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The development of models for prediction of gully growth and head advancement A case study: Queen Ede gully erosion site, Benin city, Edo state, Nigeria

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Abstract. This paper examines gully growth and head advancement at the Queen Ede gully site, Benin city. This is achieved by observing gully growth and head advancement between the year 2000 and 2012 using field surveys, aerial photographs and geographical information. Also, experimental models such as Thompson [1], [Thompson, J.R. "Quantitative effect of watershed variables on the rate of gully head advancement", *Trans ASAE*, **7**, pp. 54-55 (1964)]. the American Soil Conversation Service, SCS (I) and SCS (II), and FAO models, were used for estimating migrating headcuts over a study period. Results obtained revealed that the gully width varied from 15.6 m to 99.5 m, while the depth varied from 0.5 m to 13.8 m. The volume of soil loss was 372, 775 m^3 over an area of 104.4 m^2. A mathematical model is proposed for gully growth (G_A) and head advancement (R_A), which is hereby presented as:

(i) $$G_A = 0.15R^{0.2679}L_a^{0.0873}L_w^{0.09179}E^{0.009860}P^{0.06773}.$$

(ii) $$R_A = 0.15A^{0.5328}S^{0.14}P^{0.6778}E.$$

The model has been tested against the best existing theories and found to give the same order of error.

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1. Introduction

Gully erosion is one of the most complicated and destructive forms of water erosion. Erosion has been described as the process whereby the surface of the earth's crust or land is eaten into by gullies, valleys, and cliffs and is eventually completely washed away into rivers and seas [2]. Erosion is a global problem ravaging the lands of both developed and developing countries. According to Ahmadi et al. [3], the first studies on gully erosion were done in 1960, in the USA, and then in other countries such as Spain, Japan, China and UK etc. Milos [4] showed that four main factors are responsible for causing erosion. These are (i) Climate; rainfall, wind, humidity and temperature (ii) Geotechnics, rock and soil, and (iii) Land forms.

Gully erosion occurs as a result of water cutting down into the soil along the line of flow [5]. Gully erosion is said to take place when excessive surface run off, flowing with high velocity and force, detaches and carries soil particles down a slope [6]. It may also

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occur when run off volume from a steep slope increases sufficiently or when an increase in flow velocity cuts a deep hole along a path [7]. Gully also develops on traces formed by the movement of machinery down a slope. Possen et al. [8] noted the importance of modeling in gully erosion studies, and Ghodousi [9] observed the importance of morphology modeling and hazard zonation studies at the Zanjan Road drainage basin, in the republic of Iran.

However, it was observed that in the study area, land use pressure is caused by astronomical increases in population migration from rural to urban areas. One of the main causes of gully erosion in Edo State is road construction work with inappropriately terminated drains [10]. The road is said to induce a concentration of surface run off, with a diversion of concentrated run off to other catchments, and an increase in catchment size, which enhances gully development after road construction [11]. Changes in drainage pattern associated with urbanization result in gully erosion, particularly where illegal settlements without urban infrastructures exist. Kalu and Goodwill [12] observed that while all the various climatic factors are important in the assessment of erosion potential, rainfall is the most significant in the determination of causes of erosion in the study area. Byran [13] noted that physical properties such as the size (texture), hydrologic (permeability) and chemical (organic content) of soil are generally the main parameter that affects soil erodibility. On the other hand, Zingg [14] observed that the shape of the catchment affects the velocity and tangential stress developed by the run off within a catchment. Confirming this observation, Rascal and Francis [15] stated that runoff under a 25 mm/hr rainfall intensity increased from 69% of rainfall at a 5% slope to 86% of rainfall at a slope of 20%. Jean Poosen et al. [16], in their study on gully erosion, emphasized the importance of modelling as an essential tool in the modelling of gully erosion studies. Also, Ehiorobo and Izinyon [17], in their study on gully erosion, described the importance of GPS application with total station surveys, in combination with GIS and remote sensing, in the monitoring of gully erosion. Hum et al. [18] observed that gully erosion is the main source of sedimentation in river basins. Research carried out by various interest groups have shown that gully erosion represents one of the most important soil degradation processes in Nigeria, as it causes considerable soil loss, and produces large volumes of sediment. Gullies are also catalysts for transferring surface run off and sediment load from upland areas to valley floors; thereby, creating channels that aggravate the problem of flooding and water pollution. Many cases of damage to water courses and property by runoff from agricultural land are related to the occurrence of gully erosion [19]. Bourdman [20] observed that gully erosion is neglected by various governments and researchers, simply because it is difficult to study and control and expensive to manage. According to Nachtergele et al. [21], much research effort and resources have been invested in the development of soil erosion models, resulting in the development of variety of empirical and experimental models. These include the Universal Soil Loss Equation (USLE), its revised version (RUSLE), the Water Erosion Prediction Project (WEPP), coordination of information on the environment (CORINE), and EUROSEM [22]. The prediction of gully development using mathematical models is difficult, as the different factors involved in the prediction are not so easy to determine. Soil type and, in particular, vertical distribution of the erosion resistance of various soil horizons, largely control the size, depth and cross sectional morphology of the gullies [8,23]. Also, Valentine et al. [24] showed that many gullies grow, initially, rapidly to large dimensions, making effective control technically difficult or prohibitively expensive. This is why studies on gully processes and their modeling are scarce [25,26].

Although gullies are visually diminishing, their small spatial extent renders them undetectable in most generally available maps and satellite imageries. The use of GPS and total station data, along with high resolution satellite images and GIS, offers the potential to effectively measure gully volume and its landscape. Monitoring and experimental studies of the initiation and development of gullies at various temporal and spatial scales need to be carried out. Short term monitoring of gully heads and gully wall retreats has been conducted by measuring the change in distance between the edge of the gully or well and the bench mark point installed on the gully walls [27]. According to Oostwood and Bryan [28], some other techniques have been used in aerial photographic surveys to determine the volume of soil loss by concentrated flow methods. Thoman et al. [23] and Ries and Marzolf [29] have shown that one of the most common methods in use today in the study of gully erosion is the integration of GPS, GIS and remote sensing technologies. Also, Ehiorobo and Izinyon [17], in their recent study, used DGPS to establish 3-D controls for the gully site, while total station instruments were used to measure the morphological parameters of the gully. Land use classification within the gully area was carried out by high resolution satellite images. Ghaffari [30], using Remote Sensing (RS) and the Geographical Information System (GIS), evaluated the ability of the GEE model for predicting gully longitudinal advancement in the Charmahel and Bakhtiari region of Iran. It was found that the AGEE model is best suited for aerial measurements in gully erosion studies. Shibru et al. [31] conducted a study using a photogrammetric technique to measure gully growth and head advancement in the eastern part of Ethiopia, and found it to be very adequate. Obiadi et al. [32] used GPS, with a total station survey, remote sensing and GIS, in the monitoring of the morphology and landscape degradation processes in Anambra State, South East Nigeria, and they obtained very good results. They also applied the GEE model to predict gully growth and head advancement in that region.

