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A multi-method approach to analyse changes in gully characteristics between 2009 and 2018 in southeast Nigeria

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Abstract

Gully erosion is the dominant environmental problem in southeast Nigeria and has led to loss of human and material resources. In this study, we evaluated changes in gully characteristics in southeast Nigeria and their potential drivers between 2009 and 2018 using a multi-method approach: analysis of high-resolution satellite imagery (2–5 m) and focus group discussions. Gully numbers increased from 26 to 39 and mean gully length increased from 0.39 to 0.43 km. We found that land adjacent to rivers had the highest concentration of gullies which is associated with an increase in slope angle from 10 to 58% up to 500 m from rivers. Regarding potential gully-drivers, land-use changes were observed. Non-vegetated lands increased from 58.6 to 144.7 km^2 between 2009 and 2018, while reductions in fallow lands from 281.2 to 57.8 km^2 were observed. Results from focus group meetings indicate there was no gullying in the area before the Nigerian civil war (1967–1970). War-time activities such as digging trenches and increased population density were said to have led to the formation of the oldest gullies in the area. Although war-time activities have ceased, meeting attendees believed that present land-use changes have increased the volume of surface runoff and thus enhancing gully erosion. Incorporating local knowledge in this study has therefore provided a valuable understanding on the key drivers of gullying that pre-dates the availability of freely available high-resolution satellite data.

KEYWORDS
civil war, gully erosion, gully-drivers, land-use changes, local knowledge, surface runoff

1 | INTRODUCTION

Gully erosion is recognised globally as an important environmental problem with significant effects on the availability of land for cultivation, crop productivity and land degradation (Graves et al., 2015; Morgan & Rickson, 2003; Rickson et al., 2015; Vanmaercke et al., 2021; Zhang et al., 2002). Gully erosion is the dominant environmental problem in the southeast region of Nigeria and has led to the isolation of villages, severance of communication lines such as roads, as well as loss of homes, schools, human and material resources (Egboka et al., 1990). Several studies have been conducted on gully erosion and many factors have been found to enhance gullying, for example intensive rainfall (Afegbua et al., 2016; Obi & Salako, 1995; Ofomata, 1987; Vanmaercke et al., 2016), prolonged drought (Cerdà, 1997; Fleitmann et al., 2007), geology and lithology (Betts et al., 2003; Castillo & Gómez, 2016; Ghimire et al., 2006; Parkner et al., 2007; Sonneveld et al., 2005), soil characteristics (Egboka & Nwankwor, 1985; Okagbue & Ezechi, 1988), nearness to rivers and roads (Frankl et al., 2019; Yibeltal, Tsunekawa, Haregeweyn, Adgo, Meshesha, Masunaga, et al., 2019; Zabihi et al., 2018), land-use changes (Frankl et al., 2019; Panagos et al., 2020; Yibeltal, Tsunekawa, Haregeweyn, Adgo, Meshesha, Aklog, et al., 2019) and topography (Gómez-Gutiérrez et al., 2015; Yibeltal, Tsunekawa, Haregeweyn, Adgo, Meshesha, Masunaga, et al., 2019). These results suggest the multiplicity of gully drivers and the complexity of gullying.

Different research methods have been used to study gully erosion, for example, Okagbue & Ezechi (1988) and Iheme et al. (2016) adopted geotechnical approaches to understand drivers of gully erosion in southeast Nigeria. Their study found that soils in the area prone to gullying have higher sand content, high permeability, and low cohesion. High permeability may reduce surface runoff but facilitate infiltration and high internal flow velocities and seepage pressures, whereas low cohesion enhances dispersal by surface runoff (Okagbue & Ezechi, 1988). Ezezika & Adetona (2011) adopted a community-based method including interviews with stakeholders and informal discussions with experts on gully erosion to understand gully-drivers. Their study found that gully erosion is driven by human activities, especially, poor land-management practices. Conoscenti et al. (2014) produced a gully susceptibility map of a river catchment in central-northern Sicily using combinations of GIS, interpretations of aerial photos, analyses of land use and topography. Rahmati et al. (2017) used a conditional probability (CP) model to establish the spatial relationship between gullies and driving factors and found that slope angles less 15° had highest concentrations of gully erosion in the Kashkan-Poldokhtar watershed, Iran. Of all topographic variables associated with gullying, the size of gully upslope contributing area has a critical control on gullying as larger catchments produce higher volumes of runoff (Frankl et al., 2012; Dong et al., 2013; Vanmaercke et al., 2016; Yibeltal, Tsunekawa, Haregeweyn, Adgo, Meshesha, Masunaga, et al., 2019). However, considering the influence of changes in land use on gully evolution, it is also important to understand how these land-use changes in individual gully catchments influence gullying. One can say that no single research method provides all the answers to gullying, rather, research methods are chosen based on research questions of interest and data availability.

As already stated, gullying is a complex process. It is challenging to study gullying over medium to long timescales (10–50 years), especially, in data-scarce regions, because of the lack of observations. To overcome this challenge, some studies on gully erosion have adopted multi-method approaches such as incorporation of community-based knowledge, analysis of remotely sensed data and quantitative analysis (Frankl et al., 2016; Nyssen et al., 2006; Tebebu et al., 2010). The significance of incorporating community knowledge in gully studies is fourfold: First, to eradicate any form of mistrust for science on the part of local population. Second, incorporating local knowledge provides for comparison of scientific understanding with prevailing local expertise, thus, enriching scientific findings. This second significance forms part of the public debate model proposed by Callon (1999). Third, to avoid the adoption of non-native 'top-down' approaches which are not effective in many instances in solving local environmental problems (van Aalst et al., 2008). Finally, it provides qualitative information on gullying which extends historical record and fills the existing gap due to unavailability of data (e.g., remotely sensed imagery of study area). Adopting a multi-method research approach to study gully erosion improves scientific knowledge of gully-driving processes by comparing scientific knowledge with local expertise. Changes in gully characteristics (form) are likely driven by the interactions among dominant drivers of gully erosion (process), hence, to understand gully dynamics, knowledge of interactions of the dominant drivers is important. To this end, the aim of this paper is to use a multi-method approach to ascertain the dominant drivers of the changes in gully characteristics in the study area between 2009 and 2018.

2 | MATERIALS AND METHODS

2.1 | Study area

Five Local Government Areas (LGAs): Ideato North, Ideato South, Isu, Njaba and Orlu covering an area of 534 km^2 in Imo State, southeast Nigeria were studied (Figure 1). The climate of southeast Nigeria is tropical with rainfall decreasing from the coast inland. Rainfall generally is intense and ranges from over 2500 mm annually in the southernmost region to about 1500 mm in the northern borders (Igwe, 2012). Along the coast, mean annual minimum and maximum temperatures range between 21 and 29°C and in the interior, they range between 30 and 33°C respectively. The study area lies within the rainforest vegetation belt (Ezemonye & Emeribe, 2012) where the forests have been disturbed over the years due to demographic pressures. The soils are: cohesionless, have high sand contents and are very permeable with high infiltration rates of up to 3571 mm hr^{-1} (Chiemelu et al., 2013; Obi & Asiegbu, 1980; Okorafor et al., 2017). Four geological formations underlay the study area: Imo Shale, Benin, Ogwashi-Asaba and Ameki Formations (Usman et al., 2014). These geological formations are sandy with intercalations of clay. Two major rivers, Njaba and Orashi have their sources within the study area (Figure 1). Other streams such as *Okpii and Ezizi* also have their sources located within the study area.

