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Drivers of Surface Processes on the Bama Beach Ridge: A Quantitative Analysis of Rainfall, Vegetation and Sediment Transport

by

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Abstract

This study investigates the combined influence of rainfall characteristics, vegetation dynamics, and runoff generation on sediment yield on the Bama Beach Ridge (BBR) in the Sudano–Sahelian zone of northeastern Nigeria. Field observations were carried out on a 0.002-ha artificial catchment located on a 5% grazing slope during the 1990 and 1991 rainy seasons. Rainfall was measured using an automatic siphon-type rain gauge (German model), while runoff and sediment yield were monitored with a discharge recorder and sediment collection tank. Grass growth and density were assessed using fixed quadrats. A total of 107 discrete rainfall events were recorded, with approximately 71% delivering less than 10 mm of rainfall and producing no runoff. Runoff occurred only when rainfall exceeded threshold values of 20 mm in amount and 15 mm h^{-1} in intensity. Event-based analysis indicates that maximum rainfall intensity is the primary control on runoff generation and sediment transport, accounting for 82% of runoff variability. Partial correlation analysis further shows that rainfall intensity, the timing of events within the rainy season, and grass density together explain 93% of the variation in sediment yield. Sediment production was highest at the beginning of the rainy season, when vegetation cover was sparse and surface materials were loosely consolidated, and declined as vegetation density increased. Total sediment yield in 1991 was 3,095.62 g, corresponding to a mean erosion rate of 15.49 g m^{-2} yr^{-1} (154.9 kg ha^{-1}). The transported material was predominantly sandy (75–85%), with very fine sand forming the largest fraction. These findings highlight the importance of rainfall intensity thresholds and vegetation recovery in controlling hillslope erosion in semi-arid savannah landscapes and provide insight relevant to erosion management and geomorphic modeling.

KEY WORDS: Scene, Rainfall, Event, Intensity, Amount, Ratio, Yield

1. Introduction

Geomorphic research examines functional systemic relationships between morphology, process, and surface material, and how they interact to effect change on the landscape. Hence, current emphasis on geomorphic research aims at developing predictive models that address and resolve environmental crises at micro, meso and macro landscape levels. (Tucker and Hancock, 2010) ***The Process-Response Model*** of Schumm, (1979) views landform evolution as the interactions between weathering, erosion, deposition, and geology. It assumes that small external and internal changes induced by climate and tectonics can trigger changes in landform development at different thresholds. The concept is based on the relationships between morphology, processes and surface material. Tucker and Hancock's (2010) landform evolution model (LEM) is a computational model that incorporates factors and parameters of morphology, processes, and geology for modeling landform evolution in different environments. This northern Sudan Savannah research is a contribution in that direction.

2. The Research Environment

The research area is located in the Sudano-Sahelian transition zone, and focuses on rainfall, grass growth and surface wash processes on the Bama Beach Ridge (BBR). The BBR lithology comprises an underlying Tertiary Chad Formation, overlain by successions of lacustrine, fluvial and Aeolian deposits (Nyanganji, 1994, 2002) (Fig.1). The site is a 200m^2 plot located on a 5% slope used for grazing (Nagel and Nyanganji, 1991). The artificial basin was secured and equipped with a self-recording rain gauge and a fixed 50cm^2 quadrat with 5cm^2 mesh.

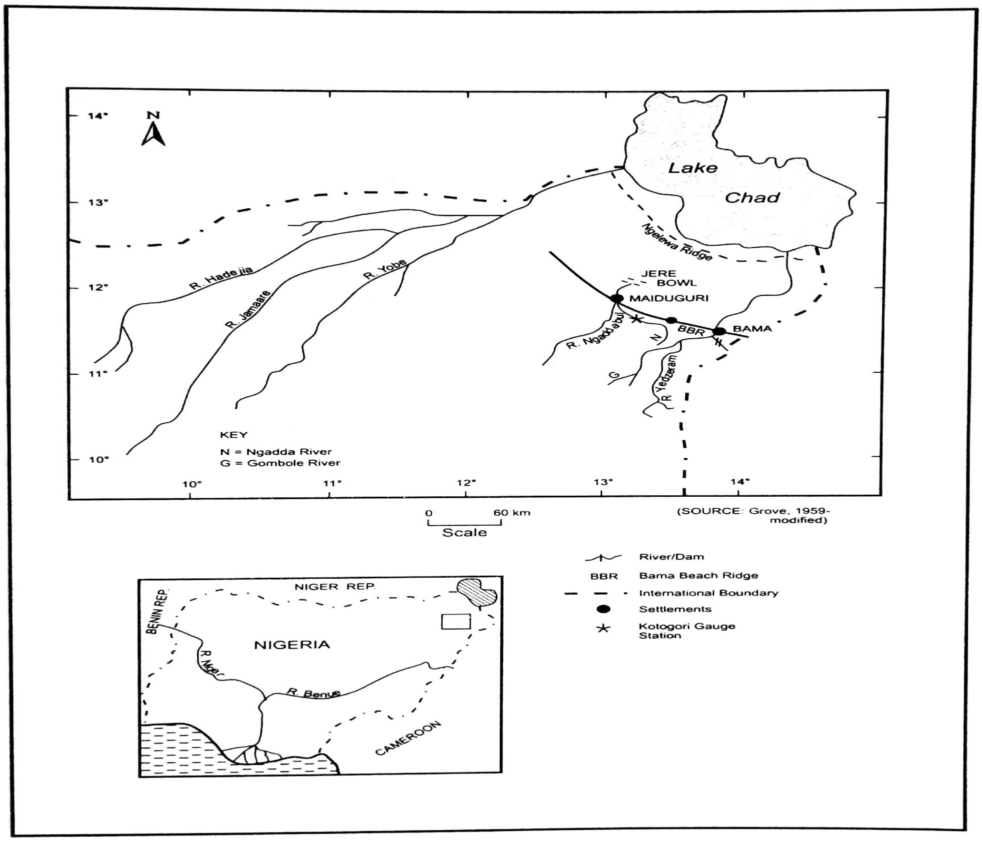

Fig. 1: Location of the Study Area in Borno State, Nigeria

3. The 1990 and 1991 Rainfall Parameters

The relationships between rainfall, runoff, sediment yield, and vegetation analyses are based on data obtained during the 1990 and 1991 rainy seasons.

