Geospatial Analysis of Gully Erosion Causative Factors: A Case Study of Anambra Erosion Prone Site, Southeastern Nigeria

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Research Article

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Abstract

Gully erosion studies are usually complex and expensive due to the multiple nature of the causative factors, heterogeneity of the underlying geologic materials, and the high volume of point source data required within a given area. For this reason, thorough gully erosion studies are rarely carried out especially in developing countries with little resources allocated to environmental studies. Thus, it becomes difficult in solving problems arising from such geologic hazard in those areas. However, the availability of data emanating from remotely sensed operations can be utilized in solving complex gully erosional problems using modern geospatial analytical tools. Consequently, gully erosion studies within the study area were carried out by integration of geomorphologic and environmental data which were acquired remotely, and geotechnical information derived from field and laboratory investigations of the underlying geologic materials. The integrated geomorphologic, environmental, and geotechnical data was analysed with analytical tools such as ArcGIS, Google Earth, and Microsoft Excel, following the frequency ratio method. Results from the study revealed that slope angle, soil plasticity, angle of internal friction, cohesion, and population density contributed about 20%, 23%, 20%, 18%, and 9%, respectively to soil's susceptibility to gullying. Slope angle and population density were positively correlated with the frequency of gully erosion, whereas plasticity, cohesion, and angle of internal friction were negatively correlated with frequency of gully erosion. The spatial distribution of the data revealed areas that are susceptible to gullying in their various degrees; thus providing affordable information for proper environmental planning and development.

Introduction

Geological sciences or earth sciences keyed towards understanding the earth constituents and the processes that shape the earth's environment. There are different branches of geosciences, each focusing on a particular subject area, be it materials that constitute the earth or processes that transform it. The implication of the realized geoscientific knowledge is the ability to properly manage the earth's resources, and to control geohazards that may arise as a result of natural and/or anthropogenic activities. One of such geohazards which is a major environmental problem in Anambra state, Southeastern Nigeria is gully erosion. This geologic hazard has caused severe damages to road infrastructure, buildings, and underground utilities (Emeh and 1gwe, 2017; Akpokodje et al., 2010). It has also led to the destruction of arable lands, flooding, and landslides (Igwe, 2005). In some cases, some communities have been separated by wide and deep gully channels, thereby creating communication barriers to the inhabitants (Emeh and Igwe, 2018). While some of these gullies are dormant, most of them are actively developing at an alarming rate. In fact, (Akpokodje et al., 2010) have reported the development of a 157 m long gully channel which is about 50 m wide and 5 m deep, in one rainy season. Such rate of gully development is common in most areas of the state and it is fast endangering the growing population within the state. The causes of gully erosion have been revealed by various authors in the field of earth sciences, which they attributed to the climatic, geologic, geomorphologic, geotechnical, and geo-environmental factors that are prevailing within the environment (Eze, 2007; Igwe et al., 2013; Igwe and Fukuoka, 2015; Egbueri et al., 2021).

Following the findings from the previous researchers, erosion control mechanisms have been designed to check the devastating effect of gully erosion within the region. Some of these control mechanisms include afforestation, good drainage facilities, proper land-use practices, and slope stabilization (Okagbue and Uma, 1987; Ijioma, 1988; Igbozurike, 1993). However, these control mechanisms have not been totally effective in controlling gully erosion within the areas that it has been applied; hence erosion continues to be a major environmental problem within this region. The reason for the partial effectiveness of the control mechanisms has been previously attributed to the inadequate application of the recommended control measures due to insufficient funding, lack of strict adherence to the proposed drainage design, and improper land-use practices (Akpokodje et al., 2010). However, a recent observation by (Emeh and Igwe, 2017) revealed that these control mechanisms were not site-specifically designed; rather a holistic application of the general soil erosion control was employed. Meanwhile, investigations have shown that soil erodibility depends on the inherent properties (geotechnical and geochemical) of a particular soil, and the prevailing geomorphologic and climatic factors within a specific area (Smith, 1999; Laker, 2004). Thus, erosion control mechanisms that are not site-specifically designed may not account for all the prevailing factors that contribute to the soil's erodibility within a specified area; hence may not be totally effective.

However, because of the heterogeneous nature of the underlying geology within the area and the multiple attributes of the erosion causative factors, high volume of point-to-point data is required in order to account for such variability. This task is often very expensive and thus may not be economically feasible; hence the need for an alternative cheaper method.

One of such cheaper methods is the application of geospatial analysis. Geotechnical and environmental data acquired both from the field, laboratory analysis, and remotely sensed information can be integrated and distributed spatially using available geospatial information system (GIS) analytical tools. It involves the distribution of point source data generated from the field or the laboratory in space using any suitable interpolation methods (Fabijańczyket al., 2017). The distribution of these soil erodibility data in space helps in determining with a high degree of certainty, erosion causative factors at points where data is not available; hence reducing the need for numerous point source sampling. The method is relatively cheap and fast because geomorphologic and environmental data needed for such analysis could be accessed from remotely sensed information.

This method has been frequently used in assessing landslide hazards (Ozioko and Igwe, 2020), desertification (Djeddaoui et al., 2017), and earthquake susceptibility (Chen et al., 2012), but has not been a usual tool in soil erodibility studies. Therefore, the aim of this study was to determine the spatial distribution of the prevailing gully erosion causative factors within the study area. The objectives to achieve this aim were to ascertain the geotechnical composition of the eroding soils, geomorphologic attributes of the area, and population distribution, which will be thereafter distributed spatially with the aid of geospatial analytical tools.

Material And Method

Study area

Geographically, the study area lies within the Southeastern part of Anambra state, Nigeria. The population density of this area is approximately one million (National Bureau of Statistics, 2020), which are scattered over many towns within the area, notably Ekwulubia, Agulu, Igboukwu, Nanka, Aguata, amongst others. Geomorphologically, it is characterized by undulating topography with the hilly areas standing at elevation of 400 m while the valley areas lies as low as 60 m above sea level (Fig. 1). The boundary between the high and the low areas is characterized by high angled slopes which have been steepened by geologic hazards, such as landslides and gullying (Egboka et al., 1990).

Tropical climate prevails within the study area, which is characterized by relatively high temperature throughout the year that ranges from 16 ^{0}C in the month of December to about 31 ^{0}C in the month of March. The total annual rainfall is about 1580 mm, with minimum rainfall of about 16 mm occurring in February and a maximum of about 350 mm in July (Eze, 2007). Tropical rain forest predominates in most part of the study area, apart from few high elevated areas that are comprised of shrubs and grasses.

Geologically, the study area lies in the Anambra basin which is part of the lower Benue Trough. The history and evolution of this Basin has been discussed extensively by several authors, as well as it's sedimentological and stratigraphical composition (Nwajide, 1979; Oboh-Ikuenobe et al., 2005; Dim, 2021). Almost the entirety of the study area is been underlain by Ameki Formation which was deposited during the Eocene (Nwajide, 1979). This Formation comprises of successive layers of fine to coarse grained tidally influenced and fluvial sandstones at the basal part. The course grained sandstone is successively overlain by intercalations of thin layers of clay, shale, and limestone, with cross-bedded coarse grained sandstones and clays at the uppermost layer (Arua and Rao, 1987). Due to intensive tropical weathering, most part of the outcropping rock units of this Formation have been severely weathered into lateritic soils. Two major soil type, deep porous red soil derived from sandy deposits, and reddish brown soils derived from sandstone and shale deposits covered more than 95 percent of the study area. The remaining five percent of the area which is seen at the edges and at some low lying terrains of the study area is been underlain by dark brownish soils derived from shale, likely from the outcropping adjacent Imo Formation (Fig. 2).

Desk study

Prior to field sampling, the digital elevation model (DEM) data of the study area was acquired from the United States Geological Survey online archives, whereas the population density data was acquired from NASA Socioeconomic Data and Applications Center (SEDAC, 2020). With the help of surfer 11, the DEM data was analysed and some geomorphologic parameters such as elevation and slope were extracted.

The extracted information was used in producing 2D and 3D contour maps which helped to identify potential gully erosion channels. The potential gully channels that were indentified from the DEM data were verified by visual confirmation using Google earth pro in order to ensure that the channels were neither man-made drainage systems nor stream channels. This helped in narrowing down the specific sites visited during field investigation and sampling.

Field investigation

At the gully sites, the depth and width of some of the gullies were measured using a long ranging pole and a measuring tape. The width and depth of some of the gullies that are relatively very wide and deep, respectively were estimated. In areas where the gullies could not be accessed, the width was measured with the help of the ruler function in Google earth pro. Because it is an arduous task to manually trace and measure the length of the gullies, their lengths were estimated using the ruler function in both surfer 11 and Google earth pro. Altogether, about 120 gullies were captured from both field investigation and through image analysis. Information from 60 gully erosion event scars were used to produce the gully hazard map, which is a 2D representation of the studied gully erosion sites on map. The remainder of the gully location points was used for model validation.

Soil Sampling

A total of sixty (60) disturbed soil samples were collected at different locations within the study area. Samples were collected considering the elevation (topographic) contour and the frequency of gully erosion. More samples (49) were collected in areas with high frequency of gully erosion, compared to 11 samples which were collected in areas with little or no presence of gully erosion. However, it was ensured that samples were collected at each contour interval which was set at 50 m. Topographic contour interval was considered because it was assumed that contour variation may represent change in physical properties of the underlying soil. Soil sampling was done by digging horizontally with a hand auger through the gully walls to a depth of about 1m. In areas where there was no gully, the digging was done vertically. Samples collection at the depth of 0.5-1m was to ensure that relatively fresh samples devoid of plant roots were collected. The soil samples were bagged in a cellophane bag and were properly labelled before transporting to the laboratory for analysis.