2.2 | Gully mapping and geomorphic analysis

High-resolution imagery (with pixel sizes of 2 × 2 m and 5 × 5 m) covering the study area were obtained for 2009, 2014 and 2018 (Table 1) to map changes in gully characteristics. Gully mapping commenced in 2009 when freely available high-resolution satellite data of the study area became available. Fieldwork was conducted between April and June 2019 to ground-truth the results. Gullies were digitised manually from the satellite imagery as polygons. The maximum length of each gully centreline was recorded. To measure gully widths, lateral measurements perpendicular to a centre line were taken at 1-m intervals and an average derived. The area of the digitised polygon represented gullied area. To ground-truth mapped gullies, a hand-held GPS (Garmin Oregon 300 model) was used to take coordinate points of seven gullies in five visited communities, Amucha, Obibi-Ochasi, Isu

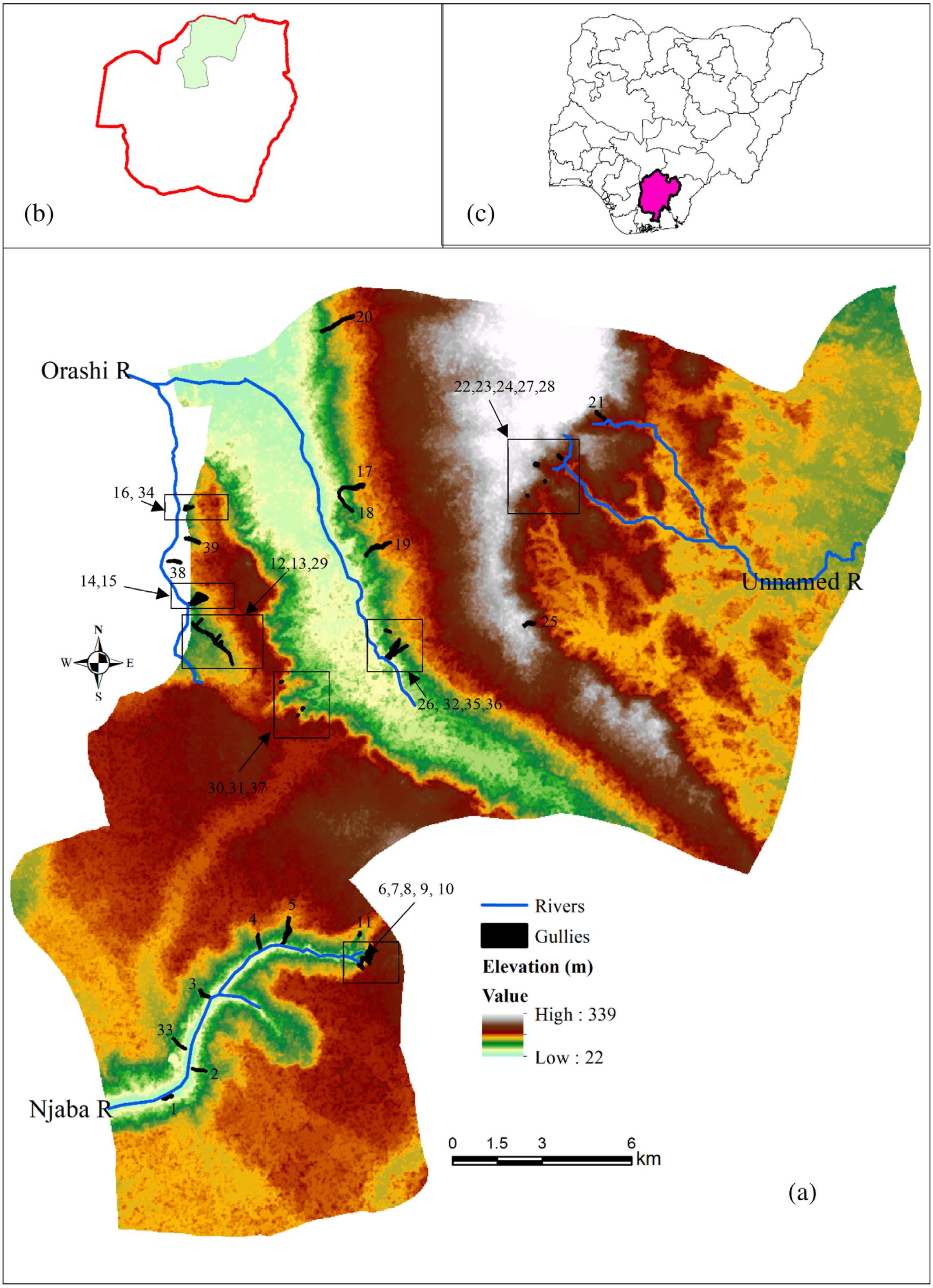

FIGURE 1 (a) study area showing gullies, rivers and elevation. Gully numbers are the same with Table 2. (b) Imo State showing study area. (c) Nigeria showing the southeast states [Color figure can be viewed at wileyonlinelibrary.com]

Njaba, Urualla, and Umueshi. These field-measured locations were used to verify the location of digitised gullies within ARCGIS. The gullies in Amucha and Obibi-Ochasi were chosen for field verification based on a government publication of 1981 which stated that gullies in both communities 'were among the oldest in the State.' The gullies in other communities were chosen based on the literature review.

TABLE 1 Satellite imagery used for gully mapping and land-use classification

Satellite	Source	No. of bands	Spatial resolution (m)	Cloud cover (%)	Date of acquisition
RAPIDEYE-1	Planet.com	5	5	0	November, 2009
RAPIDEYE-3	Planet.com	5	5	0	December, 2018
WORLDVIEW-2	DigitalGlobe Foundation	8	2	0	January, 2014

TABLE 2 Changes in the 26 old gullies between 2009 and 2018

Gully 1D	2009 length (km)	2009 width (m)	2009 area (m^2)	2018 length (km)	2018 width (m)	2018 area (m^2)
1	0.28	30.3	7224	0.36	47.3	17,024
2	0.31	15.2	4865	0.5	23.29	11,287
3	0.5	31.8	18,027	0.4	44.89	18,804
4	0.5	30.31	15,166	0.5	36.42	19,371
5	0.7	43.63	32,508	0.9	56.68	52,462
6	0.06	31.4	1723	0.23	50	11,661
7	0.09	34.9	3070	0.06	20.7	1631
8	0.22	49	10,622	0.33	57.3	19,059
9	0.19	42.3	8203	0.22	50.14	14,170
10	0.09	38.8	3040	0.11	55.4	5699
11	0.12	25	2661	0.11	17.94	2461
12	1.4	19.76	29,442	2	31.46	57,679
13	0.23	22	4254	0.34	13.2	4424
14	0.29	40	9557	0.65	60	34,105
15	0.45	39.22	22,489	0.53	38.25	24,480
16	0.1	41.05	3887	0.28	44.76	10,830
17	0.8	38.66	38,164	0.9	38.86	54,919
18	0.36	25.37	9235	0.7	27.87	19,357
19	0.93	59.24	47,530	0.98	72.23	52,235
20	1.2	31	39,183	1.2	44.84	53,182
21	0.46	30.85	11,270	0.5	29.11	16,929
22	0.16	35.67	5879	0.2	30.53	6589
23	0.1	34.09	3557	0.11	44.17	4902
24	0.05	29.3	1439	0.08	34.73	2325
25	0.33	51.1	17,031	0.37	57.6	20,060
26	0.3	27.81	8125	0.6	31.07	19,892

Two gullies were identified in Isu Njaba and Obibi-Ochasi, whereas one gully each was identified in the other communities. To determine changes in gully dimensions, the 2009 values were subtracted from the 2014 and 2018 values. Although the 2014 satellite data only covers 34% of the study area, it was used to understand stepwise changes in gully sizes where possible. Two different measurements were performed for 2018 gully dimensions:

a. Gullies mapped in the 2009 satellite imagery ('old' gullies)
b. Gullies that were identified for the first time in the 2014 or 2018 imagery ('new' gullies).