3.1 Annual Rainfall in 1990 and 1991

Rainfall during the study periods was recorded using an automatic siphon-type rain gauge. The records indicate annual rainfall amounts of 383.1 mm in 1990 and 605.4 mm in 1991 (see Fig. 2 and Table 1). The monthly distributions shown in Fig. 2 were obtained from manual records and rain gauge charts. Storm events were categorized as discrete occurrences within the rainy season and are presented as daily and monthly totals in Table 1 and Figures 3, 4, and 5.

The data reveal that rainfall amounts for these events varied significantly, ranging from 68.4 mm in August to 0.1 mm in October in 1991. August, being the wettest month, accounted for 35.6% of the annual rainfall in 1990 and 46.5% in 1991. The mean monthly rainfall during this period was 41.75 mm. Peak rainfall recorded in August was 137.7 mm in 1990 and 281.7 mm in 1991 (see Fig. 1). Rainfall frequencies between 10 mm and 30 mm were noted in June and September (see Fig. 2). Approximately 71% of the total rainfall fell within the modal class of 1 mm to 10 mm. During the study years, 37% of the rainfall occurred in the afternoon and evening hours, (between 12:00 PM and 6:00 PM), while 32% fell in the morning and 31% at night. Over the two years, only 23% of the rainy season days received measurable amounts of rainfall.

3.2 The 1990 and 1991 Rainfall Days

The rainy seasons for the two years lasted for 6-7 months (Table 1), with a single monthly rainfall peak in August. A rare rainfall of 8.6mm was registered in December 1990. In 1990, the rainy season stretched over 153 days and only 27% of the days had rainfall while in 1991, the rainy season lasted over 214 days and only 19% of the days received rainfall. A total of 49 events were recorded in 1990 in 42 days, while 58 events were recorded in 47 days in 1991, hence 107 rainfall events were observed in 367 days of two years' rainy seasons, and only 23% of the days received rainfall in the study period, during which 71% of the events were less than10mm, out of which 25% were less than 1mm.

3.3 The 1991 Rainfall Event Spacing in July and August

The spacing of rainfall events refers to the intervals in hours or days between consecutive rainfall occurrences. Figure 3 illustrates the spacing of events over several days in July and August. In July, there were six rainfall events recorded over a span of 31 days. On average, these events occurred roughly every five days. However, the actual spacing between events varied, with intervals of 8, 6, 5, 4, 3, and 2 days. Some of these dry periods extended beyond seven days (a whole week) without any rainfall. Such prolonged dry spells can be detrimental to plant growth, particularly in agricultural contexts.

3.4 The Analyses of Events' Rainfall Intensity

The rainfall intensities for the events were determined at 15-minute intervals, and the values obtained ranged from 0.1mm/hr^{-1} to 70mm/hr^{-1}. In 1990, the mean and standard deviation were 5mm/hr^{-1} and 6mm/hr^{-1}. For 1991, the range was 0.002mm/hr.$^{-1}$ to 112mm/hr^{-1}, with a mean and standard deviation of 7.1mm/hr^{-1} and 8.4mm/hr^{-1}. The standard deviations for the years indicate a slight variation in the intensities**.** The intensity graph for Event number 20 (1991) displays the typical sudden start observable in all events, rising to either single or multiple peaks (Fig. 3). The maximum intensities occurred within the first 30 to 45 minutes of the events, while the lowest declined towards the right in minor multiple peaks, revealing the unstable nature of the tropical rainfall intensities (Hudson, 1971, 1965, 1964). Analyses of the 107 events (1990-1991) showed that 85% of the Events had peak intensities between 30-45 minutes after the start of the rainfall event. During this period, 60-93% of the rainfall amount was received. Generally, intensities ranged from 0.002 to 112mm/hr^{-1} and agree with the observation made by Kowal & Kassam, (1977) in the northern guinea savannah.

3.5 Determination of Rainfall Events and Amount of Rainfall

Rainfall is the delivery of rain drops from clouds at a specified rate into a rain gauge, where it collected as the amount of rainfall measured in millimeter threshold in the cylinder or plotted on the rain gauge chart-graphs to show the b*eginning and end of a rainfall event (episode)*. A rainfall event is a discrete rainfall episode bounded by the time, revealing the beginning and end of an event. The boundaries are decoded from the rain gauge plot, and helps in determining the duration of a rainfall event. The amount of rainfall divided by its duration determines the rainfall intensity (Fig. 4)

3.6 Daily Distribution of Rainfall Events

The analysis of the daily distribution of rainfall events reveals that 37% of the events fell in the afternoon and evening; while 32% fell in the morning, and 31% in the evening. From June to September, rainfall events in the classes of 10-30 mm mostly occurred in heavy and high-intensity showers. The heaviest rainfall events in 1990 and 1991 measured 54.6 mm and 68.6 mm in August. About 98% of these events begin with high intensities, reaching peaks within the first 30-45 minutes.

3.7 Analysis of Rainfall Event Number 20: 1991

Rainfall Event number 20 recorded in 1991 is presented graphically as Fig. 3. The graph shows that the Event lasted for 8.25 hours, from 01:12 to 09:27 pm (or 1312 - 2127 hours). A maximum intensity of 43 mm/hour was observed within 45 minutes after the start of the rainfall event. The amount of rainfall delivered by the event in 495 minutes was 41.2 mm. The average rainfall intensity was 4.99mm/h. About 78% (32.1mm) of the total rainfall was delivered within 49.5min (10%) of the event's 8.25 hours duration.