The main purpose of this study is to develop an appropriate modeling tool for the study of gully growth and head advancement at the Queen Ede gully site. It is expected that at the end of the research, a robust and versatile model for use in the prediction of gully growth and head advancement at the Queen Ede gully site will have been established. The results of the study will be used for the monitoring and planning of the erosion control measures within the catchment basin.

2. Materials and methods

2.1. The study area

The study area is the Queen Ede gully erosion site, located with the UTM zone 31 in the North Eastern part of Benin city, capital of the Edo State of Nigeria. The study area is bounded by UTM coordinates 700800Mn and 795800mE to 796000mE. The gully runs in a south-easterly direction down to the Ikpoba River. The elevation of the study area ranges from 16 m to 110 m above sea level (Figure 1). The average temperature in this area is 280 C. The rainy season commences usually from April to October, with a break during the month of August, commonly referred to as the August break. Maximum recorded annual rainfall from 2001-2011 was 3000 mm, with a minimum of 22.4 mm. There is, however, a sharp deviation in the year 2012, probably as a result of climate change, as heavy rains had been experienced through January to October. Humidity is generally high, about 98% for most of the year. The area lies within the tropical rainforest zone of Nigeria.

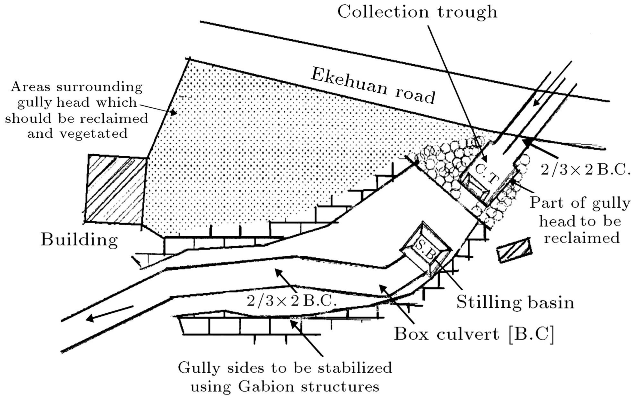

Figure 1. Layout of Queen Ede gully site, Benin city Nigeria.

2.1.1. Research methods

(i) Preparation of statistics and information included obtaining metrological data, maps and existing reports on the study area from relevant government agencies such as:
   - Topographic maps, with a scale of 1:50000, of the Federal Survey Department, the Federal Republic of Nigeria;
   - Geological maps, with a scale of 1:100,000, of the Nigerian geological survey;
   - Aerial photos, with a scale of 1:55000 (1960) and 1:40,000 (2000) from the Federal Survey Department, 1:20000 (1960) surveying organization of Nigeria.

(ii) Selection of gully: At the first stage, the Queen Ede gully area, with a drainage density over 10.435 km/km^2, was selected, based on interpretation of aerial photos and field surveys to facilitate the measurement of the length in the photos during different periods.

(iii) Determination of the spatial location of the gully: To determine the spatial location of the Queen Ede gully site and its location on the aerial photos, GPS was used. There were other gullies located but our interest is in the Queen Ede gully because of its size and magnitude. A topographical survey of the study area was carried out using Leica 500 GPS receivers.

(iv) Measurement and location of gully length: To determine the length of the gully, positioning points were geo-referenced using aerial photos, and then overlaid. Then, a thorough interpretation of the aerial photos, and their geographical positions was established.

(v) The coordinates were exported into the ARCGIS environment as an Excel slope file. With the aid of ARCGIS software, various maps, including spot height, contours and Digital Elevation Models (DEM), were generated. From the morphological parameters, cross sectional drawings and bed profiles were produced.

(vi) Rainfall intensity was determined for the entire watershed area of the Queen Ede gully site using a large scale topographic map of 1 m contour intervals, which was computed using the Kirpich equation:

$$T_c = 0.0195K^{0.770},$$

where:

$$k = \frac{\text{Max length of traveller for run-off water}}{\text{square root of main channel slope}},$$

$$T_c = \frac{0.0195L^{0.770}}{S^{0.385}},$$

T_c represents the time of concentration, L represents the length of the channel reach in meters, S represents the average slope of channel reach in m/m.

This coefficient was used to determine the peak rate of runoff for Queen Ede gully site where length L and slope S are computed. 50 years design period was chosen for the design of overland flow structures and the return period is 100 years.

The soil survey included borehole drilling with the use of a hand auger to a depth of 3 m to recover samples for laboratory analysis. In order to characterize, in engineering terms, the soil present at the gully site, the obtained soil samples were tested and analyzed to enable engineers to plan for slope stabilization and gully remediation work, to estimate the quantity of soil loss, and assist in the prediction model.

The laboratory tests included:

(i) Natural moisture content tests;

(ii) Atterberg limit test;

(iii) Specific gravity test (at least 2 samples per cross section);

(iv) Gradation (particle size analysis) with at least 3 samples using a hydrometer;

(v) California Bearing Ratio test (C.B.R.);

(vi) Universal Triaxial test and direct shear strength test;

(vii) Compaction test.

2.1.2. Field measurements

The topographical survey of the study area was carried out using a combination of the Leica Total Station and Leica 500 GPS receivers. In order to carry out the topographical survey, an existing CFG control point was used as a reference station. The national coordinates of this control point were then converted to the UTM zone 31 N reference frame, to be consistent with the satellite imagery used for site analysis. Using the CFG control as a reference station, three control points, QEDI-QED3, were established around the gully area by means of a differential GPS. These control points were then used for detailed topographical mapping of the gully bed, gully bank and the entire flood basin. All details, including buildings and other infrastructures at risk, were surveyed with the Total Station Instrument. During the topographical surveys, the average point densities in some areas, such as the gully head, edges and terraces, were more intense than in other parts of the flood basin. The gully cross sections, along with topographical profiles running along the gully channel, were recorded at a spacing of 20 m intervals in a longitudinal direction. Morphological parameters of the gully, including depth, width, length, and cross sectional areas, were recorded at 20 m intervals. The total station data were collected at centimeter level resolutions to capture breaks in the slope and other topographical features important for producing accurate Digital Elevation Models (DEM).