Geomorphic variables were extracted from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) at 30 m resolution. Relative relief and maximum slope values of the gully heads were acquired from the DEM. Relative relief reflects the difference between highest and lowest elevation values within a zone of interest and maximum slope values help one understand sites of steepest slope within a zone where the erosive power of surface runoff would be most pronounced. The DEM was used to delineate gully watersheds using a pour point analysis in ARCGIS to identify gully upslope contributing area. Some catchments had more than one gully due to one or combinations of the following reasons:

1. A 30 m DEM was used for catchment delineation in comparison with the high resolutions of the satellite imagery used to map the gullies (Table 1). Gullies were found close to each other in all catchments where more than one gully was mapped (e.g., some gullies

were <10 m apart in some catchments). Considering the 30 m resolution of the DEM and gully distance of <10 m from one another, the DEM may not likely delineate two different catchments for both gullies.

2. Tributary gullies (referred to by the villagers as gully-fingers). A gully might flow directly into another and during mapping, more than one gully is identified but the same catchment feeds both gullies.
3. Extensive vegetal cover can make a single gully appear in two different parts, and thus, during mapping, more than one gully is identified, whereas the gully is a single continuous gully which had been apparently separated into different units by vegetation.

Gully catchments were named based on the location of the gullies in the LGA or autonomous communities. To measure gully head distance from rivers, a line was drawn from the gully head to the river. Another line was drawn from gully mouths to rivers, hence representing gully mouth distance from the river.

2.3 | Land-use classification

Satellite data listed in Table 1 were used for supervised land-use classifications. Land use was classified at the regional and catchment scales. Catchment-scale land-use classifications were important to identify possible variations in land uses in different catchments which may in turn impact hydrological processes that are often perceived to be an important driver of gullying (Birhanu et al., 2019; Njoku et al. (2017). In the study area, land is used for farming, building or left to fallow, hence land use was classified into three: non-vegetated (bare surfaces and built environments), open vegetation (grasses and farms) and fallow/trees (non-farmed land left to fallow). Accuracy assessments were carried out for the land-use maps using 90 validations points generated on the RapidEye satellite imagery. A stratified confusion matrix was computed to compare true classes with mapped classes and summary statistics were computed. Road construction is an example of land-use change; roads were digitised from the satellite imagery using a line shape file. The Euclidean distance between gully head and road was calculated representing gully head distance from road.

2.4 | Statistical analysis

Principal component analysis (PCA) was used to quantify the relative importance of gully drivers (maximum slope, relative relief, nearness to rivers and roads). Although geomorphic variables were collected at all gully heads, gullies that were not within 1 km of a river or road were removed from the PCA. This threshold was selected based on the average distance of gully heads from rivers and roads (Section 3.3). To ensure a uniform number of input variables for statistical analyses, only gullies that satisfied this condition of nearness to rivers and roads were added to the PCA. Where for example a gully was <300 m from a road but >3 km from a river, the gully was excluded from the PCA. Attributes from 29 gullies were included in the PCA. Because upslope contributing areas were not defined for some gullies that satisfied the above condition (nearness to rivers and roads) and judging from the nature of the satellite data used in this study (Section 2.3), two sets of multiple regression analysis were used to relate gully changes to gully drivers.

1. Land-use changes and changes in gully sizes: two sets of multiple regression analyses were performed. First, 14 gully catchments captured in the 2009 to 2018 imagery and secondly, on seven gully catchments captured in the 2014 satellite data. A gully which was first identified in 2009 was not found in the 2014 imagery, hence, this gully catchment was removed from multiple regression analysis. Two land-use classes, non-vegetated and tree/fallow were selected as predictive variables while changes in gully length, width, and area were the outcome variables
2. Other gully drivers and changes in gully sizes: based on results of the PCA, predictive variables included relative relief, nearness to rivers and roads while changes in gully characteristics were the outcome variables.

2.5 | Focus group meetings

To learn about community knowledge on gullying, fill existing gaps due to unavailability of long term remotely sensed data and improve scientific knowledge on gully-driving factors, focus group meetings were used. Two meetings were held in Amucha and Obibi-Ochasi communities and each had 10 community leaders comprising seven men and three women. We intended to have equal number of men and women, however, in both communities, three women attended the meetings. These meetings were held at the homes of the community Chief. Prior to the meeting days, two local guides disseminated information regarding aims of the meetings. Amucha and Obibi-Ochasi communities were selected for focus group meetings based on a government publication of 1981 (Section 2.2). The agendas for the meetings were organised into five thematic areas: hazard identification, hazard mitigation, vulnerability and exposure, risk communication and factors constraining risk mitigation. Before the start of meetings, the elders were asked to give a history of the gully in their community from when it started until the present day and this availed the opportunity to ask follow-up questions about forcing factors and mode of evolution. Discussion questions were designed around the agenda items. For example, for hazard identification, participants were asked "what do you think causes gully erosion in your community"? Regarding hazard mitigation, questions included "tell me what has been done to reduce gullying in your community." Finally, regarding risk communication, we asked questions including "in what ways are risks of gully erosion communicated to the people?" With the permission of the respondents, these meetings were recorded. Focus group meetings lasted 2 hr at both communities.

TABLE 3 Summary statistics of changes in the 26 old gullies

	Mean length (km)	Mean width (m)	Mean area (m^2)
2009	0.39 (SD 0.35)	34.53 (SD 9.89)	13,775 (SD 13,158)
2018	0.50 (SD 0.43)	40.72 (SD 14.6)	21,367 (SD 18,000)
Average retreat	11 m yr^{-1}	0.6 m yr^{-1}	759 m^2 yr^{-1}

3 | RESULTS

3.1 | Changes in gully characteristics between 2009 and 2018

In 2009, 26 gullies covering 0.36 km^2 were mapped. Mean gully length was 0.39 km with a SD of 0.35 km. The mean width was 34.53 m (SD9.89 m), and the mean area was 13,775 m^2 (SD 13,158 m^2). There was an increase of 50% to a total of 39 gullies in 2018, covering 0.62 km^2, an aerial increase of 75%. Coordinate points of the seven visited gullies corresponded with mapped gully polygons digitised from satellite data, thus representing 100% accuracy of gully identification for the visited sites.

Tables 2 and 3 show changes in the 26 old gullies. The 13 new gullies had a mean length of 0.28 km (SD 0.23 km), mean width of 23.79 m (SD 11 m) and average gullied area of 7212 m^2 (SD 7340 m^2) in 2018. Eight gullies were mapped in the 2014 satellite data, six of which were present in 2009 but one of these six gullies was apparently sand filled before 2014. The other five had average headward migration rates of 5 and 10.5 m yr^{-1} between 2009–2014 and 2014–2018, respectively, with average lateral extensions of 0.1 and 2 m yr^{-1} and areal expansion rates of 262 and 1048 m^2 yr^{-1} during the same study periods. Two new gullies were mapped in the 2014 satellite data and had average headward migration rate of 36.3 m yr^{-1}, with a mean lateral extension of 1.8 m yr^{-1} and areal expansion rate 1278 m^2 yr^{-1} between 2014 and 2018. Total land area under gully occupation in the study area in 2018 was 0.62 km^2. Across the study area, changes in gully sizes were not uniform; while increases were recorded, apparent reductions in gully sizes were observed (Table 2).

3.2 | Analysis of land-use changes

Overall land-use classification accuracy was 97% for 2009 and 93% for 2018, while the kappa statistics were 0.96 and 0.9 for 2009 and 2018, respectively, showing very strong agreement and good accuracy, (see Gwet, 2002; Mensah et al., 2019). At the regional scale, the non-vegetated class covered an area of 58.6 km^2 in 2009, and increased to 144.7 km^2 in 2018, thus an increase of 146.8%. The open vegetation class increased from 195.10 to 332.4 km^2, and there was a reduction in tree/fallowed lands from 281.2 km^2 in 2009 to 57.8 km^2 in 2018 (Figure 2). These values translate to a percentage increase of 70.4% and reduction of 79.5% for open vegetation and fallow classes, respectively. Proportional changes in land use are shown in Table 4. The highest conversions of land use were from tree/fallow class to open-vegetated class.