Soil geotechnical properties

Air dried soil samples that passed American Society for Testing and Materials (ASTM) sieve No. 40 (< 425μm) was used to determine the Atterberg limit of the soils following ASTM D2487 (2011) standard procedure, and the plasticity index was calculated from the results thereafter.

The soil samples which has been air dried in the laboratory was subjected to shear strength test using the direct simple shear (DSS) test method following ASTM D3080-04 (2004) standard procedures. This test was carried out under consolidated – drained (CD) condition. For each sample, the test was repeated for four different times with increase in the normal stress at every round; thus the shear stress required to cause failure was determined for each normal stress. The failure envelope was obtained by plotting the points corresponding to the shear strength (shear stress at failure) at different normal stresses and joining them afterwards with a straight line. The intercept of this straight line on the vertical axis gives the cohesion (*c*) of the soil sample, whereas the inclination of line to the horizontal axis gives the angle of internal friction (ϕ).

Values of the plasticity index, cohesion, and friction derived from the geotechnical tests were used in creating a geospatial map which distributed these values in space within the study area. This was done by plotting the values of the geotechnical parameter against the geographical reference point where they are sampled. The distribution of the geotechnical data across the study area followed kriging's interpolation method as described in (Séguret and Huchon, 1990; Wackernagel, 2003). This resulted in three maps each of cohesion, friction, and plasticity of the soil samples.

Geomorphologic and geoenvironmental properties

The slope information was extracted from the DEM of the study area using the extract tool function in ArcGIS 10.0. The extracted information was used to produce a slope map of the study area. Similarly, the population density (POD) data was extracted from the population density raster map of the study area with the aid of ArcGIS 10.0 clip tool function.

Geospatial Analysis

The geotechnical, geomorphologic, and geo-environmental data was analysed following this stepwise procedure in order to generate the erosion susceptibility map.

1. Data rasterization and projection

All the polygon maps which include soil geotechnical properties maps (cohesion, friction and plasticity), gully event map, slope map, and population density map were converted to raster. During this process, the maps were set at a cell size of 30 by 30 m and were projected geographically using the geographic coordinate settings of the study area.

2. Map classification

The raster map was classified into several classes depending on the distribution of the values in the erodibility factors that was considered. The geotechnical parameters were classified into 9 classes each, while slope and population density were classified into five classes each (Tables 1–5). The classification of the geotechnical parameters, slope, and population density maps were done following the Jenks natural break method.

3. Reclassification (Class weightage assignment)

Weight contribution of the individual erodibility factor class (EFC) was assigned following the frequency ratio (FR) method. This method has been explained by (Lee and Sambath, 2006; Sharma and Mahajan, 2018). It relates the frequency of gully erosion occurrence to the erodibility factor under consideration. It can be mathematically represented as the area covered by gully erosion event (GEA) divided by the area covered by a particular erodibility factor class (EFCA) as shown in Eq. 1,

FR = $\frac{GEA}{EFCA}$ (Eq. 1)

GEA was determined from the gully event raster map (Fig. 3a), while the EFCA was determined from the geotechnical and geoenvironmental parameter raster maps (Figs. 3b-f) using the Tabulate Area Function (TAF) in ArcGIS version 10.0.

The relative frequency (RF) of the individual erodibility factor class, which is the percentage contribution of the FR was calculated from Eq. 2,

$$RF = \frac{FR}{\sum FR} \times 100 \text{ (Eq. 2)}$$

The value of RF was used to assign weightage values to the Individual factor classes (Tables 2–5).

4. Ranking (Factor weightage assignment)

The erodibility factors which were considered for this analysis were ranked based on their percentage contribution (PFC) to the frequency of gully erosion. This was calculated from Eq. 3;

$$PFC = \frac{FW}{\sum FW} \times 100 \text{ (Eq. 3)}$$

Where FW is factor weightage, which is the summation of the frequency ratios of each class in an erodibility factor under consideration. ΣFW is the sum of all the factor weightage for the erodibility factors that was considered. Ranking was done using the weighted overlay function of the ArcGIS version 10.0.

Two scenario of the erosion susceptibility map was created. The first scenario considered only the soil geotechnical parameters (cohesion, friction, plasticity), and slope; while the second scenario considered all the factors in the first scenario in addition to population density. The resultant susceptibility map was classified into five classes very low, low, moderate, high, and severe.

Correlation Analysis

Pearson's correlation was used to evaluate the relationships between the erodibility factors and the frequency of gully occurrence. This was achieved by plotting the mean of the erodibility factor class against their corresponding frequency ratios (Tables 1–5), using the linear model function in Genstat – a statistics analytical tool.

Model validation

Sixty (60) gully event points which were not used in building the susceptibility maps was used for the validation of the model. This was done by creating a post map with the gully event location points, which was thereafter superimposed on the generated susceptibility map. The number of gully event points that coincides with each susceptibility class was delineated using the identify object function in ArcGIS, and the percentages were thus calculated. The percentage of gully event for each susceptibility class was used in validating the gully erosion susceptibility model.

Results And Discussions

Gully characteristics and geomorphologic attributes

Gullies within the study area are extensively developed with an average width, depth, and length of about 23 m, 6 m, and 914 m, respectively (Table 6). The landform reveals that the area is roughly divided into two equal parts. The southern part are relatively high with an elevation that ranges from 240–390 m, whereas the northern part and the southeastern part are low lying at an elevation of about 40–140 m. The slope as revealed from the DEM analysis ranges from 0^{o} to 43^{o}. The spatial distribution of the slope revealed that high frequency of gully erosion was centred on the steep slopes (Fig. 3c). Similar evidence was observed from the correlation analysis, which shows that there was good positive relationship between the slope angle and the frequency of the gully erosion, with correlation coefficient of 0.99 (Fig. 4).

The analytical results collaborated with the field observations which revealed that the gullies usually originates from the steep part of the slopes, and then extends outward towards the southeastern direction. The gully widths are usually larger at the head, and narrows down towards the end of the gully channel. The reason for this pattern in the gully channel was attributed to the backward incision of the gully walls by the action of landslides; thus expansion of its width. The mechanism of this expansion was explained by (Igwe and Fukuoka, 2014; Sharma et al., 2016), where they posited that deepening of the gully leads to increase in its slope angle; thus resulting to increase in the shear stress of the overburden materials. In conjunction with increase in pore pressure due to high amount of rainfall, the shear strength of the slope material is exceeded, leading to its slumping into the gully channel. Continual slumping of the overburden materials into the gully, and subsequent removal of these materials by the eroding water widens the gully towards its head. Another reason for the outward V shape of the gullies was because of the nature of the materials along its course (Egburi and Igwe, 2020; Egburi et al., 2021). They revealed that the gullies originate from a sandy Formation which is characterized by low plastic and weakly cohesive materials which are easily susceptible to erosion. However, as the gullies progress from the west towards the eastern direction, the underlying materials changes to a more plastic and highly cohesive materials, which are more resistant to water erosion (Fig. 5).

Geotechnical properties

Soil plasticity is a measure of the detachability of its individual grains from the aggregates; thus its erodibility (Egashlra et al., 1983; Emeh and Igwe, 2018). Soil plasticity within the study area ranges from 0.32 to 32.34, with an average value of about 13.52 (Table 2). The spatial distribution of the plasticity values within the study area reveals that the low lying areas are of high plasticity compared with areas at higher elevation. This variation in the plasticity was as a result of the nature of the underlying materials in the two different reliefs. The low terrains are underlain by clayey soils derived from shaly Formations (Palaeocene Imo Fm), whereas the elevated areas are underlain by sandy soils derived from sandstone Formations (Eocene Ameki Fm). The correlation analysis reveals a moderate to good negative relationship between the frequency of gullying within the study area and the soils plasticity, with a correlation coefficient (r) of -0.64 (Fig. 6) which is statistically significant at 0.05 level. This implies that decrease in the plasticity of the underlying soil will likely result to increase in gullying.

Cohesion is another geotechnical property of a soil which has similar characteristics as that of its plasticity. It contributes to the shear resistance of soils to external forces; thus, making it important soil erodibility factor (Brunori et al., 1989). The cohesion of soil within the study area ranges from 0.49 kPa to 69.65 kPa with an average value of 35.02 kPa (Table 3). Similar to the relationship between soil's plasticity and their frequency of gully occurrence, the cohesion of the soil samples fairly correlated to the frequency of gully occurrence in the study area, with r value of -0.55 (Fig. 7). This implies that increase in cohesion of the soil particles will likely lead to decrease in gully erosion. The spatial distribution of the cohesion within the study area was also similar to that of the plasticity, which reveals that low lying terrains are predominantly of higher cohesion than those at higher elevation. The similarity between the cohesion and the plasticity of the soil could be attributed to the mineralogical make up of the soil. Noting that clay minerals are common with soils derived from argillaceous materials and such soils are associated with high plasticity and high cohesion (Bühmann et al., 2004; Emeh and Igwe, 2018).

The average angle of internal friction of the soil samples collected within the area was 35.38˚, which ranges from 18.31˚ to 52.45˚ (Table 4). Like the plasticity and cohesion properties of the soils, the angle of internal friction of the soil as revealed from the shear strength test also shows a negative correlation with the frequency of gully occurrence (Fig. 8). However, the relationships shows a poor correlation coefficient of -0.34, implying that increase in the angle of internal friction will less likely lead to reduction in gully erosion occurrence. The statistical correlation result also corresponds with the spatial distribution of the friction properties of the soil within the study area which revealed that there were relatively few gully erosions in areas with high friction values as well as in areas with low friction values (Fig. 3f). Thus, this implies that the distribution of the gully erosion within the study area with respect to the angle of internal friction was rather a random event.