2.1.3. Equipment for field work

The equipment deployed to the site for field work included: Hand auger, global pointing system, GPS receiver (hand held type Leica 500 GPS receiver), shovel and plastic bags to collect soil samples.

2.1.4. Borehole drilling

Samples were recovered from 4 different locations within the gully bed and bank. A total of four samples were collected and taken to the University of Benin Geotechnical Engineering Laboratory for tests and analysis. The sampling points were geo referenced using a handheld GPS receiver. The UTM coordinates of the sampling points are presented in Table 1.

2.1.5. Laboratory testing

The recovered samples from the sites were taken to the Geotechnical Engineering Laboratory in the Civil Engineering Department of the University of Benin. The following laboratory tests and analyses were conducted; specific gravity, particle size distribution (sieve analysis), atterberg (consistency) limit, moisture/density (compaction), U.U Triaxial, and California Bearing Ratio.

The specific gravity of a solid particle is the ratio of the mass density of solid to that of water. This was determined in the laboratory using the density bottle method and was carried out in accordance with AASHTO Tl00-70 (B.S1377:75 Test 6). The specific gravity values are presented in Table 2.

The tests were conducted to determine the percentage quantity of individual grain sizes as they occur in a particular soil layer. The test results are summarized in Table 3.

The Atterberg Limit was done to determine the index properties of the soil. It involves a measure of the plasticity of soil, which is a measure of its resistance to

Table 1. GPS coordinates of soil sampling points.

Borehole number	Location	Coordinates	
		N (m)	E (m)
BH 1	PT 1	700263.064	786552.551
BH 2	PT 2	700062.003	786350.913
BH 3	PT 3	699846.123	786151.729
BH 4	PT 4	699556.222	785932.915

Table 2. Specific gravity test results.

S/N	Borehole	Specific gravity
1	PT 1	2.51
2	PT 2	2.60
3	PT 3	2.55
4	PT 4	2.58

Table 3. Sieve analysis.

S/N	Borehole	Percentage passing sieve no.		
		1.18 mm	0.425 mm	0.075 mm
1	PT 1	98.29	69.67	31.19
2	PT 2	97.24	67.96	32.02
3	PT 3	98.07	66.9	35.94
4	PT 4	97.72	68.68	38.67

Table 4. Atterberg limits tests.

S/N	Borehole	LL (%)	PL (%)	P.I. (%)
1	PT 1	38.78	16.88	21.9
2	PT 2	41.99	16.95	25.04
3	PT 3	52.40	16.45	35.95
4	PT 4	51.09	18.83	32.26

Table 5. Compaction test.

S/N	Borehole	Maximum dry density (g/cm^3)	Optimum moisture content (%)
1	BH 1	1.76	14.60
2	BH 1	1.80	13.20
3	BH 1	1.77	14.6
4	BH 2	1.79	14.8

flow. The test carried out under this included Liquid Limit (LL), Plastic Limit (PL) and Plasticity Index (PI), all of which make up the Atterberg Limit test. These were determined in accordance with AASHTO T180- 70 (B.S1377:75; Tests 2 and 3, respectively). The Atterberg limits values are summarized in Table 4.

Compaction is the process of classification of soil by reducing air voids. The degree of compaction of a given soil is measured in terms of its dry density. This was done by protor testing and the tests were carried out in accordance with the modified AASHTO T180-70 (B.S1377:75; Test 12). The results of compaction tests are summarized in Table 5.

The Triaxial Compression Test involved the shearing of a cylindrical column of soil obtained in-situ to determine its resistance to pressure. The test results are summarized in Table 6.

Table 6. Triaxial compression test.

S/N	Borehole	Cohesion (C) (kN/m^2)	Optimum moisture content (%)
1	PT 1	42	17.50
2	PT 2	38	13.0
3	PT 3	57	21.0
4	PT 4	37	24.50

The California Bearing Ratio (CBR) test was conducted on the soil, both under soaked and unsoaked conditions, to obtain the compressive strength and shear strength of the soil sample.

The results of the CBR tests for various pits are summarised in Table 7.

2.2. Data processing and analysis

Spot elevations, along with X and Y coordinates, were obtained from Total Station Surveys based on the Differential Global Positioning System (DGPS) derived control coordinates, using the built-in software in the Total Station System. The project coordinates were downloaded into the Arc GIS environment as an Excel spreadsheet file for further processing. Shape files were created for the elevation data. The shape files were then used for the creation of a Triangulated Irregular Network (TIN) using the Z-coordinates. Digital Elevation Models (DEM) were generated by converting the TIN into Raster. Contours lines were generated using the created TIN to interpolate for contours with the aid of 3D analysis extension. The Arc scene was then used for visualization of the 3D model generated from the contour maps. Slopes were generated with the aid of high Ikono satellite imagery. The pixel size of the DEM was I m. Using the morphological data, cross sections were plotted to determine the shape of the gullies (V or U shaped), as this helps in determining the method of bank stabilization to be adopted. The cross section data were also used to compute cross sectional areas and the volume of soil loss. The cross sectional areas were computed at 20 m intervals using the end area formula, given as:

$$A = h(b + s.h), \tag{1}$$

where:

h depth of gully;

b breadth of gully;

s side slope of gully;

A cross sectional area.

Using the area of the cross sections, the volume of soil loss was computed for the various sections using the Simpson rule, given by Schoffield [33] as:

Table 7. California bearing ratio tests.

S/N	Location		Soaked		Unsoaked	
			2.5 mm	5.0 mm	2.5 mm	5.0 mm
1	PIT 1	Bottom	10.24	9.37	4.46	4.77
		Top	3.14	4.44	4.29	5.97
2	PIT 2	Bottom	13.38	14.22	6.85	8.22
		Top	6.28	9.10	11.23	9.86
3	PIT 3	Bottom	10.74	12.71	7.85	9.04
		Top	7.60	8.93	5.04	6.14
4	PIT 4	Bottom	5.04	4.66	3.06	3.56
		Top	3.30	4.22	2.89	3.1

$$V_L = \frac{L}{6}[A_1 + 4A_m + A_2], \quad (2)$$

where:

V_L volume of soil loss between the sections;

A_1 cross sectional area of first section;

A_2 cross sectional area of second section;

A_m cross sectional area of section midway between the first and second section.