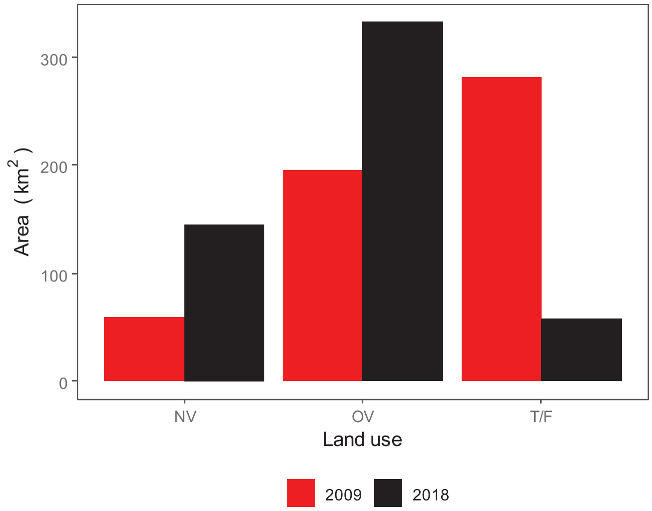

FIGURE 2 Land-use changes in the study area between 2009 and 2018. NV, non-vegetated; OV, open vegetation; T/F, tree/fallow [Color figure can be viewed at wileyonlinelibrary.com]

With regards to land-use change in gully catchments, (see Table 1 of supplementary material). There was tree/fallow-cover reduction across all catchments between 2009 and 2018. The IdeatoSouth1 catchment experienced a sustained increase in fallow. Njaba1 and IdeatoSouth1 were the only catchments that experienced reductions in non-vegetated surfaces between 2009 and 2018. These results show that whilst there is an overall change on a specific land use at the regional scale, land use is heterogeneous within individual catchments. Due to land use heterogeneity, the overall patterns of regional-scale land-use change are not manifested at smaller scales within all gully catchments, and thus the effect of land-use change on gully-driving processes is also heterogeneous.

3.3 | Nearness to roads and rivers, and geomorphic variables

Average gully-head distances from roads and rivers are 142.7 m (SD 143.6 m) and 597 m (SD 438.8 m) respectively. There are inverse associations between gully-head distance from road and changes in gully dimensions while positive correlations exist between gully head distance from rivers and changes in gully sizes (Figure 3). The study area is relatively low-lying (16–339 m above sea level) and river-adjacent lands have higher slope angles and highest gully concentrations (Figure 1 shows highest gully concentration around rivers). Steep

TABLE 4 Proportional changes among land uses

	2018 non-vegetated (km^2)	2018 open-vegetation (km^2)	2018 fallow/tree (km^2)
2009 Non-vegetated (km^2)	**47.52**	10.95	0.18
2009 Open-vegetation (km^2)	68.22	**120.2**	6.68
2009 Fallow/tree (km^2)	29	201.3	**50.91**

Note: diagonals represent portions of lands that have remained the same between 2009 and 2018
The bold values are indicates significant for intra and across comparison of land-use changes

FIGURE 3 Correlation matrix for gully drivers. There are inverse associations between nearness to roads and changes in gully sizes. GHDri, gully head distance from rivers, GHDrd, gully head distance from roads; RelRelief, relative relief; WiChange, width change; LenChange, length change; Corr, correlation legend [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 5 Eigenvectors/loadings of variables shown in Figure 3

Variable	Component 1	Component 2
Relative relief	0.69	0.16
Maximum slope	0.69	0
GHDri	−0.23	0.67
GHDrd	0	−0.73

Note: geomorphic factors have the same contribution along the first principal component. GHDri, gully head distance from rivers; GHDrd, gully head distance from roads

slopes were observed around the rivers with slope rises of 10 to 58.2% over distances less than 500 m from the rivers.

3.4 | Statistical analysis

Eigenvectors of the PCA indicate that along the first principal component, maximum slope and relative elevation have equal contribution while gully head distance from river and gully head distance from roads contribute towards the second principal component (Table 5). Principal component 1 explained 46% of variance in the data while both principal components 1 and 2 explain 82% of variance. Results of the first multiple regression (section 2.4) for the 2009–2018 land-use datasets show only the associations between change in gully length, changes in non-vegetated and tree/fallow class were significant ($p < 0.05$, adjusted $r^2 = 0.33$). For the years 2009–2014 and 2014–2018, no significant associations were found between land-use changes and changes in gully characteristics. Results of the second multiple regression analysis (Section 2.6) showed that only gully head distance from rivers had a significant positive effect on change in gullied area ($p < 0.05$, adjusted $r^2 = 0.21$).

3.5 | Community/local knowledge of gully drivers

Findings of focus group meetings suggested there were no gullies in the study area before the Nigerian civil war which lasted from 1967 until 1970. The Amucha and Obibi-Ochasi gullies started in 1969 and 1968 respectively. Local knowledge attributed gullying to the following factors:

1. Sudden increase in population density: There was a sudden increase in population density during the war when the study area provided shelters for displaced war refugees from other parts of southeast Nigeria. As the population density suddenly increased, the original forests were disturbed by refugees due to search for food and shelter. Focus group participants in Amucha attributed this forest disturbance to the outset of gully erosion in their community.
2. Military activities: Two gullies were found in Obibi-Ochasi and group meeting participants suggested that the older gully started at the *Okpii* stream in 1968 due to military activities. The Biafran Rangers (a group of Biafran soldiers) used the *Okpii* waterfall as a shooting range for training their soldiers while trenches were dug around the waterfall. These trenches are believed to have created the first artificial channels for runoff erosion, thus, setting the stage for gully initiation. One elder from the focus group meeting asserted "...in 1968, there was a heavy rainfall." Combinations of trenches and heavy rainfall event are thought to have triggered gullying.
3. Desecration of holy places: In Obibi-Ochasi, some focus group participants believed the desecration of the stream, fishing in the

sacred stream and killing the sacred pythons by soldiers led to gully erosion. In the study area, some animals are not hunted or killed out of respect for the customs and traditions of the people, one of such animals being the sacred python. Also, fishing is forbidden in some sacred streams as animals in such streams belong to the local deity. Meeting participants recounted that "...due to scarcity of food, or non-familiarity with the customs of the people, or other war time conditions, sacred pythons were killed by the soldiers who also fished in the sacred river. These conditions angered the gods and gully erosion is the consequence of desecrating the land."

4. Topography and increase in volume of surface runoff: group meeting participants in Amucha and Obibi-Ochasi agreed that topography and increased volume of surface runoff caused gully erosion. Meeting participants suggested that their communities occupied valleys and surface runoff from upstream villages flowed down to their communities, and thus enhancing gullying. Analysis of the DEM showed that both communities were low-lying in comparison to surrounding elevation values. Meeting attendees in both communities remarked that increased surface runoff due to increased non-vegetated surfaces facilitated gullying. Regarding roofing materials, meeting participants in Amucha claimed that the use of aluminium/iron roofing sheets in building construction has increased surface runoff. They suggested that many years ago, thatch roofs which produced less runoff were used for roofing.
5. Weak nature of soils: Focus group respondents in Amucha stated that the weak nature of their soils mean they are susceptible to gullying.