These results are in agreement with previous results on soil mechanical behaviours (Wang and Sassa, 2001; Igwe et al., 2007). These authors have revealed that the angle of internal friction depends more on the coarse fraction of the soil than on its fines content. This is because the coarse granular particles provide the needed grain to grain contact required to transmit load along the soil continuum. While this quality of coarse soils may be good for bearing of static loads, in the case of building foundations, they may fail to tensional or shearing stress resulting from fast moving runoffs. Therefore, for effective resistance of soils from shearing stresses, Zhang et al. (2001) and Kokusho et al. (2004) has noted the importance of soil gradation and its plasticity properties. They revealed that coarse grained soils with little or no amount of plastic fines in them was easily susceptible to shear forces due to the lack of the cementing effect which is usually contributed by the fines. Thus such un-cemented soils can easily be detached from its matrix by high energy runoff. These observations have shown that the cohesion and plasticity properties of soil particles contribute more to its shear strength than its angle of internal friction, thereby explaining the reason why cohesion and plasticity properties of soils correlated more to frequency of gully occurrence than its frictional properties, with correlation coefficients of -0.64, -0.55, and − 0.34, respectively.

Population density

Population density (POD) is one of the major factors that affect land-use. Thus population density was used as an indirect measure of land use in this research. The average population density was 1977 persons/km^2, which ranges from 462 to 5333 person/km^2 (Table 5). Surprisingly, the correlation analysis result revealed that increase in population density resulted to decrease in frequency of erosion with r value of -0.56 (Fig. 9). The distribution of gully frequency on the spatial map of the population density (Fig. 3b) also corroborated with the correlation analysis results. The findings from the results did not correspond with works of other authors on the impact of population densities on gully erosion, such as Olaniya et al. (2020) and Begy et al. (2021).The reason for the observed anomaly could be because the gullies predated the human population growth; thus areas with high frequency of gullies where naturally avoided due to its proneness to geohazard occurrence. This assumption could only be proved if time steps of the gully formation could be ascertained as way back as possible before urban development of the study area; which could be an impossible task. Another plausible reason while the population density gave an anomalous result could be because of the land-use by the population. This is because when a land area is altered from a natural forested ecosystem to an urbanized land-use consisting of rooftops, streets, and parking lots; it reduces its ability to infiltrate water (Horner et al., 1994). Essentially, any surface which does not have the capability to pond and infiltrate water will produce runoff during storm events. The enormous runoff that is produced is channelled away from the urban areas into the nearby water bodies. Where there are no nearby water bodies, they are discharged directly into relatively low populated areas at the edge of the urban centres. High rate of gully formation within the edge of urban settlements were observed in unpaved areas that serves as drainage channels for the urban and agricultural farm runoffs (Hill, 2010; Emeh and Igwe, 2018). Thus this could explain the negative relationship that was observed between erosion frequency and population density.

Therefore from this case study, using population density in frequency ratio model of erosion susceptibility may give an unreliable erosion susceptibility model if the history of the erosion channels and the land-use system were not ascertained. This is because increase in population density may not translate to increase in the frequency of gully erosion. Thus a proposal of more intrinsic properties that defines the contribution of environmental factor in gully erosion formation is recommended for subsequent studies.

Gully erosion Susceptibility

The results from the previous sections have revealed the individual contribution of the geotechnical, geomorphologic, and geo-environmental factors to soil susceptibility to gullying. However, the heterogeneous distribution of these factors will complicate the ease of detecting the severity of erosion in a given area. Hence, integration of these factors became necessary in order to delineate where they overlap, and the resultant effect of such interaction. It is true that rainfall amount and its intensity are important factors that control soil erosion (Zidat and Taimeh 2013; Zhao et al. 2019). However, in this study, the contributory factor of rainfall was assumed to be a constant since the area receives almost uniform amount and intensity of rainfall per time as revealed in Ifeka and Akinbobola (2015) and Nnadi et al. (2019). Thus, introduction of rainfall data will not produce any significant variation in the spatial analysis.

The integration of the soil geotechnical parameters and geomorphologic attribute of the area using the frequency ratio analysis revealed that slope contributed more to gully formation with percentage factor contribution (PFC) of 32.68%. This was followed by the plasticity of the soil with PFC of 25.50%, friction with PFC of 22.05%, and cohesion with PFC of 19.77% (Table 7). Gully erosion susceptibility map which resulted from integration of these parameters at their contributing percentages was classified based on their degree of severity (Fig. 10). This revealed that 11% of the total area falls within very low susceptibility, whereas 47% of the total area was within low susceptibility. Twenty one percent (21%), 15%, and 6% of the total area falls within moderate, high, and very high susceptibility, respectively (Table 8).

Inclusion of the population density to the susceptibility model resulted to slight variation in the PFC of other contributing factors; thus slight adjustment in the susceptibility map (Fig. 11). The result revealed that there was about 3% reduction in area with very low susceptibility and about 3% increment in area with low susceptibility. About 0.7% increment in area with moderate susceptibility was observed, whereas areas with high and severe susceptibility increase by 0.21% and 1.03%, respectively (Table 8). These variations in the gully erosion susceptibility map of the study area on inclusion of the POD to the model showed that increase in population resulted to decrease in frequency of erosion occurrence. This outcome could have been normal if urbanization led to conversion of must gully sites into urban infrastructures, thus resulting to lower gully events with increasing population. However, similar research from authors working on the effect of population and land-use on soil erodibility such as Roose (1996) and Fenta et al. (2021) revealed otherwise. Hence, the observed relation between the population density and erosion susceptibility as revealed from this research could be regarded as an anomaly. Therefore, the frequency ratio model may not be suitable for modelling erosion susceptibility which will account for population density as a contributory factor. This is because most gully channels may have predated urbanization, and erosion prone sites are naturally avoided; thus their relatively sparse population.

Comparing the soil distribution map (Fig. 2), the slope angle distribution map (Fig. 3c), and the susceptibility map (Fig. 10), it was observed that most areas with high to severe susceptibility are along steeps slopes which also coincides with the boundary of the two major soil types. This evidence validates the position of Egboka et al. (1990), who has suggested that the gullying activities are active denudation process which is cutting the sandstone Formation down to the water base level at the underlying shale Formation. This process which may have started long ago before urbanization would have created most of the deep gully scars that were mapped during the field study and which were used for the frequency ratio model.

From model that excluded population density as a contributory factor to gullying, the susceptibility map revealed that about 62% of the gully points which was used for the validation fell within high-severe susceptible area whereas 22% fell within the moderate susceptible area. The remaining 16% percent fell within low-very low susceptible area (Fig. 10). For the second model that integrated the population density factor, about 68% of the gully points fell within the high-severe susceptible area, whereas 17% and 15% of the gully points fell within the moderate and low-very low susceptible areas, respectively.

Therefore the validation result implies that the spatial distribution of gully erosion causative factors using the frequency ratio model can successfully be used to predict soil susceptibility to gullying with high degree of accuracy. Adoption of this method in soil erodibility studies will help in predicting areas that are susceptible to gullying, and thus reduce the financial implications of carrying out such project.

Conclusions

Results from the frequency ratio analysis revealed that slope – a geomorphologic factor, has a direct correlation with the gully formation within the study area, whereas population density, plasticity, friction, and cohesion properties of the soil show a negative correlation. It was found that the sequence of contribution of these soil erodibility factors to gully erosion frequency was slope > plasticity > cohesion > friction > population density with percentage contribution of 30%, 23%, 20%, 18%, and 9%, respectively.

The susceptibility map which resulted from Integration of geomorphologic and geoenvironmental factors with soil geotechnical properties revealed the severity distribution of gully erosion susceptibility with the study area. It shows that about 58% of the total land area is less likely to be susceptible to gullying, since these area fell within the very low-low susceptibility area of the map. Twenty one percent (21%) of the total area fell within the moderate susceptibility area of the map; hence are likely to be susceptible to gullying. The remaining 21% of the total area are very likely to be susceptible to gully because they fell within high-severe susceptibility area of the map.

The model that excluded population density as gully erosion contributory factor predicted 62% of the gully points within the high-severe susceptible area, 22% at the moderate susceptible area, and the remaining 16% at the low susceptible area. Integration of the population density to the model resulted to prediction of 68% of the gullies within the high-severe susceptible area, whereas 17% and 15% of the gully points fell within moderate and low-very low susceptible areas, respectively.

The observation that Increase in population density lead to decrease in gully erosion was anomalous, since it was not a usual trend from previous observations. Therefore, authors recommend the use of frequency ratio model with integration of slope and geotechnical properties of soils in geospatial analysis of gully erosion. They however, advised against the integration of population density factor to the model since it may not be a suitable for soil erodibility studies and thus suggested the use of other intrinsic environmental factor such as land-use, instead.