4. Runoff Yielding Events and Runoff/Rainfall Ratio for 1990 and 1991

Rainfall refers to the process of raindrops falling from clouds to the earth's surface at certain intensity. The soil absorbs this rainfall based on its infiltration capacity. However, when the intensity of the rainfall exceeds the soil's ability to absorb it, the surplus water becomes runoff. If the rainfall intensity is within the soil's absorption capacity, then no runoff occurs. Rainfall and runoff ratio is obtained by dividing the runoff by the rainfall total.

4.1 Runoff Yielding Events

Rainfall events that produced runoff were quite rare, and when runoff did occur, its volume was low relative to the total amount of rainfall. This limited runoff was primarily due to high rates of evaporation and infiltration at the site (Rayar, 1983). In general, less than 30% of rainfall events resulted in runoff.

4.2 Runoff and Rainfall Ratio for 1990 and 1991

The ratio of runoff to total rainfall was less than 15%, ranging from 0.4% to 13.4% in 1990 and from 0.037% to 12.2% in 1991, with an average of 4.85%. Out of 107 rainfall events, only 29.2% resulted in runoff that was less than 15% of the total rainfall. This was expected because 71% of the recorded rainfall events had amounts of less than 10 mm, while the threshold for generating runoff was 20 mm. To produce runoff, a maximum intensity of 15 mm/hr was required. The mean runoff-to-rainfall ratio of 4.85% indicates a significant loss of approximately 95% of rainwater, which is lost due to infiltration into the soil and evaporation into the atmosphere. When rainfall reached the 20 mm threshold at the maximum intensity of 15 mm/hr, approximately 60-93% of the rainfall led to flash runoff or mini-flash flood events. The highest rainfall intensity accounted for 82% of the runoff that transported loose sand, silt, and clay particles downslope at the start of the rainy season.