4 | DISCUSSION

4.1 | Changes in gully sizes

Poesen et al. (2003) identified three stages of gully evolution according to their age since initiation: short (<5 years), medium (5–50 years) and long term (>50 years). The Obibi-Ochasi gully started in 1968 and was the only long-term gully in the area in 2018. Analysis of the seven gullies identified in the 2014 imagery demonstrated there were variations in headward retreat rates over time (2009–2014 and 2014–2018). Of the gullies surveyed in 2009, 2014 and 2018, mean retreat rates were lower between 2009–2014 (5 m yr^{-1}) than 2014–2018 (10.5 m yr^{-1}). For the two gullies identified in 2014, mean retreat rate of 36.3 m yr^{-1} between 2014 and 2018 was measured. A potential reason for the higher headward retreat rates of the two new gullies is related to land use. Vanmaercke et al. (2016) opined that land uses that promote runoff may also increase gully headcut retreat rates. Both new gullies are closer to tarmac roads than the five older gullies. It is also possible the five older gullies are beginning to attain a level of stability with time hence, the reduction in headward retreat. One of the five older gullies remained apparently unchanged between 2009 and 2014, but changes in gully sizes were identified in 2018, this gully is the reason for a spike in average headward extension in 2018 among the old gullies.

Gully-head retreat rates of the 'old gullies' reported in this study are low compared to some results found in other parts of southeast Nigeria where gully retreat rates between 30 and 60 m have been documented (Egboka & Nwankwor, 1985; Hudec et al., 2005). It is not known over what period these studies were conducted. However, retreat rates of the old gullies are high when compared to other parts of the world, for example, Frankl et al. (2012) documented retreat rates of 0.34 m yr^{-1} for gullies less than 5 years in the Ethiopian northern highlands; Hu et al. (2007) measured retreat rates of 0.35–7.7 m yr^{-1} in northeast China for young gullies; Liu et al. (2019) reported retreat rates of 0.46 and 1.10 m yr^{-1} for two gullies in southern China. In the medium-term, Li et al. (2012) documented retreat rates of 0.36 to 0.44 m yr^{-1} in the loess region of China. However, a gully length retreat rate of 182.7 m yr^{-1} has been recorded for a short-term period in the Akusity watershed, Upper Nile basin of Ethiopia (Yibeltal, Tsunekawa, Haregeweyn, Adgo, Meshesha, Aklog, et al., 2019). Differences in rainfall regimes, interactions among gully-driving factors, sample size and age of gullies account for the variations in retreat rates between those reported in this research and cited references.

4.2 | Land use and land-use changes and gully erosion

Previous authors have documented sustained land-use changes, especially, changes from vegetated to paved surfaces in parts of southeast Nigeria (AC-Chukwuocha, 2015; Enaruvbe & Atedhor, 2015; Enaruvbe & Ige-Olumide, 2015; Njoku et al., 2017). However, results presented here show that while the entire study area experienced reductions in fallow-cover at the regional scale, land uses in gully catchments are heterogeneous (Table 1 of supplementary material). Multiple regression results show that increase in non-vegetated surfaces and reductions in tree/fallow cover between 2009 and 2018 significantly correlated with increased gully length. During the study period, extensive land-use changes were observed while increase in gully dimensions were measured. These findings are consistent with the observations of Ionita et al. (2015) and Castillo & Gómez (2016) who suggested that gully evolution is linked to major land-use changes, especially, reduction in forested lands. The reason for the insignificant associations between gully dimensions and changes in land use between 2009 and 2014 and 2014 and 2018 could be due to the shorter-term nature of these study periods in comparison with the longer-term land use changes between 2009 and 2018.

Road construction as an example of both land use and land-use change can increase concentration of surface runoff and likely increase in gullying. Inverse associations exist between gully head distance from roads and changes in gully sizes (Figure 3). Figure 4 shows proximity of three visited gullies to roads in the study area. Associations between nearness to roads and gully evolution are well established (Collison, 2001; Frankl et al., 2012) and results from this study agree with referenced studies. Wrong termination of drainage

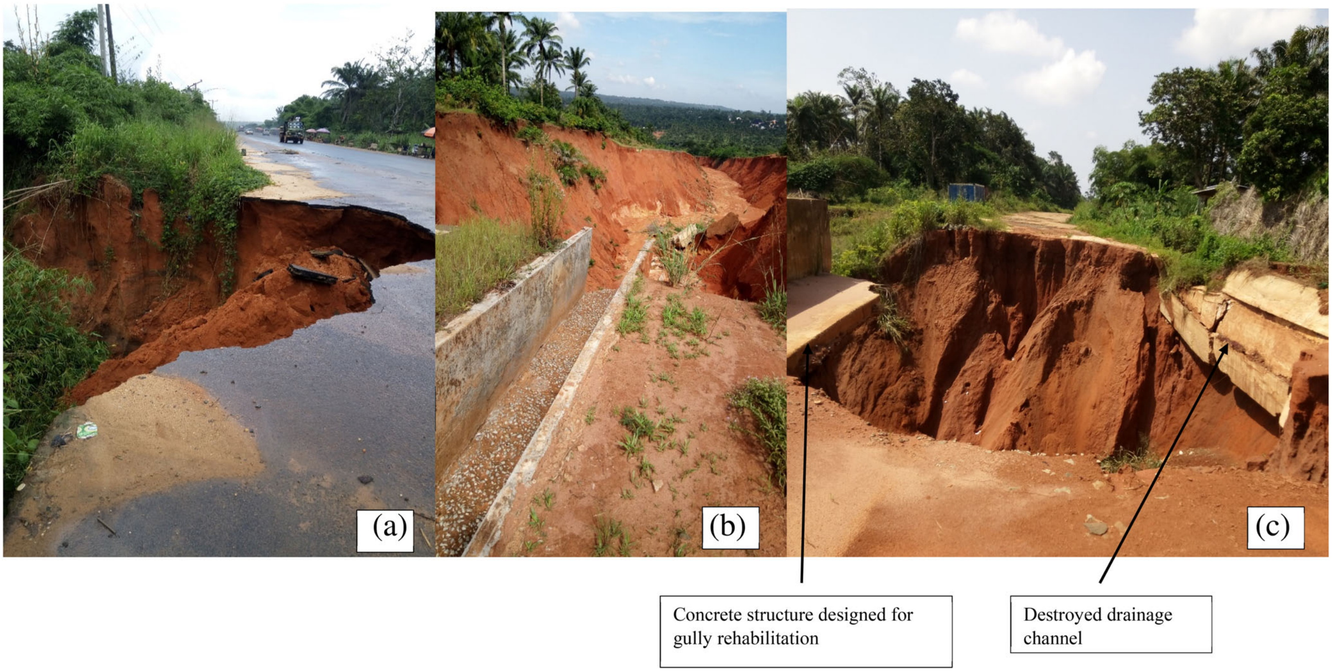

FIGURE 4 Proximity of gully heads to main roads. (a) Shows a moving truck close to a gully in Okwudor, Njaba LGA. In the first month of fieldwork (April 2019), no gully was identified on this axis of the road, but in June when the picture was taken, it had grown to where it is on the picture. (b) Shows drainage structure which empties into a newly formed gully in Obibi-Ochasi, Orlu LGA. Road construction was abandoned at this site and eyewitness account suggests that (b) started in 2017 following abandoned road construction. (c) Shows gully head advancement following abandoned gully restoration project in Umueshi community. The gully destroyed the local road connecting two communities. Also visible in (c) are destroyed drainage channels which deliver runoff directly into the gully and concrete structure designed to control gully erosion [Color figure can be viewed at wileyonlinelibrary.com]

channels by contractors often associated with road construction facilitates gullying. Nwankwor et al. (2015) noted that soils in southeast Nigeria were not easily erodible as is hitherto believed because most gullies in the region can be traced back to improper termination of road runoff concentration. Concentrated surface runoff from these drainage channels (especially when the endpoints of such channels are nearby bushes, as is observed in the study area) potentially initiates new gullies. In the first month of fieldwork (April 2019), no gully was identified at the Okwudor axis of the Owerri-Orlu highway. However, in June 2019, a gully had destroyed part of the highway (Figure 4a). A villager informed us that the gully started due to construction of road drainage which was terminated in the nearby bush. Focus group meeting participants informed us that one of the gullies identified in Obibi-Ochasi was less than 2 years old as at the time of our field visit. This gully (Figure 4b) was said to have started due to concentrated runoff from road drainage (road drainage is visible in Figure 4b) following abandonment of road construction. These examples support the findings of Nwankwor et al. (2015) regarding control of road drainage on gully formation in southeast Nigeria.