Declarations

Data Availability Statements

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Funding' and/or 'Competing interests

Authors declare that there is no conflict of interest. No funds, grants, or other support was received. Also, all authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Emeh Chukwuebuka, Ogbonnaya Igwe, and Ugwoke Tochukwu Anthony Silas . The first draft of the manuscript was written by Emeh Chukwuenuka and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Tables

Table 1: Summary statistics of the slope angles

Class	Min	Max	Mean	GEA (m^2)	EFCA (m^2)	FR	RF
1	0	2.54	1.27	1564	173904	0.009	3.52
2	2.55	5.07	3.81	2984	176247	0.017	6.62
3	5.08	8.45	6.765	2283	73755	0.031	12.11
4	8.46	14.37	11.415	1350	24604	0.055	21.47
5	14.38	43.12	28.75	558	3880	0.144	56.27
					FW	0.256	

Table 2: Summary statistics of the soil plasticity

Class	Min	Max	Mean	GEA (m^2)	EFCA (m^2)	FR	RF
1	0.32	3.25	1.785	1581	141822	0.011	5.59
2	3.26	6.19	4.725	2017	39923	0.051	25.33
3	6.2	9.12	7.66	1776	30932	0.057	28.78
4	9.13	12.05	10.59	1076	30838	0.035	17.49
5	12.06	14.99	13.525	1018	57233	0.018	8.92
6	15	17.92	16.46	818	72666	0.011	5.64
7	17.93	20.86	19.395	183	33894	0.005	2.71
8	20.87	23.79	22.33	207	27984	0.007	3.71
9	23.8	26.72	25.26	63	17271	0.004	1.83
					FW	0.199	

Table 3: Summary statistics of the soil cohesion

Class	Min	Max	Mean	GEA (m^2)	EFCA (m^2)	FR	RF
1	0.49	8.17	4.33	3048	162123	0.019	12.16
2	8.18	15.86	12.02	2522	53876	0.047	30.27
3	15.87	23.54	19.705	1375	50229	0.027	17.70
4	23.55	31.23	27.39	916	66955	0.014	8.85
5	31.24	38.91	35.075	487	51710	0.009	6.09
6	38.92	46.6	42.76	101	38444	0.003	1.70
7	46.61	54.28	50.445	233	20828	0.011	7.23
8	54.29	61.97	58.13	24	6843	0.004	2.27
9	61.98	69.65	65.815	33	1555	0.021	13.72
					FW	0.155	

Table 4: Summary statistics of the soil angle of internal friction

Class	Min	Max	Mean	GEA (m^2)	EFCA (m^2)	FR	RF
1	18.31	22.1	20.205	489	51661	0.009	5.49
2	22.11	25.9	24.005	1221	133857	0.009	5.29
3	25.91	29.69	27.8	1737	50826	0.034	19.82
4	29.7	33.48	31.59	2236	43827	0.051	29.58
5	33.49	37.28	35.385	2835	46002	0.062	35.73
6	37.29	41.07	39.18	187	31436	0.006	3.45
7	41.08	44.86	42.97	0	33415	0.000	0.00
8	44.87	48.66	46.765	34	30855	0.001	0.64
9	48.67	52.45	50.56	0	30684	0.000	0.00
					FW	0.172	

Table 5: Summary statistics of the population density

Class	Min	Max	Mean	GEA (m^2)	EFCA (m^2)	FR	RF
1	467.29	791.67	629.48	6399	130694	0.049	66.35
2	791.68	1459.49	1125.585	1111	106243	0.010	14.17
3	1459.5	2070.07	1764.785	59	36135	0.002	2.21
4	2070.08	2661.57	2365.825	345	80472	0.004	5.81
5	2661.58	5332.87	3997.225	825	97616	0.008	11.45
					FW	0.074	

Table 6: Summary statistics of the gully physical attributes

	Length	Width	Depth
Count	49.00	49.00	49.00
Mean	914.33	23.35	6.20
SD	357.26	18.27	2.32
Max	1780.00	63.00	13.00
Min	270.00	3.00	3.00

SD = Standard deviation

Table 7: Percentage factor contribution of the gully erodibility parameters

	Without POD		With POD	
Parameter	**FW**	**PFC%**	**FW**	**PFC%**
Slope	0.256	32.68	0.256	29.86
Plasticity	0.199	25.50	0.199	23.30
Friction	0.172	22.05	0.172	20.15
Cohesion	0.155	19.77	0.155	18.07
POD			0.074	8.62

POD = Population density, FW = Factor weightage, Percentage factor contribution

Table 8: Summary of gully erosion susceptible areas with and without population density factor

Severity	Class	ESA-POD	ESA-POD (%)	ESA+POD	ESA+POD (%)	%Variation	GEP (%)
very low	<2	5669	10.99	4242	8.26	-2.73	8
low	2-3	24459	47.40	26034	50.70	3.29	8
moderate	3-4	10705	20.75	11000	21.42	0.67	29
high	4-5	7836	15.19	7690	14.98	-0.21	23
Vey high	5-7	2928	5.67	2385	4.64	-1.03	31
Total		51597	100	51351	100		100

GEP = gully event point, ESA-POD = Erosion Susceptible Area without population density factor, ESA+POD = Erosion Susceptible Area with population density factor