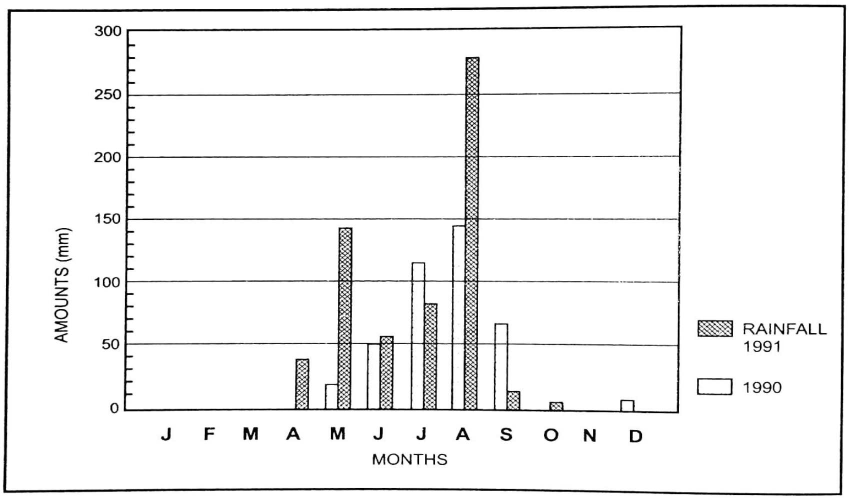

Fig. 2: Monthly Rainfall Event Amounts (mm) for 1990 and 1991

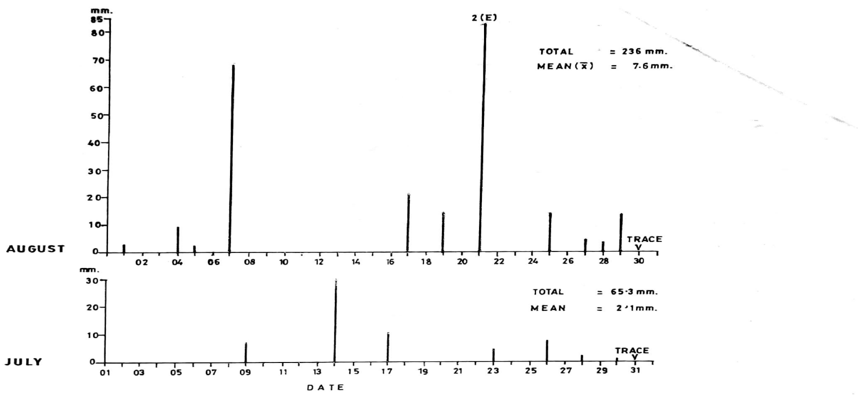

Fig. 3 Distribution of Daily Rainfall Event Amounts in July and August 1991

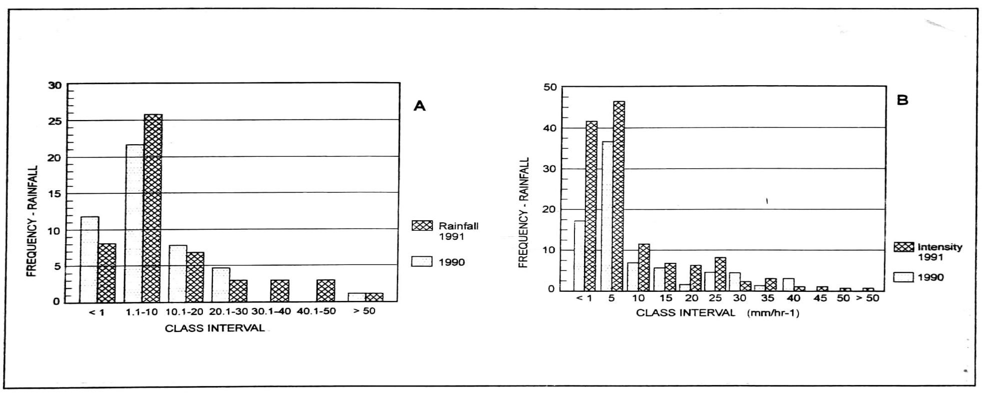

Fig. 4; Rainfall Intensity Graphs 1990 and 1991

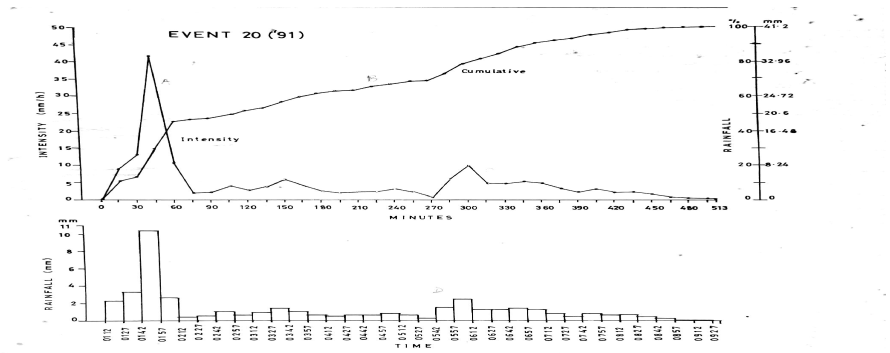

Fig. 5: Event No. 20 (1991) Rainfall Amounts, Intensity and Cumulative Rainfall Graphs.

Table1. Monthly Rainfall Distribution for 1990 and 1991

Year	1990			1991		
Mont	Amount (mm)	Rainy Days	No. of Events	Amount (mm)	Rainy Days	No. of Events
JAN	0	0	0	0	0	0
FEB	0	0	0	0	0	0
MAR	0	0	0	0	0	0
APR	0	0	0	36.2	04	07
MAY	17.1	05	05	136.2	04	11
JUN	48.1	05	07	53.7	04	04
JUL	109.4	11	12	79.8	08	09
AUG	137.7	09	13	281.7	16	22
SEP	62.1	10	11	13.5	03	03
OCT	0.1	01	0	4.3	02	02
NOV	0	0	0	0	0	0
DEC	8.6	01	01	0	0	0
TOTAL	**383.1**	**42**	**49**	**605.4**	**41**	**58**

5. Probability of Maximum Intensity and Rainfall Amount to Yield Runoff

The probabilities of maximum intensity and rainfall amounts produce runoff were below 30% (Fig. 7 and), even though maximum intensity accounted for 82% of the runoff yield.