4.3 | Community knowledge

Although increase in demographic pressure has been suggested as a gully driver (Fanciullacci, 1978), the role of civil war first as a catalyst of increased demographic pressure and secondly, as a driver of gully erosion has not been documented previously in the study area. The Orlu area was considered a safe haven and provided shelters for displaced war refugees from other parts of southeast Nigeria. Focus group attendees identified that increased population density facilitated the removal of natural vegetation which left the soils bare and thus increasing erosive effects of surface runoff. In addition to removal of vegetation, military activities (e.g., digging trenches) created artificial and unpaved channels for concentrated runoff. Focus group attendees remarked that these trenches were never covered after the war. It follows therefore that concentrated surface runoff flowing through these unpaved channels potentially led to gully formation in 1968/69 by abrasion. In addition to the removal of vegetation due to increased population density, postwar reconstruction activities of the government (e.g., road and road drainage construction) potentially increased surface runoff and further enhanced gullying at the end of the war. In conclusion therefore, four processes appear to have directly linked the civil war to gully initiation:

1. High population density which led to vegetation cover removal,
2. Increased erosivity of surface runoff due to exposure of bare soils,
3. Concentration of surface runoff in unpaved channels (trenches),
4. High volume of surface runoff produced from new road constructions after the war.

Surface runoff, topography, weak nature of the soil and land-use changes were also identified as drivers of gully erosion by focus group participants. Relating community suggestions to published works, combined actions of topography and surface runoff as gully drivers are well known (Gómez-Gutiérrez et al., 2015; Knapen & Poesen, 2010; Poesen et al., 2003) and the susceptibility of soils of southeast Nigeria to dispersion by erosive forces due to their composition has been suggested (Egboka & Nwankwor, 1985; Idowu & Oluwatosin, 2008; Okagbue & Ezechi, 1988).

4.4 | The value of a multi-method approach

While traditional geomorphic methods (e.g., analysis of remotely sensed data and quantitative analyses) are important to establish correlations between gully-drivers and gully erosion, in some cases, they are insufficient to provide better understanding of gullying, for example gully commencement dates or forcing factors that led to gully initiation. As an example, in the study area, three high-resolution satellite data were available, and within intermediate years, initiations of gullies were identified. Exact years these gullies began or principal driving factors that led to gully commencements are not known and hence, use of traditional geomorphic methods alone can tell an incomplete story of gullying. Although the activities of the civil war are said to have led to the initiation of the oldest gullies, it was identified as well that a heavy rainfall occurred during the war in 1968. It is therefore possible that combinations of war-time activities and the heavy rainfall of 1968 led to gully initiation. The roles of both civil war and heavy rainfall of 1968 as potential drivers of gullying in the study area would have remained unknown if not for the focus group discussions. Results from focus group meetings support quantitative indicators of dominant drivers of gullying based on multiple regression, analysis of land-use changes, geomorphic interpretations, and published studies. These findings signify the importance of using multi-method research approach which helps us to mitigate the effects of data gaps and allows for comparison and enhanced interpretation of quantitative understanding with community knowledge.

5 | CONCLUSIONS

This paper aimed to use a multi-method approach to ascertain the dominant drivers of the changes in gully characteristics in the study area between 2009 and 2018. Focus group meetings suggest that gullying was not known in the study area before the civil war. Sudden increase in population density (due to influx of refugees), removal of natural vegetation due to search for food and shelter, digging trenches for military training (which enhanced concentration of surface runoff in unpaved channels and subsequent channel abrasion) were among war-time activities identified as primary causes of the oldest gullies. Although these war-time activities which facilitated the initiations of the oldest gullies have ceased, extensive land-use changes, especially, removal of vegetal cover, have facilitated gullying in the post-civil war era. Although the villagers may not be experts in gully studies, they have a high awareness level of driving factors of gully erosion. Their suggested gully-driving factors are consistent with findings of analysis of remotely sensed data, and published literature. This local knowledge has also provided us with valuable information on what was happening before 2009, which would have otherwise been unknown to us. Therefore, incorporating local knowledge and scientific techniques in this work has ensured comparisons of both methods, and will eliminate likely mistrusts of scientific findings on the part of the villagers. Within the study period (2009–2018), reductions in fallow-cover across the study area were identified and gully characteristics also changed in response to these land-use changes. Although it has been suggested that while it is possible for land-use changes to occur in one direction across a region (e.g, reduction in tree-cover), it is possible for changes in land use in the opposite direction (e.g., increase in tree-cover) to occur within individual catchments. Finally, this work has shown the importance of within and between catchment heterogeneity, a widespread characteristic with implications for understanding and managing gully erosion.

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DATA AVAILABILITY STATEMENT

Data available on request from the authors

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REFERENCES

AC-Chukwuocha, N. B. (2015). Analysis of structural changes in land use and land cover of Otamiri watershed in Owerri, south east Nigeria. *Journal of Environment and Earth Science*, *5*, 51–59.

Afegbua, U. K., Uwazuruonye, J., & Jafaru, B. (2016). Investigating the causes and impacts of gully erosion in Auchi, Nigeria. *Journal of Geography, Environment and Earth Science International*, *4*, 1–13. https://doi.org/10.9734/JGEESI/2016/22582

Betts, H. D., Trustrum, N. A., & Rose, R. C. D. (2003). Geomorphic changes in a complex gully system measured from sequential digital elevation models, and implications for management. *Earth Surface Processes and Landforms, The Journal of the British Geomorphological Research Group*, *28*, 1043–1058. https://doi.org/10.1002/esp.500

Birhanu, A., Masih, I., van der Zaag, P., Nyssen, J., & Cai, X. (2019). Impacts of land use and land cover changes on hydrology of the Gumara catchment, Ethiopia. *Physics and Chemistry of the Earth, Parts A/B/C*, *112*, 165–174. https://doi.org/10.1016/j.pce.2019.01.006

Callon, M. (1999). The role of lay people in the production and dissemination of scientific knowledge. *Science, Technology and Society*, *4*, 81–94. https://doi.org/10.1177/097172189900400106

Castillo, C., & Gómez, J. A. (2016). A century of gully erosion research: Urgency, complexity and study approaches. *Earth-Science Reviews*, *160*, 300–319. https://doi.org/10.1016/j.earscirev.2016.07.009

Cerdà, A. (1997). Soil erosion after land abandonment in a semiarid environment of southeastern Spain. *Arid Land Research and Management*, *11*, 163–176. https://doi.org/10.1080/15324989709381469

Chiemelu, N., Okeke, F., Nwosu, K., Ibe, C., Ndukwu, R., & Ugwuoti, A. (2013). The role of surveying and mapping in erosion management and control: Case of Omagba erosion site, Onitsha Anambra State, Nigeria. *Journal of Environment and Earth Science*, *3*, 129–137.