Figures

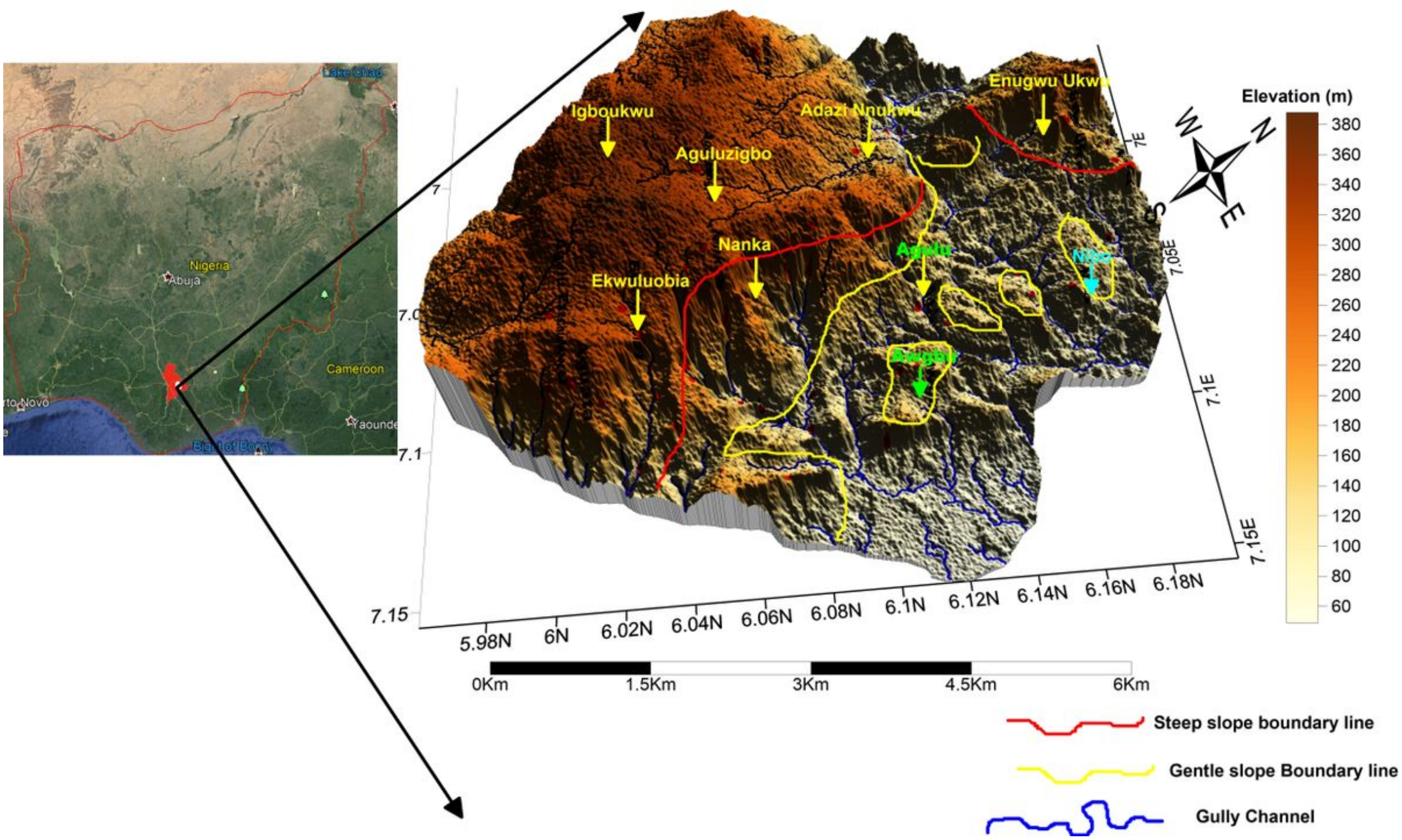

Figure 1

map of the study area showing 3D physiographic features

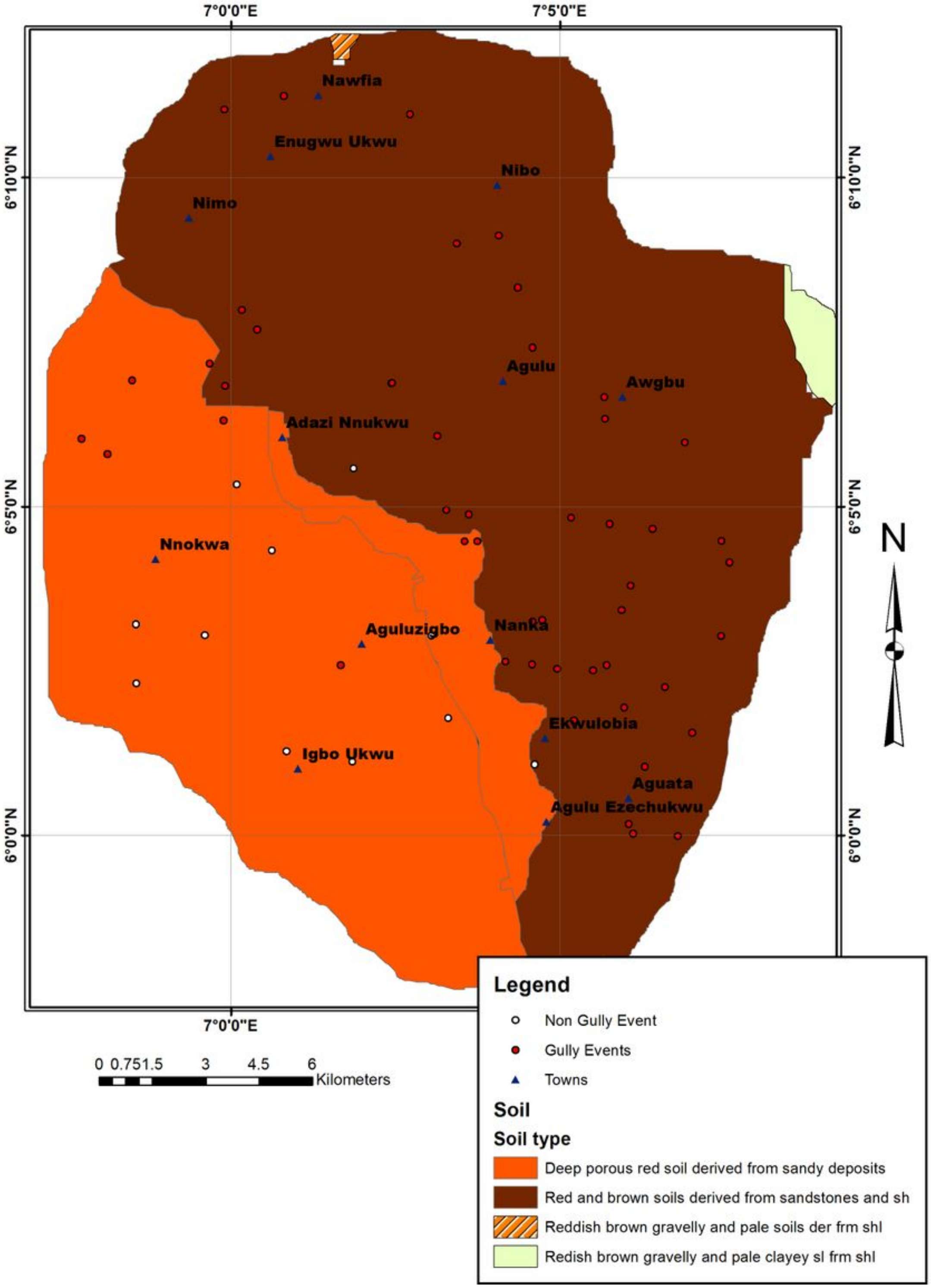

Figure 2

Soil map of the study area

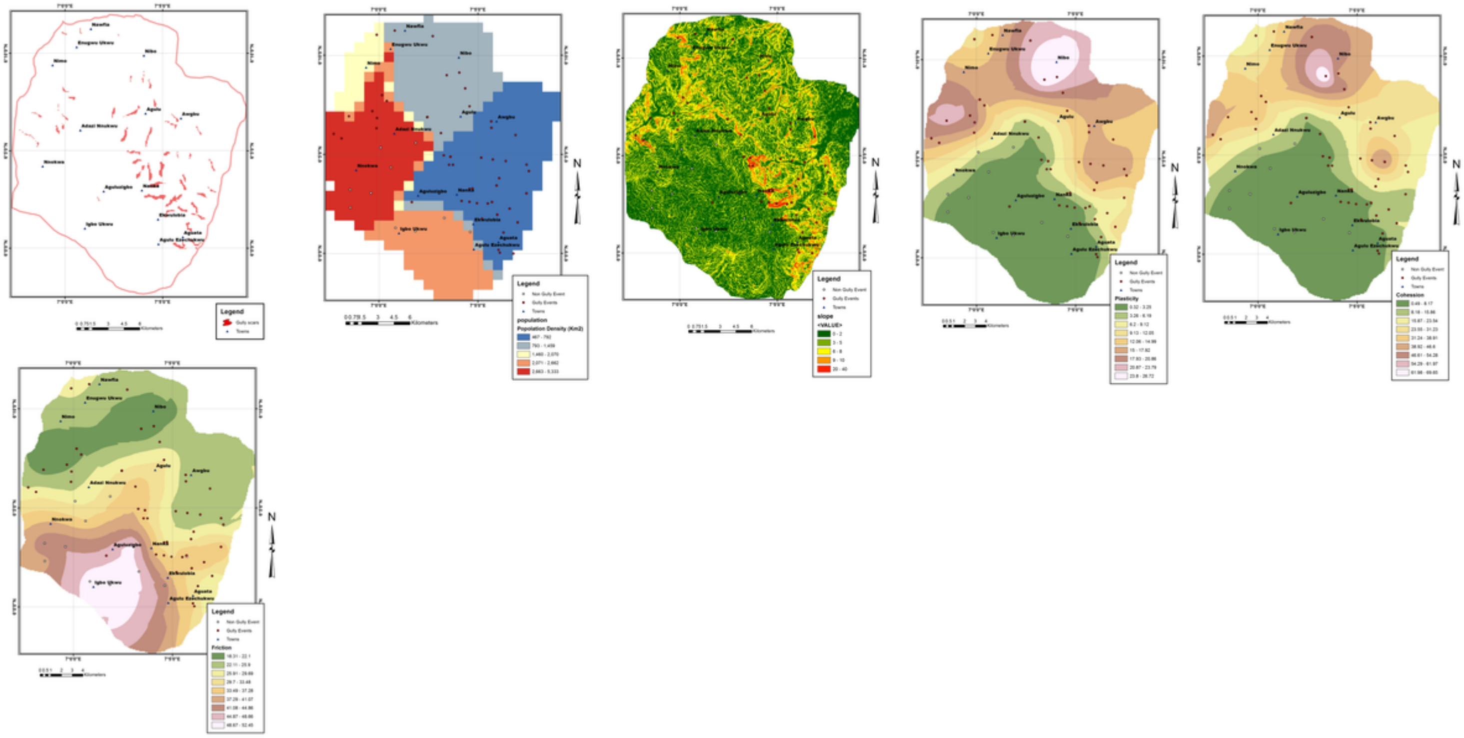

Figure 3

a Gully erosion event hazard map

b Population density map

c Spatial distribution of slope angle of the study area