Also computed were the breadth and depth ratio and the slope gradient to enable determination of the time of concentration for the hydraulic design.

The time of concentration was computed using the Kirpich equation given by Suresh [34] as:

$$T_c = \frac{0.0195L^{0.770}}{S^{0.385}}, \quad (3)$$

where:

T_c time of concentration in minutes;

L length of channel reach in meters;

S average slope of the channel reach in m/m.

In order to determine L and S, a topographical map covering the catchment basin, with contour intervals of 1 m, was produced from $l/2500$ Benin city sheets.

The gully area, together with the catchment basin, was delineated in this topographical map. High resolution Ikono satellite imagery was also acquired and the topographical map super imposed on the image for land cover analysis.

(i) Calculation of longitudinal growth of gully. The longitudinal growth of the gully was computed in three periods as 2000-2005, 2005-2010 and 2010-2012.

(ii) Estimation of gully head advancement with the use of studied models.

(iii) Calculation of total area of gully growth: The total area of growth for the gully was calculated for two consecutive years, with the difference or change in width as ordinates, and using the trapezoidal rule:

$$A = 1/2\,(h_1 + h_n) + h_2 + h_3 + h_4 - -h_{n-1}, \quad (4)$$

where A represents the area of growth in m^2, and $h_1\ h_2 \cdots h_n$ represents the ordinates.

Using the morphological data, cross sections were plotted in order to determine the cross sectional area and the volume of soil loss in the gully. The eroded volume of the gully segment was calculated using the cross sectional area and the distance between the cross sections as:

$$V = \sum LA, \quad (5)$$

where L is the length of the gully section in meters and A is the cross sectional area in m^2.

Computation of the morphological data, along with the cross sectional area and volume of soil loss, was carried out using AUTODESK Land Development Software. Short term erosion rates (tons ha^{-1} yr^{-1}) (E_s) were calculated in order to determine the rate of erosion over the period of study, using the equation given in Nyssen et al. [11]:

$$E_s = \frac{(V_{2010} - V_{2011})\,\rho_d}{T.A}, \quad (6)$$

where:

E_s erosion rate;

T period of gully development in years;

ρ_d bulk density of soil occurring in the contributing area;

A watershed area in hectares.

Erosion per unit gully surface (tm^{-2}) was estimated using the equation:

$$E_p = \frac{V\rho_d}{A_p}, \tag{7}$$

where:

V current volume of soil loss in gully;

A_p plan area of gully (m^2);

E_p erosion per unit gully surface;

ρ_d bulk density.

2.2.1. Estimation of gully head advancement with the use of studied model determination of model exponential factors

Using the area calculated and other parameters obtained from fieldwork, e.g. geotechnical factors, the exponential factors for the Bear and Johnson [7] Eq. (8) for gully growth, and the Thompson [1] Eq. (9) for head advancement, the models exponential factors were formulated.

(a) The Bear and Johnson [7] model for head advancement is given as:

$$G_A = KR^x L_g^y L_w^z e^m P, \tag{8}$$

where:

G_A surface growth of gully (m^2);

R index of surface runoff, which depends on type of soil and catchment;

L_g length of gully (m);

L_w distance from head of gully to watershed divide;

e base of natural log;

P deviation of precipitation from normal, which may be taken as average precipitation [35];

K coefficient of growth;

x, y, z, m exponential factors, which depend on catchment characteristics.

b) The Thompson [1] model is given as:

$$R = 0.15A^{0.49}S^{0.14}P^{0.74}.E, \tag{9}$$

where R is gully head advancement (meter/year), A is gully head watershed area (m^2), S is gully bed slope (%), P is constant precipitation equal to or more than 0.5 mm in 24 hrs, and E is percentage of clay in the soil of the watershed area.

c) The first model of the American soil conservation service, SCS (1), is given as:

$$R = 1.5W^{0.46}P^{0.2}, \tag{10}$$

where R is gully head growth (m), W is gully head watershed area (m^2) and P is total precipitation in 24 hours equal to or more than 0.5 mm during the formation and advancement of the gully (mm).

d) The second model of American Soil Conservation Service, SCS (II), is given as:

$$R_A = R_1 \left(\frac{A_1}{A_2}\right)^{0.46} \left(\frac{P_2}{P_1}\right)^{0.2},$$

where R_A is gully longitudinal growth in future years (meter/year), and R_1 is gully longitudinal growth in previous years (meter/year). It is important to mention that with regard to R_1, this method will be used to measure periods of 2000-2005, 2005-2010 and 2010 to 2012 in Nigeria. $(\frac{A_1}{A_2})$ is ratio of watershed area to entire gully watershed area, and $(\frac{P_1}{P_2})$ is ratio of amount of precipitation equal to or more than 0.5 mm in 24 hours and mean annual precipitation.

e) The FAO model is given as:

$$R_f = R_1 (A)^{0.46} (P)^{0.02} \tag{11}$$

where R_1 is mean rate of gully longitudinal growth in previous years (m), and R_f is gully longitudinal growth in future years (m). It is important to mention that this can be used for periods between 2000-2005, 2005-2010 and 2010-2012 in Nigeria. The parameter, A, is a ratio of watershed area, A_1, to the entire gully watershed area, A_2. P is the amount of precipitation equal to or more than 0.5 mm in 24 hours, P_1, and mean annual precipitation, P_2.

3. Results

The UTM coordinates of sampling points are contained in Table 1. The specific gravity values of the soil samples are presented in Table 2. Test results for the sieve analysis conducted on the soil sample are presented in Table 3. The atterberg limit values for the soil sample are summarized in Table 4. The results of the compaction test are presented in Table 5. Table 6 contains the result of the triaxial compression test. The result of the California Bearing Ratio (CBR) test is presented in Table 7. Table 8 contains the results of Morphological Parameters of the gully from (Choo+oo-choo+960), along with the cross-sectional areas and volume of soil loss obtained during the monitoring period 2010-2012.

Table 9 contains the results of the measured values obtained for the gully head advancement at the Queen Ede gully site, for the period 2000-2012, using aerial photos. Table 10 contains the results of the computed values obtained for gully head development at the Queen Ede gully site, Benin city, for the period 2000-2012, using the Thompson [1] model.