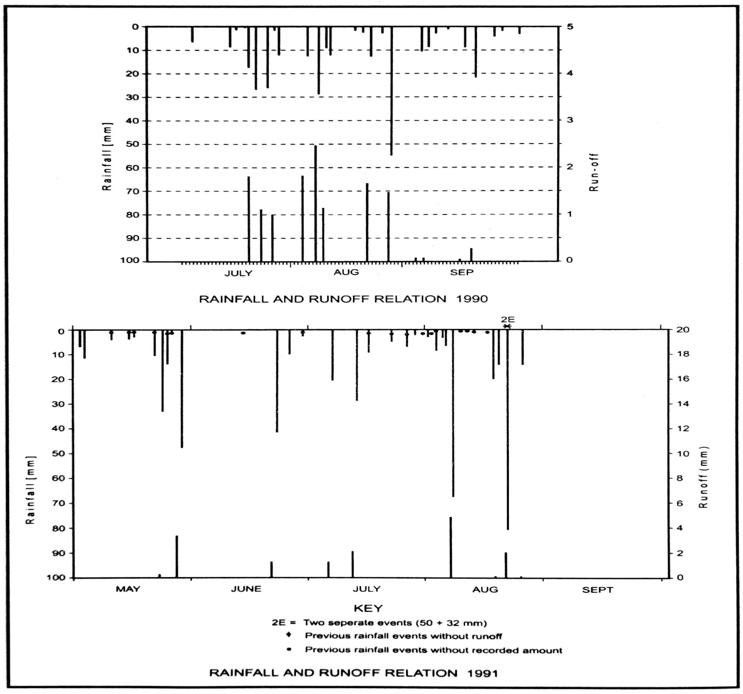

Fig. 6 Rainfall and Runoff Relationships in 1990 and 1991

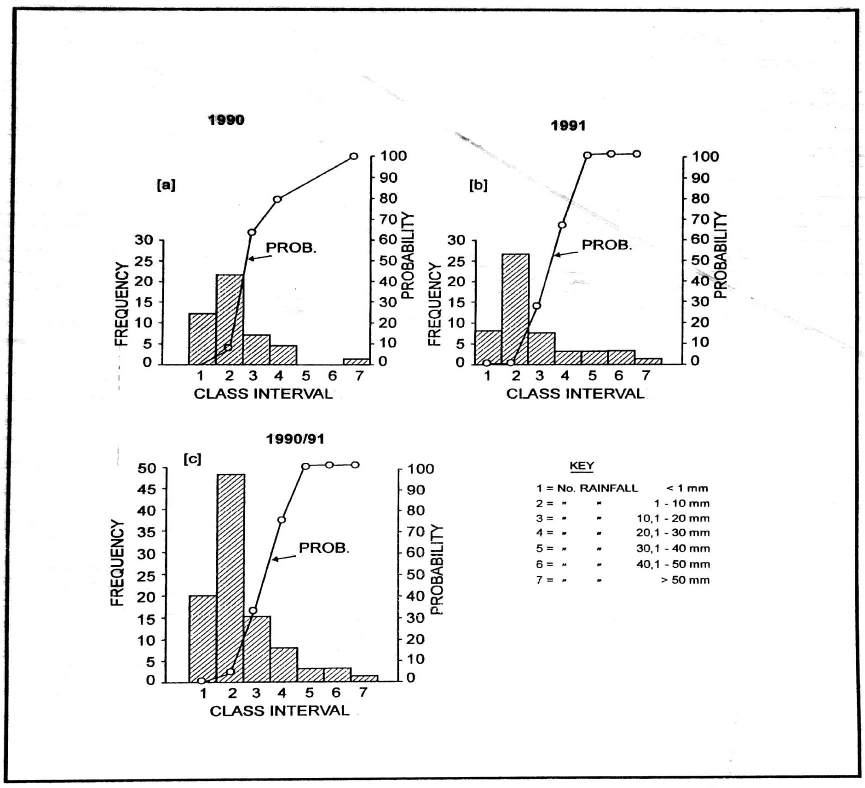

FIG. 7: Probability of Rainfall Amount to Yield Runoff

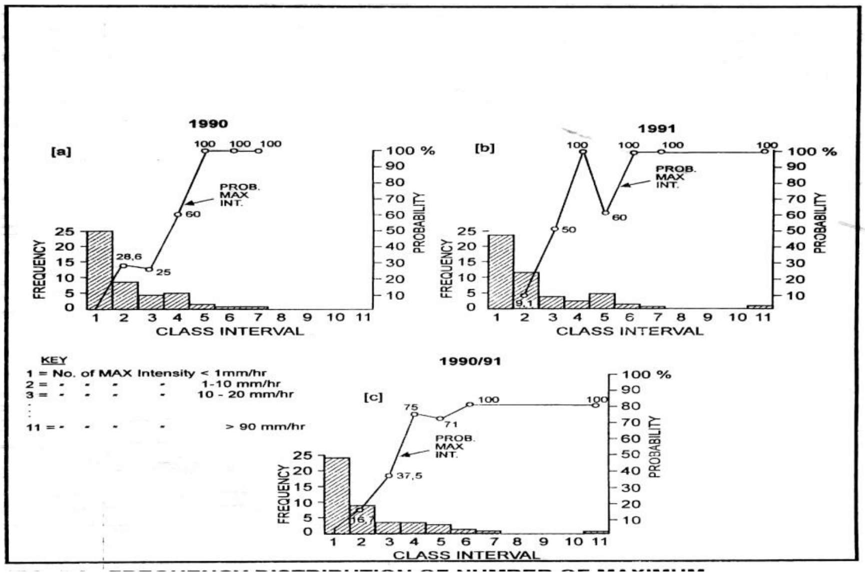

Fig. 8 Maximum Intensity and Probability to Yield Sediments

Table 2: Bivariate Correlation between Factors and Sediment Yield

Factors	Coefficient (r)	%	Sig. level	R^2
Rainfall Event Amount	.4379	2	0.02	19.2
Spacing of Events	.1234	NS	Nil	1.5
Rainfall Duration	.2379	NS	Nil	5.7
Maximum Intensity	.9055	1	0.01	82
Precipitation Antecedent Index	.1146	NS	Nil	1.3
Wind Velocity	.1147	NS	Nil	1.3
Evaporation Rate	.2244	5	0.05	5.0
Soil Temperature	.4751	2	0.02	22.6
Maximum Temperature	.3905	2	0.02	15.2
Rainfall/Runoff Ratio	.4438	2	0.02	19.7
Grass Density	.6709	1	0.01	45.0

6. Monitoring Dynamics of Grass Growth and Density

The life cycle of grass is annual and is influenced by rainfall. When it rains, the seeds of plants that have withered during the dry season germinate, grow, and mature to produce new seeds. After this, the plants wither again in the dry season, leaving the seeds on the soil for the next cycle.

6.1 Grass Growth and Density Trends

In April 1991, the rainfall induced massive germination of undifferentiated grass species with an initial density of 65 plant seedlings per square meter (m^2). This density sharply rose to a high density 90/m^2 creating a continuous ***"carpet green scene"*** on the slope.

6.1.1 Effects of Competition on Grass Density

The compact seedling density led to stiff competition for nutrients and sunlight where only the stronger survived. The initial competition elimination process reduced about 15% of the tender shoots.

6.1.2 Effects of Pest Invasion on Grass Density

Pest and insect attacks decreased plant density from 90 to 70 plants per square meter (see Tables 3, 4, 5, 6, and Fig. 9). The loss of certain species allowed the survivors to grow rapidly in height and leaf development. However, in June, armyworms invaded and cut the plant population by about 50%. This reduction increased splash and sheet erosion, leading to higher sediment yields that month (See Fig. 9 and Tables 3, 4, 5, and 6).

6.2. Grass Growth Phases and Density Trends

The significant reduction in plant density allowed the remaining plants to grow taller and expand their leaves. This increase in space, sunlight, and additional soil nutrients, resulting from the loss of some plants, benefited their growth. The surviving plants produced more leaves, which helped protect the topsoil from raindrop splash) erosion and reduced sediment yield on the slope (see Fig. 9 and Tables 3, 4, 5, and 6).

6.2.1 Grass Growth in Height and Density Dynamics

The density of the plants sharply increased from 65 plants per square meter (m^2) in April and rose to 90 plants per m^2 in May. However, following pest and insect attacks, there was a significant decline in density from 90 plants per m^2 to 70 plants per m^2 in May and June. After this, the grass experienced steady growth, reaching a height of approximately 40 cm by August. Flowering began in mid-July, and the seeds matured in August. After this period, the weight of the matured seeds caused the height of plants decline, during the wilting and withering stages (see Fig. 9). Subsequently, a second recovery phase saw the density stabilize at 70 plants per m^2, only to gradually decrease again to 25 plants per m^2. This was followed by a minor decline to 15 plants per m², and finally, a slight increase back to 25 plants per m², which continued until the withering period (see Tables 3, 4, 5, 6 and Fig. 9).