d Spatial distribution of plasticity index of the underlying soils

e Spatial distribution of cohesive strength of the underlying soils

f Spatial distribution of frictional force of the underlying soils

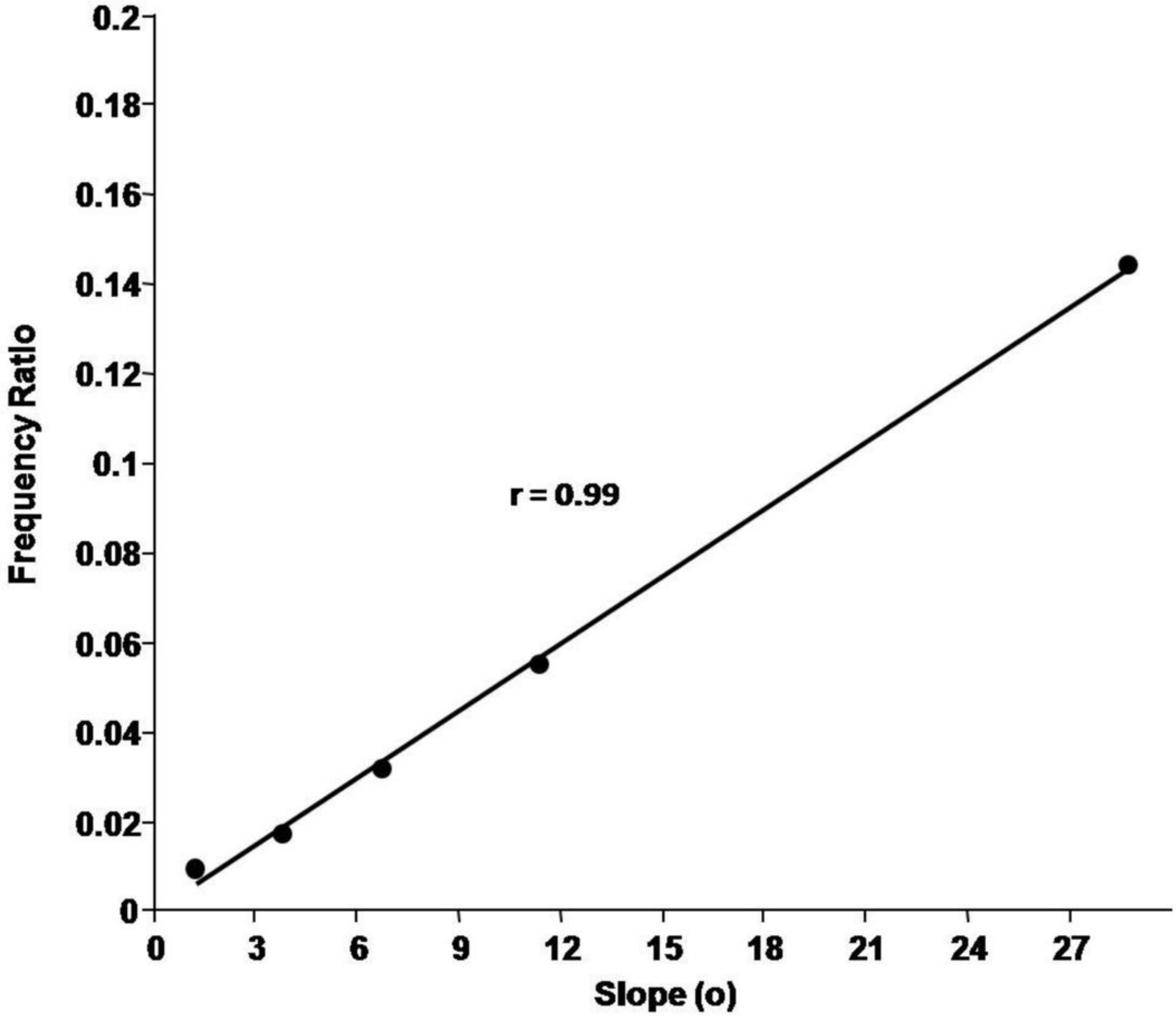

Figure 4

Relationship between slope and frequency of gully erosion

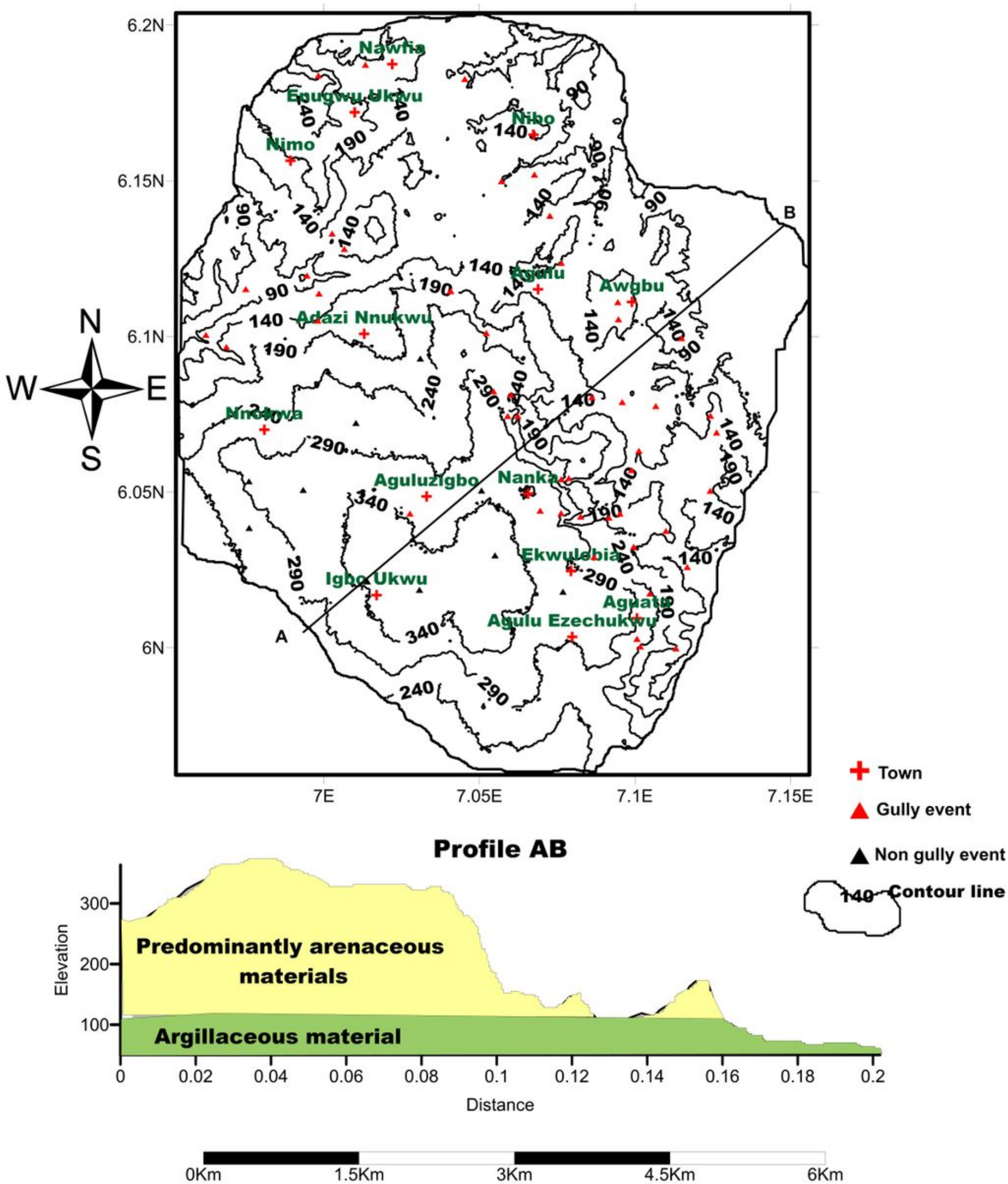

Figure 5