Table 8. Morphological parameters of the gully from Choo+oo-choo+960 along with the cross ional areas and volume of soil loss obtained during the period 2010-2012 monitoring period.

S/N	Chain-age	Topwidth			Bottom width			Depth			Cross section area			Volume			Cumulative volume of soil loss		
		2010	2011	Diff.[a]	2010	2011	Diff.	2010	2011	Diff.	2010	2011	Diff.	2010	2011	Diff.	2010	2011	Diff.
1	00+00	15.604	15.604	0.000	10.000	10.000	0.000	0.374	0.374	0.000	3.510	3.510	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	00+20	36.993	36.993	0.000	13.466	13.466	0.000	3.478	3.478	0.000	55.172	55.172	0.000	1103.440	1103.440	0.000	1103.440	1103.440	0.000
3	00+40	62.702	88.582	5.880	28.556	28.920	0.364	4.751	4.751	0.000	173.467	176.780	3.313	3489.340	3535.600	66.260	4572.780	4639.040	66.260
4	00+60	39.300	43.288	3.9880	29.873	30.002	0.129	9.889	9.889	0.000	242.322	247.670	5.348	4848.440	4953.480	107.040	9419.220	9592.520	173.300
5	00+80	61.687	61.587	0.000	17.500	17.600	0.000	7.846	7.846	0.000	316.256	318.288	0.000	6325.120	6325.120	0.000	15744.340	15917.640	173.300
6	00+100	99.454	101.218	1.764	81.556	82.877	1.321	9.155	9.155	0.000	429.739	431.335	1.598	8594.780	8626.700	31.920	24339.120	24544.340	205.220
7	00+120	76.554	75.554	0.000	85.998	65.996	0.000	6.988	6.988	0.000	328.321	328.321	0.000	6566.420	8566.420	0.000	30905.540	31110.760	205.220
8	00+140	80.297	80.297	0.000	66.556	66.556	0.000	13,788	13.788	0.000	726.142	726.142	0.000	14522.840	14522.840	0.000	45428.280	45833.600	205.220
9	00+160	81.627	81627	0.000	69,784	69.246	0.000	10.585	10.585	0.000	593,031	593.031	0.000	11880.620	11880.620	0.000	57289.000	57494.220	205.220
10	00+180	76.533	76.533	0.000	71,784	71.784	0.000	7,112	7.112	0.000	283.207	283.207	0.000	5664,140	5664,140	0.000	62953.140	633158.360	205.220
11	00+200	74.184	74.184	0.000	80.000	80.000	0.000	12,394	12.394	0000	709.756	709.756	0.000	14195,120	14195,120	0.000	77148,280	77353.480	205.220
12	00+220	75.820	82.181	6.341	60.870	60.000	0.870	13.007	13.007	0.000	897.077	914.951	17.874	17941.540	16299.020	367.480	95659.500	95652.500	662.700
13	00+240	40.418	50.173	9.755	32.232	32.232	0.000	10.727	10.727	0.000	367.197	386.609	29.812	7143.940	7736.120	692.240	102233.740	103388.580	1164.940
14	00+260	41.971	54.266	12.295	37.500	38.060	0.680	7.492	7.492	0.000	288.332	313.481	26.148	5766.640	6269.620	502.980	108000.380	109658.300	1657.920
15	00+280	36.292	49.53	13.238	22.500	22.500	0.000	7.208	7.208	0.000	204.210	224.344	20.134	4084.200	4488.880	402.680	112084.580	114145.180	2060.600
16	00+300	31.752	31.752	0.000	18.026	18.026	0.000	8.432	8.432	0.000	213.881	213.881	0.000	4277.620	4277.620	0.000	116362.600	118422.800	2060.200
17	00+320	32.290	32.290	0.000	22.098	22.098	0.000	8.855	8.855	0.000	220.372	220.372	0.000	4407.440	4407.440	0.000	120769.600	122830.240	2060.640
18	00+340	30.000	30.000	0.000	23.894	23.894	0.000	7.975	7.975	0.000	218.855	218.855	0.000	4377.100	4377.100	0.000	125146.740	127207.340	2060.600
19	00+360	31.780	31.780	0.000	19.505	19.505	0.000	7.046	7.046	0.000	179.625	179.625	0.000	3592.500	3592.500	0.000	125146.740	127207.340	2060.600
20	00+380	41.297	41.297	0.000	30.705	30.705	0.000	8.737	8.737	0.000	283.715	283.715	0.000	5674.300	5674.300	0.000	128739.240	130799.840	2060.600
21	00+400	56.205	68.205	0.000	40.841	40.841	0.000	8.981	8.981	0.000	391.768	391.768	0.000	7835.360	7835.360	0.000	134413.540	136474.140	2060.600
22	00+420	62.090	62.090	0.000	45.441	45.441	0.000	10.306	10.306	0.000	499.879	499.879	0.000	9997.680	9997.560	0.000	142248.900	144309.500	2060.600
23	00+440	62.348	62.348	0.000	47.8318	47.8318	0.000	11.046	11.046	0.000	533.251	533.251	0.000	10655.020	10665.020	0.000	162246.480	154307.080	2060.600
24	00+460	80.045	80.045	0.000	51.288	51.288	0.000	21.614	21.614	0.000	1523.144	1523.144	0.000	30662.880	30662.880	0.000	162911.500	164972.100	2060.600
25	00+480	69.477	69.267	0.000	54.260	54.260	0.000	16.874	16.874	0.000	774.909	774.909	0.000	15496.060	15498.060	0.000	193574.380	195634.980	2060.600
26	00+500	70.000	70.000	0.000	62.580	62.580	0.000	16.378	16.378	0.000	841.278	841.278	0.000	16825.560	16825.560	0.000	209052.440	211133.040	2080.800
27	00+520	69.477	699.477	0.000	49.455	49.455	0.000	18.125	18.125	0.000	788.434	788.434	0.000	15368.680	15368.680	0.000	225598.040	227968.600	2360.560
28	00+540	86.885	88.865	0.000	55.914	55.914	0.000	19.078	19.078	0.000	1187.323	1187.323	0.000	23346.480	23346.460	0.000	241266.680	243327.280	2080.600
29	00+560	85.458	85.458	0.000	55.814	55.814	0.000	9.362	9.362	0.000	445.352	445.352	0.000	8907.040	8907.040	0.000	264513.140	266673.740	2060.600
30	00+580	111.139	111.139	0.000	65.229	65.229	0.000	12.857	12.857	0.000	989.622	989.622	0.000	19390.440	19390.440	0.000	273520.180	275580.780	2060.600
31	00+600	112.000	112.000	0.000	59.430	59.430	0.000	13.409	13.409	0.000	970.039	970.039	0.000	19400.780	19400.780	0.000	292910.620	294971.220	2060.600
32	00+620	43.992	43.992	0.000	24806	24806	0.000	15.080	15.080	0.000	526.558	526.558	0.000	10531.160	10531.160	0.000	312311.400	314372.000	2060.600
33	00+640	31.865	31.865	0.000	20.279	20.279	0.000	11.392	11.392	0.000	288.565	288.565	0.000	5731.300	5731.300	0.000	322342.500	324903.160	2560.660
34	00+660	32.077	32.077	0.000	23.008	23.008	0.000	13.889	13.889	0.000	372.530	372.530	0.000	7450.600	7450.600	0.000	326024.460	338085.060	2060.550
35	00+680	23.191	23.191	0.000	15.000	15.000	0.000	11.000	11.000	0.000	180.685	180.685	0.000	3613.720	3613.720	0.000	339638.180	341696.780	2060.600
36	00+700	17.383	17.363	0.000	14.300	14.300	0.000	9.854	9.854	0.000	128.751	128.751	0.000	2575.020	2575.020	0.000	342213.200	344273.800	2060.600
37	00+720	15.000	15.000	0.000	11.379	11.379	0.000	9.586	9.586	0.000	105.702	105.702	0.000	2114.040	2114.040	0.000	344327.240	346387.840	2060.800
38	00+740	16.790	16.790	0.000	11.090	11.090	0.000	8.496	8.496	0.000	103.483	103.483	0.000	2069.660	2069.660	0.000	349396.900	348457.500	2060.600
39	00+760	12.312	12.312	0.000	9.461	9.461	0.000	4.393	4.393	0.000	48.678	48.678	0.000	933.500	933.500	0.000	347330.410	349391.000	2060.600
40	00+780	22.292	22.282	0.000	13.941	13.941	0.000	8.877	8.877	0.000	149.781	149.781	0.000	2996.620	2996.620	0.000	350328.020	352386.620	2060.590
41	00+800	19.363	19.363	0.000	13.948	13.948	0.000	7.780	7.780	0.000	127.897	127.897	0.000	2557.940	2557.940	0.000	352883.980	354944.560	2060.600
42	00+820	21.557	21.557	0.000	15.248	15.248	0.000	7.202	7.202	0.000	133.749	133.749	0.000	2674.980	2674.980	0.000	355558.940	357619.540	2060.500
43	00+840	24.080	24.080	0.000	18.115	18.115	0.000	6.422	6.422	0.000	124.698	124.698	0.000	2493.960	2493.960	0.000	358052.900	360113.500	2060.600
44	00+860	31.696	31.696	0.000	20.000	20.000	0.000	5.361	5.361	0.000	128.396	128.396	0.000	2667.920	2667.920	0.000	350620.820	362681.420	2060.600
45	00+880	42.771	42.771	0.000	25.000	25.000	0.000	3.771	3.771	0.000	118.481	118.481	0.000	2389.220	2389.220	0.000	362990.040	365050.640	2060.600
46	00+900	77.226	77.226	0.000	32.500	32.500	0.000	3.890	3.890	0.000	198.260	198.260	0.000	3925.000	3925.000	0.000	366915.040	368975.640	2060.600
47	00+920	119.049	119.049	0.000	100.000	100.000	0.000	5.458	5.458	0.000	298.924	298.924	0.000	5978.480	5978.480	0.000	372893.520	374954.120	2060.600
48	00+940	22.401	29.604	7.203	7.500	7.500	0.000	5.126	5.126	0.000	70.761	82.062	11.291	1415.220	16410.04	14994.820	374308.740	391364.160	17055.420
49	00+960	18.387	40.815	22.448	7.890	7.890	0.000	4.480	4.48	0.000	50.658	85.271	34.615	1013.000	1705.42	692.420	375321.740	393069.580	17747.840