Collison, A. J. C. (2001). The cycle of instability: Stress release and fissure flow as controls on gully head retreat. *Hydrological Processes*, *15*, 3–12. https://doi.org/10.1002/hyp.150

Conoscenti, C., Angileri, S., Cappadonia, C., Rotigliano, E., Agnesi, V., & Märker, M. (2014). Gully erosion susceptibility assessment by means of GIS-based logistic regression: A case of Sicily (Italy). *Geomorphology*, *204*, 399–411. https://doi.org/10.1016/j.geomorph.2013.08.021

Dong, Y., Xiong, D., Su, Z., Li, J., Yang, D., Zhai, J., Lu, X., Liu, G., & Shi, L. (2013). Critical topographic threshold of gully erosion in Yuanmou Dry-hot Valley in Southwestern China. *Physical Geography*, *34*, 50–59. https://doi.org/10.1080/02723646.2013.778691

Egboka, B. C. E., & Nwankwor, G. (1985). The hydrogeological and geotechnical parameters as agents for gully-type erosion in the rain-forest belt of Nigeria. *Journal of African Earth Sciences*, *3*, 417–425. https://doi.org/10.1016/S0899-5362(85)80084-1

Egboka, B. C. E., Nwankwor, G., & Orajaka, I. (1990). Implications of palaeo-and neotectonics in gully erosion-prone areas of southeastern Nigeria. *Natural Hazards*, *3*, 219–231. https://doi.org/10.1007/BF00124578

Enaruvbe, G. O., & Atedhor, G. O. (2015). Spatial analysis of agricultural landuse change in Asaba, southern Nigeria. *IFE Journal of Science*, *17*, 65–74.

Enaruvbe, G. O., & Ige-Olumide, O. (2015). Geospatial analysis of land-use change processes in a densely populated coastal city: The case of Port Harcourt, south-east Nigeria. *Geocarto International*, *30*, 441–456. https://doi.org/10.1080/10106049.2014.883435

Ezemonye, M., & Emeribe, C. (2012). Rainfall erosivity in southeastern Nigeria. *Ethiopian Journal of Environmental Studies and Management*, *5*, 112–122. https://doi.org/10.4314/ejesm.v5i2.1

Ezezika, O. C., & Adetona, O. (2011). Resolving the gully erosion problem in southeastern Nigeria: Innovation through public awareness and community-based approaches. *Journal of Soil Science and Environmental Management*, *2*, 286–291. https://doi.org/10.5897/JSSEM.9000059

Fanciullacci, D. (1978). *Soil erosion and degradation. A study methodology developed for a project in Imo and Anambra States in Ni'geria* (Vol. 33, pp. 441–447). *Rivista trimestrale di studi e documentazione dell'Istituto italiano per l'Africa e l'Oriente* Retrieved on May 24, 2021, from http://www.jstor.org/stable/40759038

Fleitmann, D., Dunbar, R. B., McCulloch, M., Mudelsee, M., Vuille, M., McClanahan, T. R., Cole, J. E., & Eggins, S. (2007). East African soil erosion recorded in a 300 year old coral colony from Kenya. *Geophysical Research Letters*, *34*, 1–5. https://doi.org/10.1029/2006GL028525

Frankl, A., Deckers, J., Moulaert, L., Van Damme, A., Haile, M., Poesen, J., & Nyssen, J. (2016). Integrated solutions for combating gully erosion in areas prone to soil piping: Innovations from the drylands of Northern Ethiopia. *Land Degradation & Development*, *27*, 1797–1804. https://doi.org/10.1002/ldr.2301

Frankl, A., Nyssen, J., Adgo, E., Wassie, A., & Scull, P. (2019). Can woody vegetation in valley bottoms protect from gully erosion? Insights using remote sensing data (1938–2016) from subhumid NW Ethiopia. *Regional Environmental Change*, *19*, 2055–2068. https://doi.org/10.1007/s10113-019-01533-4

Frankl, A., Poesen, J., Deckers, J., Haile, M., & Nyssen, J. (2012). Gully head retreat rates in the semi-arid highlands of Northern Ethiopia. *Geomorphology*, *173*, 185–195. https://doi.org/10.1016/j.geomorph.2012.06.011

Ghimire, S. K., Higaki, D., & Bhattarai, T. P. (2006). Gully erosion in the Siwalik Hills, Nepal: Estimation of sediment production from active ephemeral gullies. *Earth Surface Processes and Landforms, The Journal of the British Geomorphological Research Group*, *31*, 155–165. https://doi.org/10.1002/esp.1320

Gómez-Gutiérrez, Á., Conoscenti, C., Angileri, S. E., Rotigliano, E., & Schnabel, S. (2015). Using topographical attributes to evaluate gully erosion proneness (susceptibility) in two Mediterranean basins: Advantages and limitations. *Natural Hazards*, *79*, 291–314. https://doi.org/10.1007/s11069-015-1703-0

Graves, A. R., Morris, J., Deeks, L. K., Rickson, R. J., Kibblewhite, M. G., Harris, J. A., Farewell, T. S., & Truckle, I. (2015). The total costs of soil degradation in England and Wales. *Ecological Economics*, *119*, 399–413. https://doi.org/10.1016/j.ecolecon.2015.07.026

Gwet, K. (2002). Kappa statistic is not satisfactory for assessing the extent of agreement between raters. Statistical methods for inter-rater reliability assessment, No. 1 1–6. Retrieved on 24/05/21 from https://www.agreestat.com/papers/kappa_statistic_is_not_satisfactory.pdf

Hu, G., Wu, Y., Liu, B., Yu, Z., & You, Z. (2007). Short-term gully retreat rates over rolling hill areas in black soil of Northeast China. *Catena*, *71*, 321–329. https://doi.org/10.1016/j.catena.2007.02.004

Hudec, P. P., Simpson, F., Akpokodje, E. G., & Umenweke, M. O. (2005). Anthropogenic contribution to gully initiation and propagation in southeastern Nigeria. In J. Ehlen, W. C. Haneberg, & R. A. Larson (Eds.), *Humans as geologic agents* (Vol. 16). Boulder, CO: Geological Society of America.

Idowu, O., & Oluwatosin, G. (2008). Hydraulic properties in relation to morphology of a tropical soil with hardened plinthite under three land use types. *Tropical and Subtropical Agroecosystems*, *8*, 145–155 Retrieved on 24/05/21 from https://www.redalyc.org/articulo.oa?id=93980204

Igwe, O. (2012). ICL/IPL regional activities in West Africa. *Landslides*, *9*, 433–437. https://doi.org/10.1007/s10346-012-0324-x

Iheme, O., Okoye, V., Chinwuko, A., Usman, A., Ejeke, C., & Osele, C. (2016). Evaluation of geotechnical properties of gully erosion materials in ORLU and its environs, Imo State, Nigeria. *International Journal of Advanced Geosciences*, *4*, 8–14. https://doi.org/10.14419/ijag.v4i1.5991

Ionita, I., Niacsu, L., Petrovici, G., & Blebea-Apostu, A. M. (2015). Gully development in eastern Romania: A case study from Falciu Hills. *Natural Hazards*, *79*, 113–138. https://doi.org/10.1007/s11069-015-1732-8

Knapen, A., & Poesen, J. (2010). Soil erosion resistance effects on rill and gully initiation points and dimensions. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, *35*, 217–228. https://doi.org/10.1002/esp.1911

Li, Z., Zhang, Y., Yao, W., & Zhu, Q. (2012). Estimating gully development rates in hilly loess region of Western Shanxi Province based on QuickBird images. *Transactions of the Chinese Society of Agricultural Engineering*, *28*, 141–148. https://doi.org/10.3969/j.issn.1002-6819.2012.22.021

Liu, H., Qian, F., Ding, W., & Gómez, J. A. (2019). Using 3D scanner to study gully evolution and its hydrological analysis in the deep weathering of southern China. *Catena*, *183*, 104218. https://doi.org/10.1016/j.catena.2019.104218

Mensah, A. A., Sarfo, D. A., & Partey, S. T. (2019). Assessment of vegetation dynamics using remote sensing and GIS: A case of Bosomtwe Range Forest Reserve, Ghana. *The Egyptian Journal of Remote Sensing and Space Science*, *22*, 145–154. https://doi.org/10.1016/j.ejrs.2018.04.004

Morgan, R. P., & Rickson, R. J. (2003). Water erosion control. In R. P. Morgan & R. J. Rickson (Eds.), *Slope stabilization and erosion control: A bioengineering approach* (p. 288). London, UK: Taylor & Francis.