Topographic contour map with cross-section of the study area

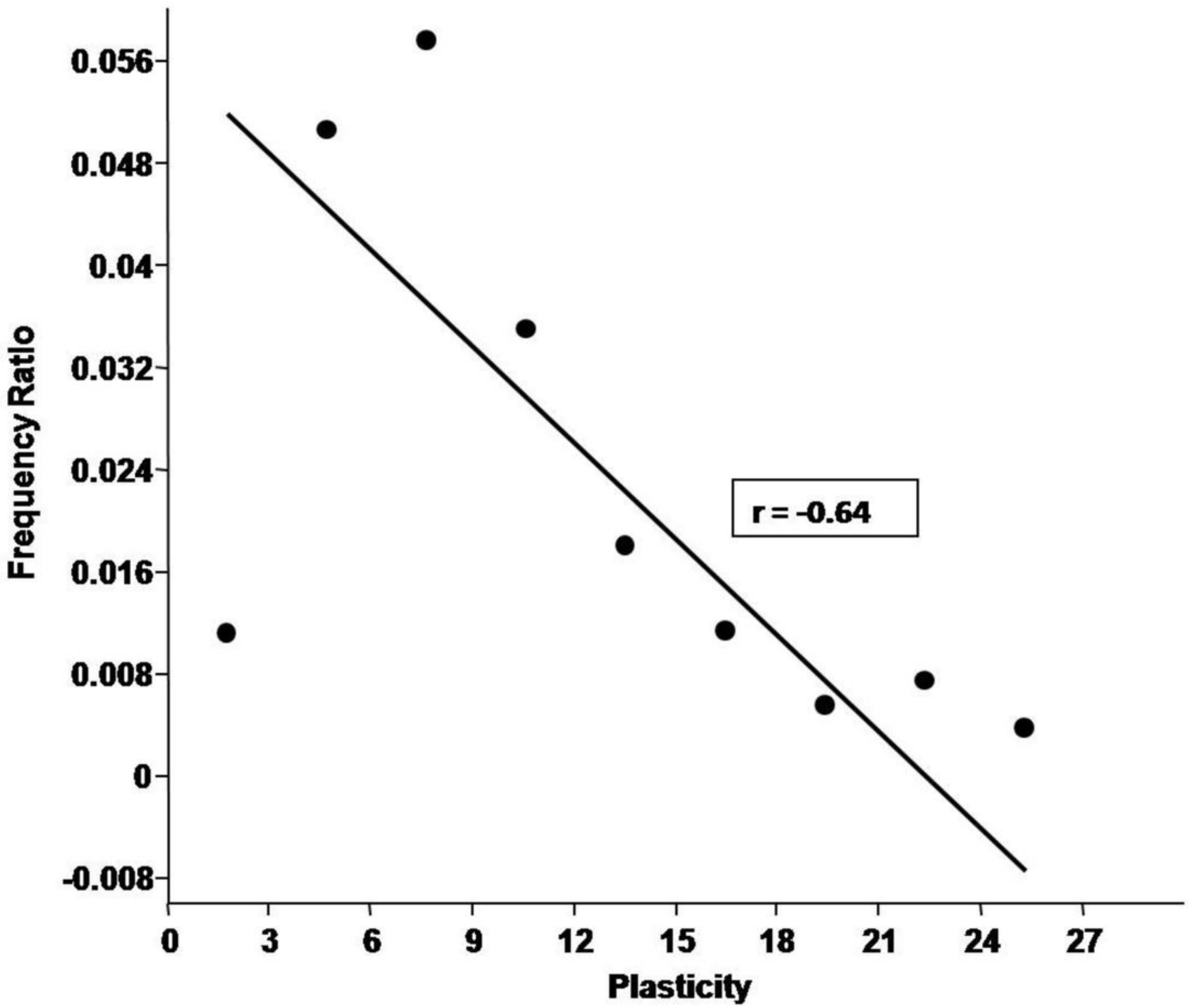

Figure 6

Relationship between soil plasticity and frequency of gully erosion

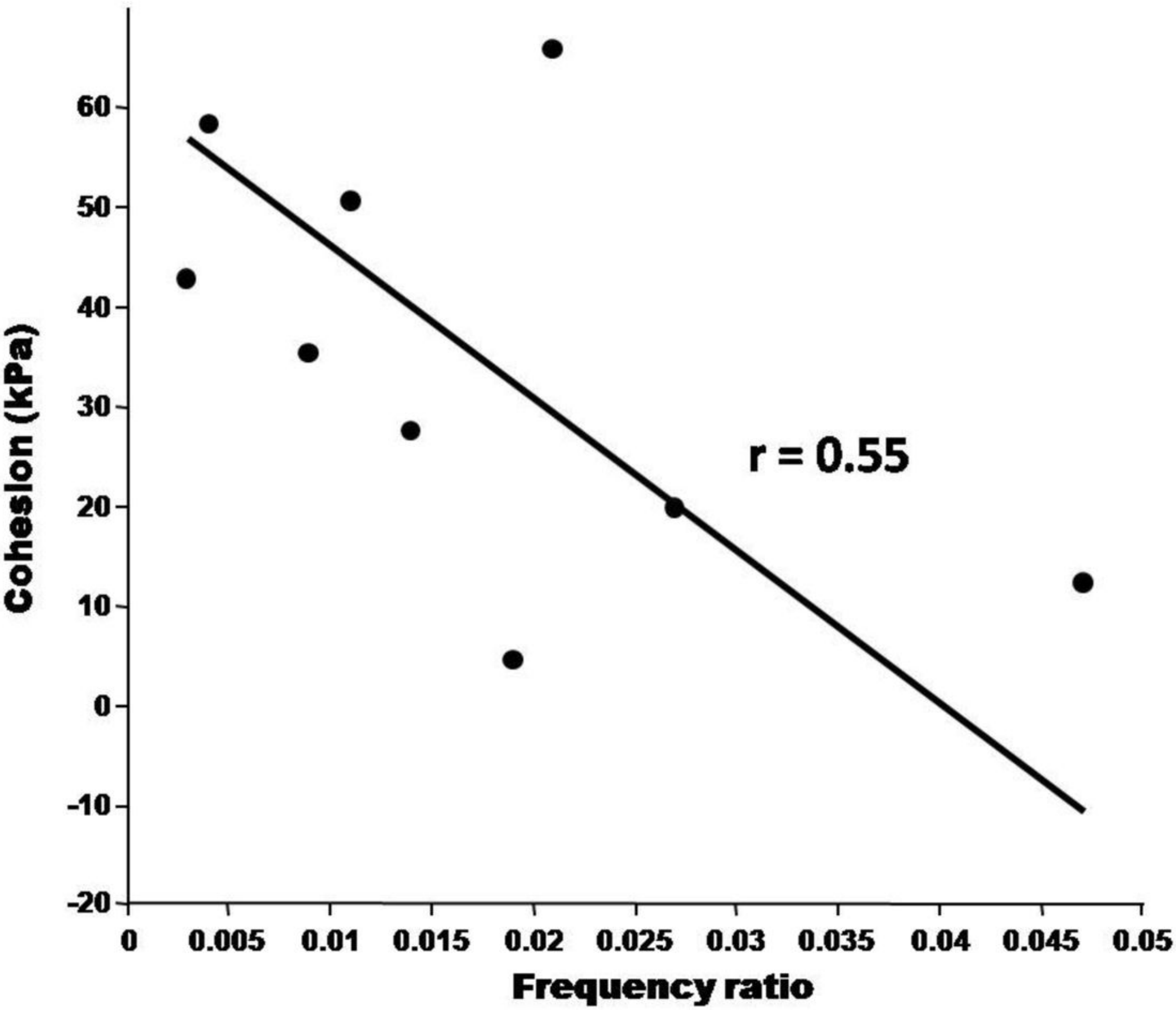

Figure 7

Relationship between soil cohesion and frequency of gully erosion

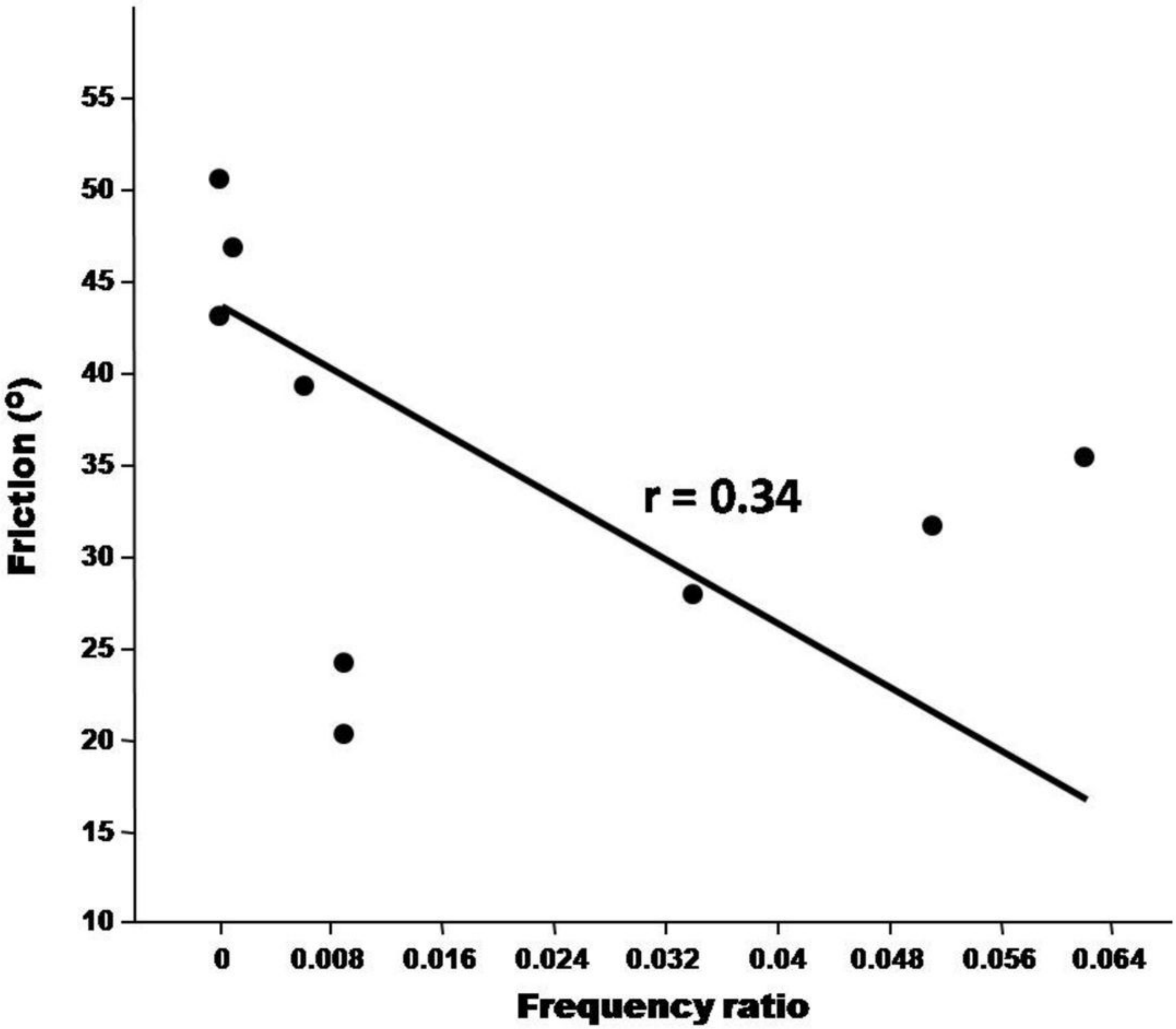

Figure 8

Relationship between soil friction and frequency of gully erosion