[a]: Diff.: Difference

Table 11 contains the results of estimated values obtained for gully head advancement at the Queen Ede gully site between the 2000-2012 study period, using the SCS (I) model.

Table 12 contains the results of estimated values obtained for gully head advancement at the Queen Ede gully site, between the 2000-2012 study period, using the SCS (II) model. Estimation of gully head advancement at the Queen Ede gully site, Benin city, between 2000-2012 study periods, using the FAO model, is presented in Table 13. Tables 14 and 15 contain the amount of variable error percent, absolute error percent and mean error percent calculated for the period 2000-2012 for the four models, Thompson, SCS (I), SCS (II) and FAO. This is a statistical comparative analysis of the four models. Figure 2 shows the comparison between the predicted and measured data for the gully.

4. Discussion of results

The result of the soil test carried out showed that the specific gravity of the soil obtained varied between 2.51 to 21.60 (the soil is finely graded). The plasticity index of the soil sample varies between 21.9% to 35.95%,

Table 9. Measuring of gully head development in Queen Ede gully site Benin city Nigeria in three period of time using Aerial photos.

	Gully head advancement			
Gully number	**2000-2005**	**2005-2010**	**2010-2012**	**Mean longitudinal growth**
	Meter/year	**Meter/year**	**Meter/year**	**Meter/year**
1	0.332875	0.20976	0.19906	0.24389
2	0.64375	0.4333	0.41439	0.4637
3	0.7566	0.3662	0.23566	0.4528
4	0.2381	0.28385	0.12464	0.2152
5	0.37901	0.58946	0.35827	0.44245
6	0.2606	0.4455	0.30276	0.33600
7	0.4028	0.2954	0.12525	0.25335
8	0.4455	0.1954	0.25945	0.30001
9	0.2931	0.2442	0.2442	0.2605
10	0.4973	0.0792	0.0351	0.2035
11	0.09437	0.07667	0.05432	0.07512
12	0.06895	0.07810	0.04652	0.06385
13	0.4780	0.35097	0.3660	0.3983
14	0.25403	0.4785	0.3890	0.3738
Sum	5.144985	4.12651	3.15462	4.08247
Annual growth	**0.3674989**	**0.29475**	**0.22533**	**0.291605**

Table 10. Estimation of gully head development in Queen Ede gully site Benin city, Nigeria using Thompson Model.