Njoku, J. D., Ukaegbu, K. O., Osumgborogwu, I. E., Udeh, A. O., & Telu, M. (2017). Correlate mapping of impervious surfaces as flood risk assessment strategy in southeastern Nigeria. *Asian Journal of Environment and Ecology.*, *2*, 1–11. https://doi.org/10.9734/AJEE/2017/33974

Nwankwor, G. I., Udoka, U. P., Egboka, B. C., & Opara, A. I. (2015). The mechanics of civil–works induced gully erosion: Applications to development of preventive measures in south eastern Nigeria. *Applied Ecology and Environmental Sciences*, *3*, 60–65. https://doi.org/10.12691/aees-3-2-5

Nyssen, J., Poesen, J., Veyret-Picot, M., Moeyersons, J., Haile, M., Deckers, J., Dewit, J., Naudts, J., Teka, K., & Govers, G. (2006). Assessment of gully erosion rates through interviews and measurements: A case study from northern Ethiopia. *Earth Surface Processes and Landforms, The Journal of the British Geomorphological Research Group*, *31*, 167–185. https://doi.org/10.1002/esp.1317

Obi, M., & Salako, F. (1995). Rainfall parameters influencing erosivity in southeastern Nigeria. *Catena*, *24*, 275–287. https://doi.org/10.1016/0341-8162(95)00024-5

Obi, M. E., & Asiegbu, B. O. (1980). The physical properties of some eroded soils of southeastern Nigeria. *Soil Science*, *130*, 39–48.

Ofomata, G. E. K. (1987). *Soil erosion in Nigeria: The views of a geomorphologist*. Ibadan: University of Nigeria Press.

Okagbue, C. O., & Ezechi, J. I. (1988). Geotechnical characteristics of soils susceptible to severe gullying in eastern Nigeria. *Bulletin of the International Association of Engineering Geology*, *38*, 111–119. https://doi.org/10.1007/BF02590454

Okorafor, O. O., Akinbile, C. O., & Adeyemo, A. J. (2017). Soil erosion in south eastern Nigeria: A review. *Scientific Research Journal*, *5*, 30–37.

Panagos, P., Ballabio, C., Poesen, J., Lugato, E., Scarpa, S., Montanarella, L., & Borrelli, P. (2020). A soil erosion indicator for supporting agricultural, environmental and climate policies in the European Union. *Remote Sensing*, *12*, 1365. https://doi.org/10.3390/rs12091365

Parkner, T., Page, M., Marden, M., & Marutani, T. (2007). Gully systems under undisturbed indigenous forest, East Coast region, New Zealand. *Geomorphology*, *84*, 241–253. https://doi.org/10.1016/j.geomorph.2006.01.042

Poesen, J., Nachtergaele, J., Verstraeten, G., & Valentin, C. (2003). Gully erosion and environmental change: Importance and research needs. *Catena*, *50*, 91–133. https://doi.org/10.1016/S0341-8162(02)00143-1

Rahmati, O., Tahmasebipour, N., Haghizadeh, A., Pourghasemi, H. R., & Feizizadeh, B. (2017). Evaluating the influence of geo-environmental factors on gully erosion in a semi-arid region of Iran: An integrated framework. *Science of the Total Environment*, *579*, 913–927. https://doi.org/10.1016/j.scitotenv.2016.10.176

Rickson, R. J., Deeks, L. K., Graves, A., Harris, J. A. H., Kibblewhite, M. G., & Sakrabani, R. (2015). Input constraints to food production: The impact of soil degradation. *Food Security*, *7*, 351–364. https://doi.org/10.1007/s12571-015-0437-x

Sonneveld, M. P. W., Everson, T. M., & Veldkamp, A. (2005). Multi-scale analysis of soil erosion dynamics in Kwazulu-Natal, South Africa. *Land Degradation & Development*, *16*, 287–301. https://doi.org/10.1002/ldr.653

Tebebu, T. Y., Abiy, A. Z., Zegeye, A. D., Dahlke, H. E., Easton, Z. M., Tilahun, S. A., … Steenhuis, T. S. (2010). Surface and subsurface flow effect on permanent gully formation and upland erosion near Lake Tana in the northern highlands of Ethiopia. *Hydrology and Earth System Sciences*, *14*, 2207–2217. https://doi.org/10.5194/hess-14-2207-2010

Usman, A. O., Iheme, O. K., Chinwuko, A. I., Opia, F. O., & Okonkwo, C. C. (2014). Hydrogeological implications of environmental devastation in Orlu and its environs south eastern, Nigeria. *Journal of Environment and Earth Science*, *4*, 23–41.

van Aalst, M. K., Cannon, T., & Burton, I. (2008). Community level adaptation to climate change: The potential role of participatory community risk assessment. *Global Environmental Change*, *18*, 165–179. https://doi.org/10.1016/j.gloenvcha.2007.06.002

Vanmaercke, M., Panagos, P., Vanwalleghem, T., Hayas, A., Foerster, S., Borrelli, P., Rossi, M., Torri, D., Casali, J., Borselli, L., Vigiak, O., Maerker, M., Haregeweyn, N., De Geeter, S., Zgłobicki, W., Bielders, C., Cerdà, A., Conoscenti, C., de Figueiredo, T., … Poesen, J. (2021). Measuring, modelling and managing gully erosion at large scales: A state of the art. *Earth-Science Reviews*, *218*, 103637. https://doi.org/10.1016/j.earscirev.2021.103637

Vanmaercke, M., Poesen, J., Van Mele, B., Demuzere, M., Bruynseels, A., Golosov, V., Vanmaercke, M., Poesen, J., Van Mele, B., Demuzere, M., Bruynseels, A., Golosov, V., Bezerra, J. F. R., Bolysov, S., Dvinskih, A., Frankl, A., Fuseina, Y., Guerra, A. J. T., Haregeweyn, N., … Yermolaev, O. (2016). How fast do gully headcuts retreat? *Earth-Science Reviews*, *154*, 336–355. https://doi.org/10.1016/j.earscirev.2016.01.009

Yibeltal, M., Tsunekawa, A., Haregeweyn, N., Adgo, E., Meshesha, D. T., Aklog, D., Masunaga, T., Tsubo, M., Billi, P., Vanmaercke, M., & Ebabu, K. (2019). Analysis of long-term gully dynamics in different agro-ecology settings. *Catena*, *179*, 160–174. https://doi.org/10.1016/j.catena.2019.04.013

Yibeltal, M., Tsunekawa, A., Haregeweyn, N., Adgo, E., Meshesha, D. T., Masunaga, T., Tsubo, M., Billi, P., Ebabu, K., Fenta, A. A., & Berihun, M. L. (2019). Morphological characteristics and topographic thresholds of gullies in different agro-ecological environments. *Geomorphology*, *341*, 15–27. https://doi.org/10.1016/j.geomorph.2019.05.012

Zabihi, M., Mirchooli, F., Motevalli, A., Khaledi Darvishan, A., Pourghasemi, H. R., Zakeri, M. A., & Sadighi, F. (2018). Spatial modelling of gully erosion in Mazandaran Province, northern Iran. *Catena*, *161*, 1–13. https://doi.org/10.1016/j.catena.2017.10.010

Zhang, X., Drake, N., & Wainwright, J. (2002). Scaling land surface parameters for global-scale soil erosion estimation. *Water Resources Research*, *38*, 19–11. https://doi.org/10.1029/2001WR000356

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