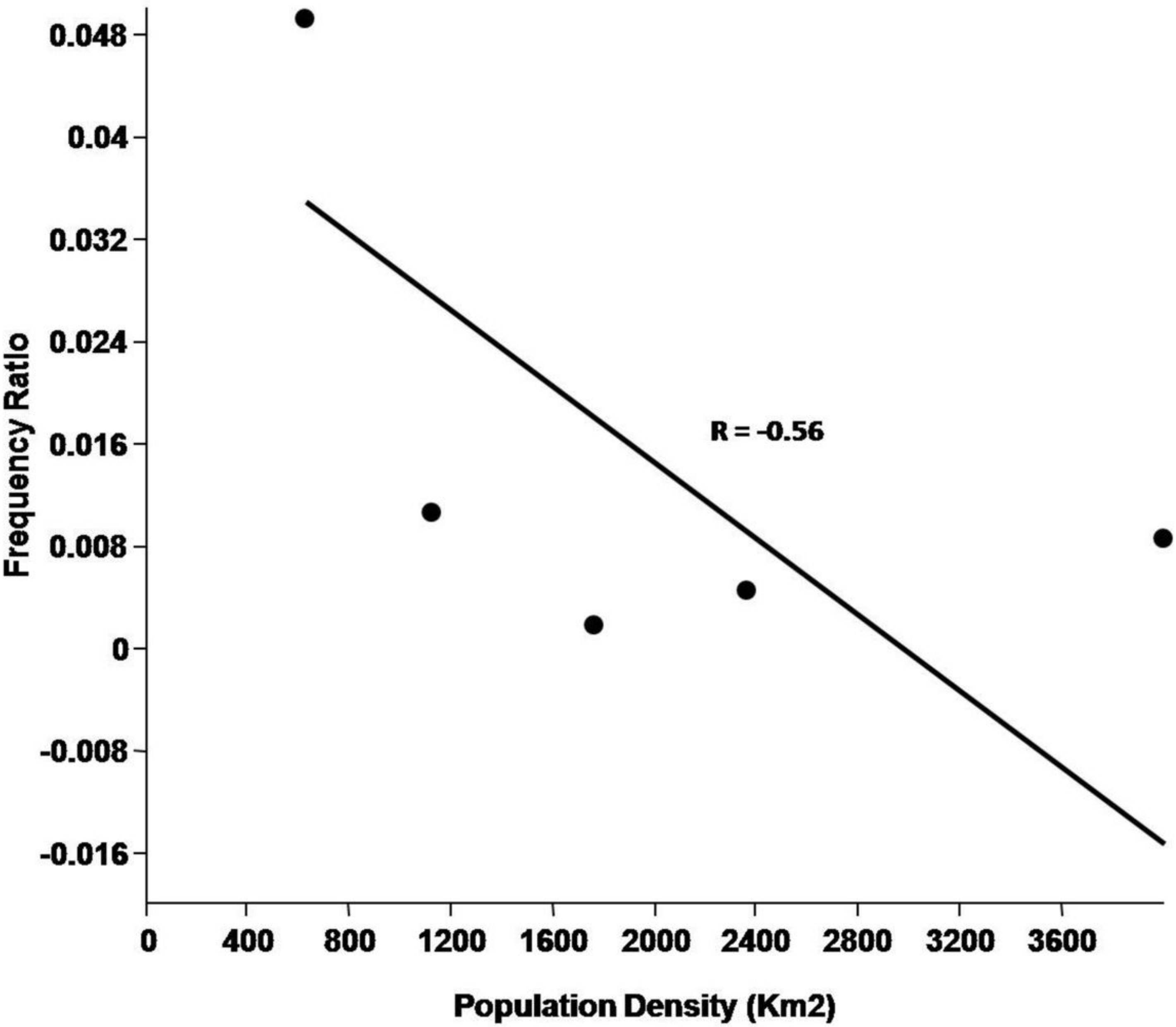

Figure 9

Relationship between population density and frequency of gully erosion

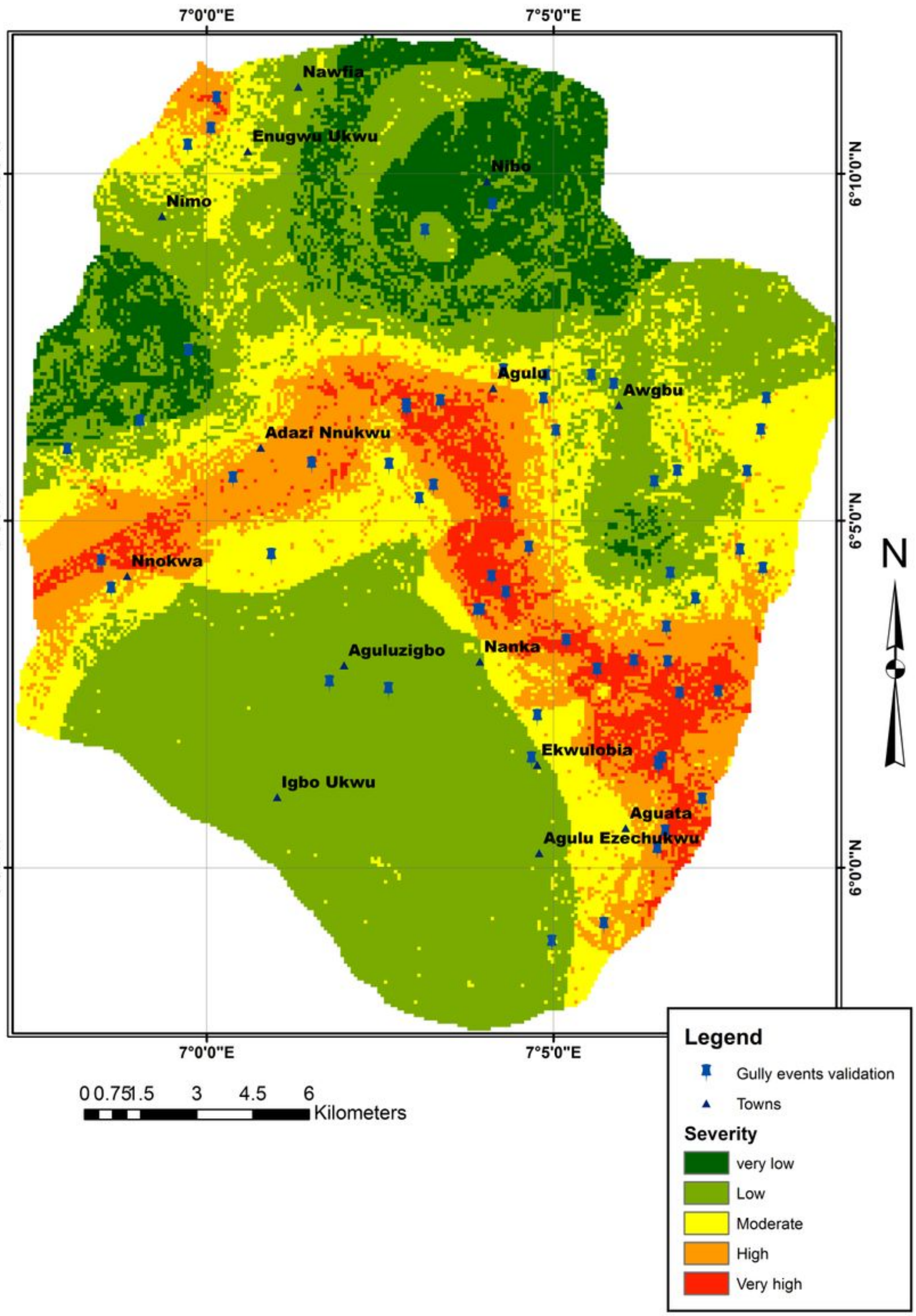

Figure 10

Gully erosion susceptibility map excluding population density factor

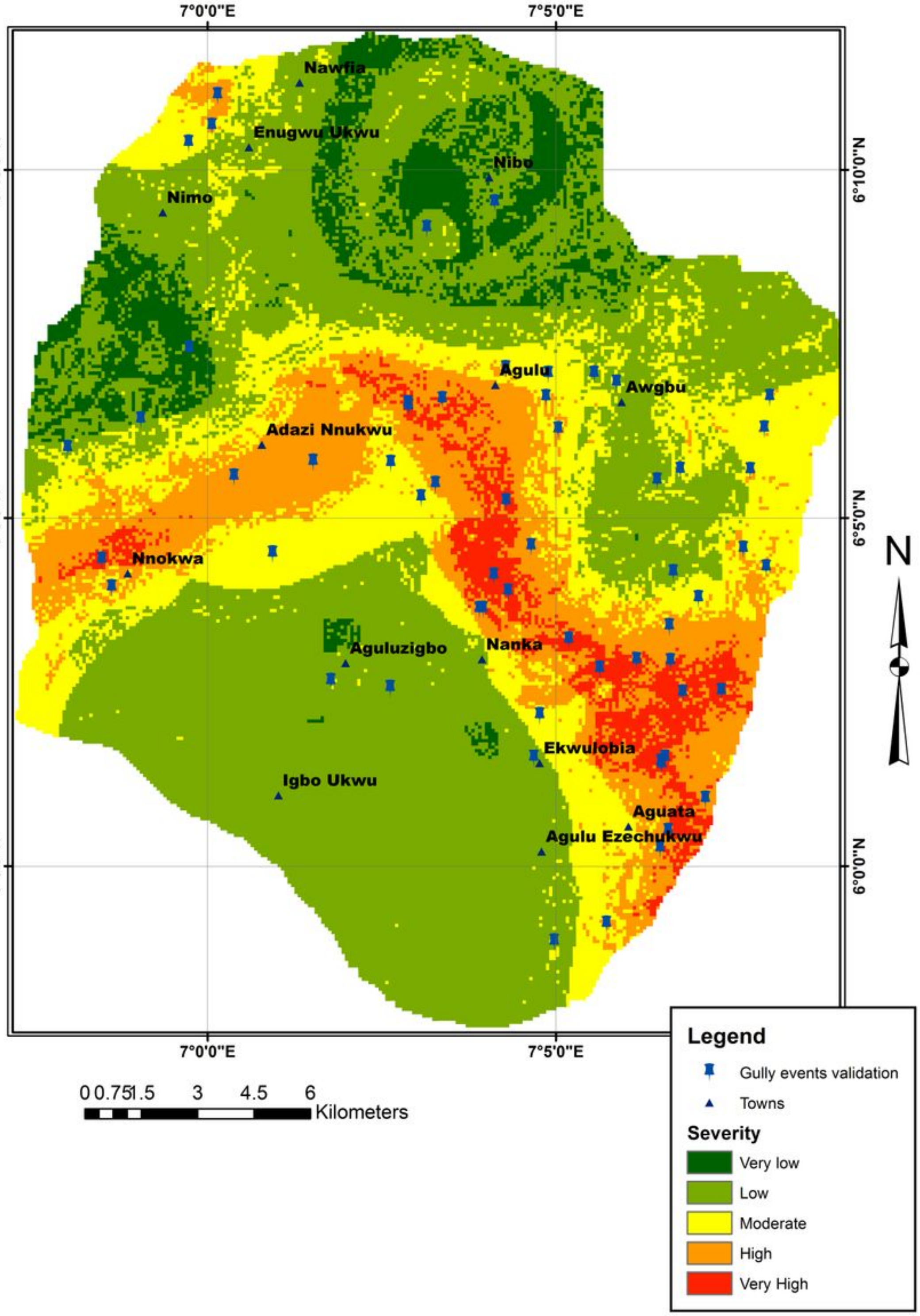

Figure 11

Gully erosion susceptibility map including population density factor