	Gully head advancement			
Gully number	**2000-2005**	**2005-2010**	**2010-2012**	**Mean longitudinal growth**
	Meter/year	**Meter/year**	**Meter/year**	**Meter/year**
1	11.6686	11.8684	11.8692	11.8694
2	35.7979	35.9082	35.7918	35.8010
3	17.2776	16.0595	16.0676	16.9038
4	5.8569	5.8019	5.7988	5.8004
5	17.4225	17.3910	17.2020	17.2066
6	14.4225	14.5646	14.4200	14.5270
7	17.4286	17.4194	17.3072	17.4164
8	5.9362	5.9109	5.90699	5.9246
9	17.3159	17.3127	17.2044	17.2008
10	10.7887	10.7866	10.7826	10.7866
11	10.5874	10.5883	10.5844	10.5844
12	28.5570	28.5570	28.5562	28.5574
13	36.3965	36.3965	36.3764	36.3898
Sum	229.4558	192.6576	226.86859	228.9682
Annual growth	**16.3897**	**1376125**	**16.20489**	**16.35487**

and the soil optimum moisture content is about 15%, indicating the presence of clayey soil. The minimum plasticity showed that the soil has a tendency to be eroded by water. Therefore, the period of the rainy season means that the soil in the area is likely to be eroded. This is the period of gully recession and bank slumping. Adequate control measures should be put in place to prevent further expansion of the gully. Results of the studies revealed that gully width varied from 15.6 m to 99.5 m, the depth varied from

Table 11. Estimation of gully head development in Queen Ede gully site Benin city, Nigeria using SCS (I).

	Model gully head advancement			
Gully number	**2000-2005**	**2005-2010**	**2010-2012**	**Mean longitudinal growth**
	Meter/year	**Meter/year**	**Meter/year**	**Meter/year**
1	9.5199	0.3657	0.4760	10.03247
2	9.4217	0.3526	0.4626	10.2369
3	4.8715	0.2302	0.3413	5.443
4	5.237	0.2427	0.3548	5.8345
5	5.1217	0.2327	0.3438	5.6982
6	5.1116	0.2315	0.3426	5.6857
7	9.1405	0.3612	0.4623	9.964
8	5.1261	0.2330	0.3441	5.7032
9	9.1671	0.3549	0.4650	9.987
10	9.1476	0.3532	0.4643	9.9706
11	8.8855	0.3587	0.4698	9.7085
12	8.9845	0.3532	0.4643	9.802
13	9.4156	0.3544	0.4655	10.2355
14	9.4162	0.3626	0.4738	10.2526
Sum	80.004	3.7907	4.65318	123.9997
Annual growth	**5.7145**	**0.27076**	**0.33237**	**8.8571**

Table 12. Estimation of gully head development in Queen Ede gully site Benin city, using SCS (II).

	Model gully head advancement			
Gully number	**2000-2005**	**2005-2010**	**2010-2012**	**Mean longitudinal growth**
	Meter/year	**Meter/year**	**Meter/year**	**Meter/year**
1	0.3147	0.09639	0.09840	0.48949
2	0.5873	0.3002	0.3113	1.1988
3	0.3879	0.2175	0.2042	0.8096
4	0.3495	0.01565	0.01676	0.7712
5	0.2276	0.3154	0.3065	0.8495
6	0.6253	0.2798	0.2899	1.195
7	0.3761	0.2294	0.2095	0.715
8	0.0615	0.0239	0.0340	0.1196
9	0.28405	0.1189	0.11026	0.51321
10	0.1640	0.03062	0.0211	0.21572
11	0.18619	0.03020	0.0205	0.23689
12	0.1522	0.04376	0.0668	0.2676
13	0.3311	0.2177	0.2050	0.7538
14	0.2367	0.3121	0.2011	0.7499
Sum	4.28414	1.95885	2.07532	8.88531
Annual growth	**0.30601**	**0.13980**	**0.14837**	**0.63466**

0.5 m to 13.8 m, and the width to depth ratio (WRD) varied from 1.6 m to 41.7 m. The volume of the soil loss was 372,775 m^3 over an area of 104.4 m^2, which is equivalent to 3.57 m^3/m^2. Recent research in estimating gully erosion in China and Spain produced the result of 0.86 to 2.24 m^3/m and 2.11 m^3/m^2, respectively. The cross section shows that the gully is U-shaped, indicating a large catchment with a large volume of discharge passing through the gully. The slope of the area is generally steep, with slope gradient

Table 13. Estimation of gully head development in Queen Ede gully site, Benin city, Nigeria using FAO model.

	Gully head advancement			
Gully number	**2000-2005**	**2005-2010**	**2010-2012**	**Mean longitudinal growth**
	Meter/year	**Meter/year**	**Meter/year**	**Meter/year**
1	0.2782	0.09849	0.07239	0.44908
2	0.6384	0.4204	0.18694	1.24574
3	0.2986	0.12864	0.09638	0.52362
4	0.3755	0.02607	0.01635	0.041792
5	0.0765	0.2349	0.01238	0.32378
6	0.66801	0.15875	0.01128	0.838104
7	0.2989	0.1420	0.09876	0.53966
8	0.06792	0.0356	0.01416	0.11768
9	0.19673	0.16750	0.07326	0.43749
10	0.16895	0.033346	0.019857	0.222153
11	0.2003	0.05476	0.01656	0.27162
12	0.17319	0.07564	0.02764	0.27647
13	0.47284	0.42131	0.16112	1.05527
14	0.15862	0.20672	0.17885	0.54419
Sum	4.07268	2.20413	0.985927	7.266733
Annual growth	**0.29091**	**0.15743**	**0.070423**	**0.519052**

Table 14. Mean amount of variable error percent and absolute error percent of studied models.

Row number	**Models**	**Mean of relative error percent**	**Mean of absolute error %**
1	Thompson	12195.64	12195.74
2	SCS (I)	97.01	62.03
3	SCS (II)	37.5	7.62
4	FAO	40.05	18.31

Table 15. Mean amount of change variable percent of studied models.

