threshold. *Earth Surface Processes and Landforms*, 37(6), 607-619. DOI: <https://doi.org/10.1002/esp.2273>
- Teng, H., Rossel, R. A., Viscarra, S., Zhou, B., Thorsten, C., A., and Bui, E., 2016. Assimilating satellite imagery and visible-near infrared spectroscopy to model and map soil loss by water erosion in Australia. *Environmental Modelling and Software*, 77, 156-167. DOI: <https://doi.org/10.1016/j.envsoft.2015.11.024>
- Torri, D., and Poesen, J., 2014. A review of topographic threshold conditions for gully head development in different environments. *Earth-Science Reviews*, 130, 73-85. DOI: <https://doi.org/10.1016/j.earscirev.2013.12.006>
- UNCCD [United Nations Convention to Combat Desertification], 1994. Paper presented at the United Nations Environmental Programme, Geneva.
- Vachtman, D., M., Neil C., and Gawthorpe, R., 2013. Morphologic signatures in submarine canyons and gullies, central USA Atlantic continental margins. *Marine and Petroleum Geology*, 41, 250-263. DOI: <https://doi.org/10.1016/j.marpetgeo.2012.02.005>
- Vaezi, A. R., Abbasi, M., Bussi, G., and Keesstra, S., 2017. Modeling sediment yield in semi-arid pasture micro-catchments, NW Iran. *Land Degradation and Development*, 28(4), 1274-1286. DOI: <https://doi.org/10.1002/ldr.2526>
- Valentin, C., Poesen, J., and Li, Y., 2005. Gully erosion: Impacts, factors and control. *Catena*, 63(2-3), 132-153. DOI: <https://doi.org/10.1016/j.catena.2005.06.001>
- Valjarević, A., Srećković-Batočanin, D., Živković, D., and Perić, M., 2015. GIS analysis of dissipation time of landscape in the Devil's city (Serbia). *Acta Montanistica Slovaca*, 20(2).
- Vijith, H, and Dodge-Wan, D., 2019. Modelling terrain erosion susceptibility of logged and regenerated forested region in northern Borneo through the Analytical Hierarchy Process (AHP) and GIS techniques. *Geoenvironmental Disasters*, 6(1), 8. DOI: <https://doi.org/10.1186/s40677-019-0124-x>
- Wang, Q., L., Wenping, Chen, W., and Bai, H., 2015. GIS-based assessment of landslide susceptibility using certainty factor and index of entropy models for the Qianyang County of Baoji city, China. *J. of Earth System Sci.*, 124(7), 1399-1415. DOI: <https://doi.org/10.1007/s12040-015-0624-3>
- Wang, R., Zhang, S., Yang, J., Pu, L., Yang, C., Yu, L., Chang, L., and Bu, K., 2016. Integrated use of GCM, RS, and GIS for the assessment of hillslope and gully erosion in the Mushi River Sub-Catchment, Northeast

- China. *Sustainability*, 8(4), 317. DOI: <https://doi.org/10.3390/su8040317>
- Warren, S. D., Ruzycki, T. S., Vaughan, R., and Nissen, P. E., 2019. Validation of the unit stream power erosion and deposition (USPED) model at Yakima Training Center, Washington. *Northwest Sci.*, 92(5), 338-345. DOI: <https://doi.org/10.3955/046.092.0504>
- Wischmeier, W. H., and Smith, D. D., 1978. Predicting rainfall erosion losses-a guide to conservation planning. Predicting rainfall erosion losses-a guide to conservation planning.
- Xiong, X., Shi, Z., Xiong, Y., Peng, M., Ma, X., and Zhang, F., 2019. Unsaturated slope stability around the three gorges reservoir under various combinations of rainfall and water level fluctuation. *Engineering Geology*, 261, 105231. DOI: <https://doi.org/10.1016/j.enggeo.2019.105231>
- Yalcin, A., and Bulut, F., 2007. Landslide susceptibility mapping using GIS and digital photogrammetric techniques: A case study from Ardesen (NE-Turkey). *Natl Hazards*, 41(1), 201-226. DOI: <https://doi.org/10.1007/s11069-006-9030-0>
- Yusoff, I. M., Rahman, A. A., and Katimon, A., 2007. GIS based hydrologic modelling for infiltration excess overland flow. Paper presented at the proceedings of *joint international symposium & exhibition on geoinformation 2007 & international symposium on GPS/GNSS (ISG-GNSS2007)*, Persada Johor International Convention Centre, Johor Bharu Malaysia.
- Zabihi, M., Mirchooli, F., Motevalli, A., Darvishan, A., Khaledi, P., Hamid R., Zakeri, M. A., and Sadighi, F., 2018. Spatial modelling of gully erosion in Mazandaran Province, northern Iran. *Catena*, 161, 1-13. DOI: <https://doi.org/10.1016/j.catena.2017.10.010>
- Zabihi, M., Pourghasemi, H. R., Motevalli, A., and Zakeri, M. A., 2019. Gully erosion modeling using GIS-based data mining techniques in northern Iran: A comparison between boosted regression tree and multivariate adaptive regression spline. In *Natural Hazards GIS-Based Spatial Modeling Using Data Mining Techniques*, 1-26. Springer.