Table 3: Sediment Yield 1990 and 1991

Year	Maximum Weight (g)	Minimum Weight (g)	Total Weight (g)	Mean Weight (g)	Standard Deviation	Erosion Rates g/m^2
1990	412.3	57.2	651.14	217.2	180.14	3.2
1991	184.85	84.49	3095.62	442.18	432.18	15.49

Table 4: Changes in Grass Density and Sediment Yield g/m^2

Months	Density	Range /m^2	Mean/m^2	Description	Sediment Yield g/m^2	%	Description
April	65-90	(38.5%)	80	sharp rising phase	9.37	20%	High
May	90-70	(22.2%)	80	sharp drop phase	11.23	80%	Higher
June	70-25	(36%)	47	steady recovery phase	211.28	97.4%	Highest
July	25-20	(25%)	23	mini recovery phase	5.42	17%	Lower
Aug.	20-25	(25%)	23	micro rise phase	4.62	14.7%	Lowest

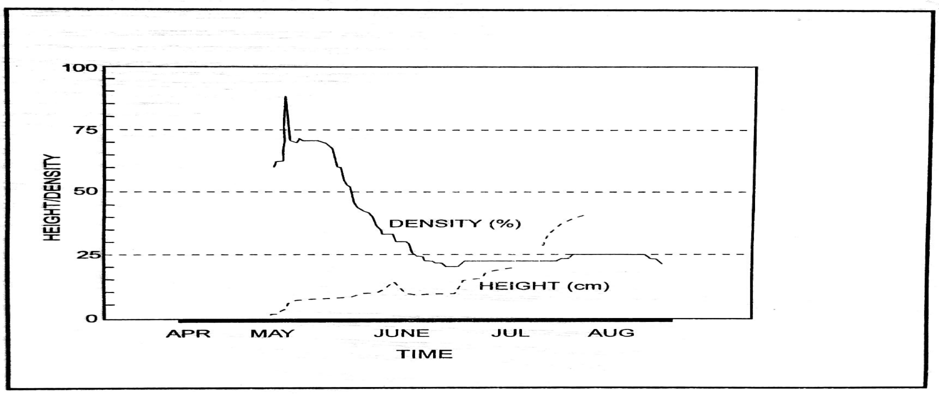

Fig. 9: Grass Change in Height and Density Over Time

Figure 9: 1. Sharp Density Increase Phase 2 Sharp Density Decrease Phase 3. Steady Density Recovery

Phase 4. Micro Density Decrease, 5. Mini Density Rise Phase 6. Wilting & Withering Phase

Table 5: Dynamic Grass Growth Phases

Phase	Month	Dynamic Phase	Density Class per m^2	Mean per m^2	Height (cm)	Environmental Influencers

1	April	Sharp density rising Phase	65-90	80	0.5	competition, pest & insects
2	May	Sharp density decreasing phase	90-70	80	1.5-10	Army worm invasion
3	June	Steady density decreasing phase	70-25	48	10-15	
4	July	Mini-density decreasing phase	25-15	20	15-25	Recovery/steady declining
5	Aug	Micro-density rising phase	15-25	20	30-45	Flowering/bearing
6	Sept	Wilting & withering phase	25-0	13	45-0	Maturing Matured plants

7. Sediment Yield and Grain Size Distribution

The erosion and movement of particles on a slope depend on their size and binding force. Sand particles are easily eroded but require a stronger velocity to be transported downhill. In contrast, clay particles are more difficult to dislodge due to their strong adhesive properties, but once they are in motion, they require minimal force to be transported and suspended in transit. In savannah regions, the lack of vegetation cover at the beginning of the rainy season is likely to result in higher sediment levels due to increased erosion caused by the absence of initial plant cover.

7.1 Sediment Yield

The total sediment yield was 3,095.63 grams, with a minimum of 84.47 grams recorded in July and a maximum of 1,874.85 grams in May. Both grass density and sediment yield decreased as the rainy season advanced. The mean erosion rate was 15.49 g/m^2,amounting to 154.9 kg/ha, with a minimum rate of 0.4223 g/m^2 (4.223 kg/ha) and a maximum rate of 6.786 g/m^2 (67.86 kg/ha) for observed events (Table 3). For the 5% slope in 1991, the total sediment data was 3,095.62 grams, with minimum and maximum values of 84.47 grams and 1,875.85 grams, respectively. The estimated erosion rate for the 1991 season was also 15.49 g/m^2, equivalent to 154.9 kg/ha. Sediment yield decreased as the rainy season progressed, primarily due to topsoil capping tendency and the presence of grass cover. Table 3 highlights the factors affecting sediment yield as maximum intensity (r^2 = 0.82), the location of the event (r^2 = 0.4627), grass density (r^2 = 0.4501), soil temperature (r^2 = 0.1918), and evaporation rate (r^2 = 0.0501). Among these, maximum intensity was the most significant contributor, followed by grass density and the location of the event. Collectively, these variables accounted for 93% of the runoff and sediment yield. The results of the partial correlation analysis indicated that maximum intensity accounted for 82% of the variance, while the location of the event and grass density explained 46% and 45%, respectively. Notably, only the location of the event showed a negative correlation with sediment yield, suggesting that events occurring later in the rainy season are less likely to generate runoff and sediments.

7.2. Sediment Yield Dynamics and Plants Density Changes

In April, grass density was 90 plants per square meter (m^2), and the sediment yield was 9.37 grams per square meter (g/m^2). In May, a 22.2% drop in plant density to 70/m^2 caused sediment yield to rise by approximately 20% to 11.23 g/m^2. From May to June, the decline in plant density due to pests and armyworms led to a staggering 1,781% increase in sediment yield. In July and August, grass densities fluctuated between 25/m^2 and 15/m^2, with sediment yields of 1.28 g/m^2, 5.42 g/m^2, and 4.62 g/m^2. These results indicate that erosion rates generally decrease as the rainy season progresses. The initial high sediment yield resulted from loose particles deposited on the slope by the Harmattan wind before the dense grass cover. These findings suggest that while vegetation density has limited control over erosion, higher grass density correlates with lower sediment yields. As grass density decreases, competition lessens, allowing leaves to grow wider, which helps cover the soil and reduces splash erosion. Ultimately, grass density and sediment yield decline as the rainy season progresses.