Row number	**Models**	**Estimated primary change variable (C.V[a])**	**Mean of measure**	**C.V (%)**
1	Thompson	1038.31	0.675	153738.51
2	SCS (I)	0.033	0.675	95.11
3	SCS (II)	0.1306	0.675	80.65
4	FAO	0.134	0.675	80.14

[a]: Coefficient of significance.

varying from 15 to 22, and the soil was generally loose with very low organic and clay content ranging between 0.2 to 0.4 and 1 to 6, respectively. The result showed that the highest mean gully advancement (0.28 m year^{-1}) took place from 2000-2005, with most gullies having lower steady headcut retreat rates of 0.25 m per year^{-1} between 2005-2010, and 0.12 m per year^{-1} between 2010-2012. This suggests that the Queen Ede gully site was still in the early stages of formation in the first study period. This formation may be linked to land use or climate changes before the year 2000.

The morphological parameters of the gully from ch 00+00-ch 00+960, along with the cross sectional areas and volume of soil loss obtained during the study period 2010 and 2012 are presented in Table 8. The result of the execution of the models can be summarized as follows. The result of gully longitudinal growth and the amount of gully head advancement, using aerial photos, is shown in Table 9. The amount

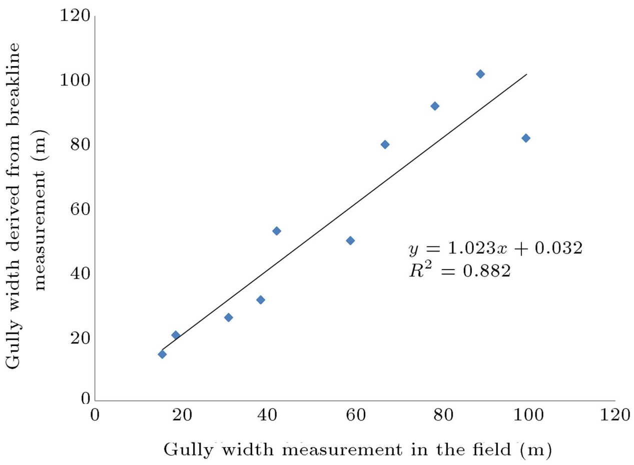

Figure 2. Comparison between predicted (breakline) data and measured field data for gully width.

of gully head development with the Thompson [1] model is shown in Table 10. The amount of gully head development using the SCS (I) model is shown in Table 11. The amount of gully head development using the SCS (II) model is shown in Table 12. The amount of gully head development using the FAO model is shown in Table 13. Tables 14 and 15 contain statistical computations of the four models as a base index for calibration. Comparisons of gully head estimation and development are presented by means of calculations of variable error percent, absolute error percent and change error percent. The results of the statistical study showed that SCS (II) and FAO models have a lesser mean of relative error percent with amounts 37.5 and 40.05, and also a lesser mean of absolute error percentage with amounts 7.62 and 18.31, respectively. It, therefore, shows that these two models perform better than the Thompson [1] and SCS (I) models, and are best suited for the study area.

Figure 2 showed that there is significant agreement between the predicted (breakline) data and the measured (field) data for the gully width for selected points ($R^2 = 0.882$). The developed model showed that the average exponent factors, X, Y, Z and M, for surface growth are 0.2679, 0.0873, 0.09170, 0.009860 and 0.6773, with K value of 0.5, while the head advancement factors, X, Y, Z, are 0.5328, 0.14 and 0.6773.

A mathematical model has been developed for gully growth (G_A) and head advancement for the Queen Ede gully site was obtained and presented as:

(i) For gully growth; $G_A = 0.15\ R^{0.2679}\ L_a^{0.0873}\ L_w^{0.09170}\ e^{0.009860}\ P^{0.06773}$;

(ii) For head advancement; $R_A = 0.15A^{0.5328}S^{0.14}\ p^{0.6773}E$.

The results of the gully growth and head advancement predictions using the test models are presented in Tables 9 to 13, respectively. Tables 14 and 15 contain the results of statistical tests.

5. Conclusion

The study showed that three main types of erosion are prevalent in the area; sheet wash, rill and gully erosion, the latter being the most precarious. The study also revealed that the study area possesses all the characteristics of an erosion prone area. These characteristics are (i) rainfall of very high intensity (annual rainfall ranges from 2700-3200 mm); (ii) steep slopes resulting in large runoff; and (iii) soil with low organic content and relatively low shear strength.

From the morphological parameters, cross sectional drawings and bed profiles were obtained. Results from studies revealed that the gully width varied from 15.6 m to 99.5 m, while the depth varied from 0.5 m to 13.8 m, and the width to depth ratio (WRD) varied from 1.6 m to 14.7 m. The volume of soil loss was 372,775 m^3 over an area of 104.4 m^2, which is equivalent to 3.57 m^3/m^2. The cross section shows that the gully is U-shaped, indicating a large catchment area and a large volume of discharge passing through the gully. Analysis of the immediate catchments around the gully showed that 17.4% of the land area is degraded by gully, 30% by large sediment deposit and 52.6% by marsh land with mild and medium sediment deposit. The study revealed that GPS, with total station surveys, in combination with GIS and remote sensing, can be used for monitoring gully morphology.

The results of the study can be used for planning for further monitoring, gully erosion control and management within the catchment basin. A mathematical model has been developed for gully growth (G_A) and head advancement (R_A) for the Queen Ede gully site, Benin city, Nigeria. The model showed that the average exponential factors, X, Y, Z and M, for surface growth, are 0.2679, 0.0873, 0.09170, 0.009860 and 0.6773, with K assuming values between 0.2 and 2, depending on the magnitude of growth, while head advancement factors, X, Y, Z, are 0.5328, 0.14 and 0.6773. The mathematical model prediction for the Queen Ede gully site, Benin city, is hereby presented as:

1. For gully growth: $(G_A) = 0.15R^{0.2679}L_a^{0.0873}\ L_w^{0.09170}e^{0.009860}p^{0.6773}$;
2. For head advancement: $(R_A) = 0.15A^{0.5328}S^{0.14}\ P^{0.6773}E$,

where R represents index of surface runoff, which depends on the soil type, L_a is length of gully (m), L_w represents distance of gully head to water shed divide, P is precipitation in mm, E is percentage of clay in the soil of the watershed area, A is cross sectional area of gully in m^2.

In conclusion, it can be stated that the predicted models performed well when compared with established models, such as Ahmadi et al. [3], Vandekerchova et al. [27] and Ghodousi Jamal [9].

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