7.3 Top Soil and Sediment Grain Size Distribution

Approximately 75-85% of the sediments consist of sand, with very fine sand accounting for about 38-55% of both the sediments and the topsoil samples. In contrast, silt makes up less than 15%. Although sand particles are considered the most erodible fraction, they require a significant force to be moved them downslope. This force is typically provided by the high velocity of the mini-flash floods that occur during periods of brief maximum rainfall intensity.

8. Discussion

The start and duration of the rainy period varied significantly between the two years studied. Additionally, the amount of rainfall fluctuated widely both between events and over time. A considerable number of rainfall events resulted in no runoff, as the maximum rainfall intensity and total amounts fell below the thresholds of 15 mm/hr and 20 mm, respectively. Monthly rainfall is primarily concentrated within the rainy season; however, the events are spaced apart, which impacts plant growth and health during dry spells. Figure 11 indicates that the maximum intensity of rainfall events accounts for 82% of runoff, which leads to mini-flash flood episodes and contribute to high rates of slope wash. This correlation also explains why maximum intensity contributes to 82% of sediment yield in the artificial catchment. Higher peak rainfall intensity and greater rainfall amounts significantly increase the likelihood of runoff and sediment yield, particularly between June and August. These findings align with those of Kowal (1970), Kowal and Stockinger (1977) in Zaria, where it was noted that less than 38% of rainfall events in the savannah produce runoff, compared to 92% in the forest belt (Jeje, 1986), where the runoff threshold is lower than 10 mm. The predominantly sandy and silty sediments differ slightly from the topsoil, with loose sediments being transported downslope by mini-flash flood episodes. Furthermore, the decrease in sediment yield supports the observations of Langbein and Schumm (1958) and Schumm (1965), which state that erosion rates diminish during the rainy season in the savannah. The artificial catchment exhibited only splash, sheet, and rill erosion types, contrasting with the rill and gully erosion observed along the banks of the River Ngadda Channel, which is exacerbated by farming activities on the BBR slopes (Nyanganji, 1994, 2002).

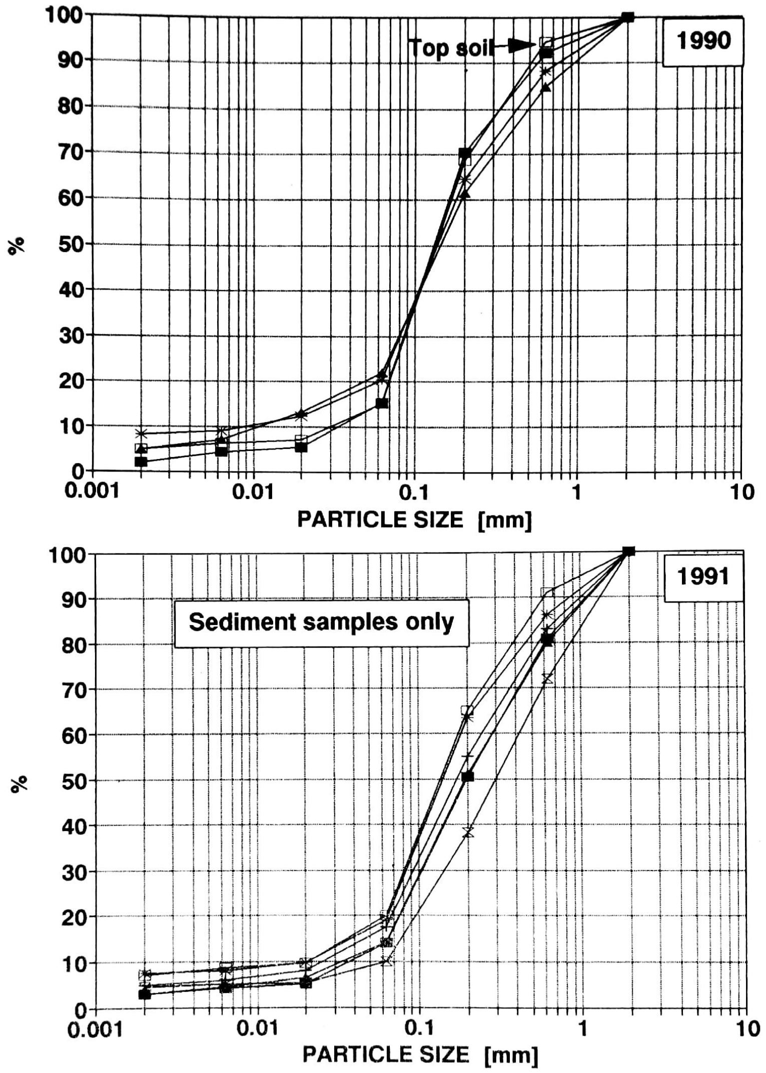

Fig. 10: Particle Size Distribution in the Top Soil and Sediments

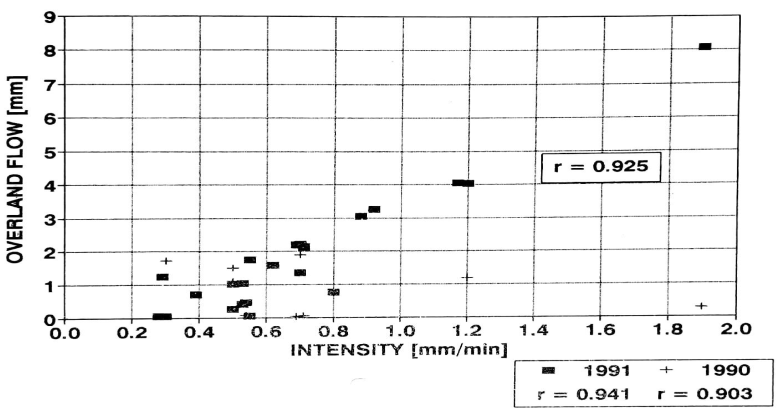

Fig. 11: Relationship Between Overland Flow and Maximum Intensity

Table 6: Changes in Grass Density/m^2 and Sediment Yield g/m^2 in 1991

Month	Density/m^2	Mean/m^2	Description	Sediment Yield g/m^2	Description
April	65-90	80	sharp rising phase	9.37	High
May	90-70	80	sharp drop phase	11.23	Higher
June	70-25	47	steady drop phase	211.28	Highest
July	25-20	23	mini drop	5.42	Low
Aug.	20-25	23	micro rise	4.62	Lower

9. SUMMARY

Geomorphic research investigates the relationships between landform, processes, and surface materials, focusing on how they interact to change landscapes. Current efforts aim to develop predictive models that address environmental crises at micro, meso, and macro levels (Tucker and Hancock, 2010). The Process-Response Model by Schumm (1979) explains landform evolution through interactions among weathering, erosion, deposition, and geology. It suggests that small climate and tectonic changes can trigger significant shifts in landform development. Tucker and Hancock's (2010) Landform Evolution Model (LEM) integrates these factors to model landform evolution in different environments. This research in the northern Sudan Savannah contributes to this field.

This study was conducted on a 0.002-hectare artificial catchment located on a 5% grazing slope. The catchment was equipped with a self-recording siphon-type rain gauge, a sediment yield tank, and a water level gauge recorder. Fixed quadrats, fitted with vertical rulers, were used to monitor grass growth. Annual rainfall for the years 1990 and 1991 was recorded as 383.1 mm and 605.4 mm, respectively. August was the wettest month, accounting for 35.6% of the annual rainfall in 1990 and 46.5% in 1991. Rainfall frequency classes between 10 and 30 mm occurred in June and September. Approximately 71% of the recorded rainfall events had amounts of less than 10 mm, with 25% of these events measuring less than 1 mm. In total, 107 discrete rainfall events were recorded during the study period. On a daily basis, about 37% of these events occurred in the afternoon and evening, 32% at night, and 31% in the morning. Only 23% of the 367 rainy season days received rainfall, with amounts ranging from 68.4 mm in August to 0.1 mm in October 1991. During 1990, there were 153 days in the rainy season, and only 27% of those days experienced rainfall. In contrast, 1991 saw a 7-month rainy season lasting 214 days, during which only 19% of the days received rainfall. The thresholds for rainfall amounts and intensity that generated runoff on the slope were 20 mm and 15 mm/hr, respectively. At these thresholds, mini-flash flood episodes were triggered, resulting in erosion on the slopes. This phenomenon explains why maximum rainfall intensity accounted for 82% of runoff and sediment yield in the catchment.

The research findings indicate variations in the start of the rainy season and the amounts of rainfall. Only 23% of the 367 days in the wet seasons experienced rainfall events. About 98% of these events were brief, reaching peak intensities within 45 minutes, which yielded 60% to 93% of the rainfall, which generated runoff that was strong enough to dislodge and transport sand, silt, and clay particles downslope. The types of erosion observed were primarily rain splash, sheet, and rill erosion. Notably, about 71% of these events delivered less than 10 mm of rain and did not result in runoff because the intensity and amount were below the runoff thresholds. Some of these findings corroborate those of Kowal (1970) and Kowal and Stockinger (1977) in Zaria, where less than 38% of rainfall events in the savannah yielded runoff, in contrast to 92% in the forest belt (Jeje, 1986). The predominance of sand and silt observed was due to the loose particles that were dislodged and transported downslope by runoff during mini-flash floods.

Furthermore, the sediment yield results confirm observations by Langbein and Schumm (1958) and Schumm (1965) indicating that erosion rates decrease as the rainy season progresses in the savannah. Only splash, sheet, and rill erosion types were noted on the catchment. This result contrasts with the rill and gully erosion observed along the Ngadda Channel, where vegetation was cleared from the BBR slopes for farming (Nyanganji, 1994, 2002). In April, the initial grass density was described as a "green carpet," with a density of 65-90 plants per square meter. The sediment yield for that month was measured at 9.37 g/m². However, in May, the density sharply dropped by 22%, which led to an increase in sediment yield by about 20%. During parts of May and June, the grass density entered a decreasing recovery phase, yielding the highest sediment yield, which increased by 1,781% due to the cumulative effects of pests and armyworm invasion, which reduced plant density by 50%.

The high grass density decreased by 50% in May and June, allowing the surviving plants to expand and multiply due to lower competition for sunlight and nutrients. This reduction created space that enabled the plants to increase their leaf coverage, which helped minimize raindrop impact, reduced rain splash and sheet erosion, and lowered runoff and sediment yield on the slope.

In 1991, a total of 3,095.62 grams of sediment yield was collected, indicating higher sediment yield rates at the start of the rainy season, with a decline toward the end. The mean erosion rate was calculated at 15.49 grams/m²/year, equivalent to 154.9 grams per hectare. The results of the partial correlation analysis indicated that the major factors contributing to sediment yield included maximum rainfall intensity ($r^2 = 0.82$), the rank of the rainfall event in the season ($r^2 = 0.463$), grass density ($r^2 = 0.450$), soil temperature ($r^2 = 0.226$), runoff/rainfall ratio ($r^2 = 0.197$), total rainfall ($r^2 = 0.192$), and maximum temperature ($r^2 = 0.152$). These variables accounted for 93% of the sediment yield. The sediment texture consisted of 75% to 85% sand, with very fine sand components comprising 38% to 55%, while silt and clay accounted for less than 15%.

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