Estimation of geomorphic threshold in permanent gullies of lateritic terrain in Birbhum, West Bengal, India

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The present geomorphic study focusses on predicting threshold conditions and vulnerable locations where gully heads might develop in the lateritic terrain, located at the eastern plateau fringe of Rajmahal Basalt Traps, Birbhum, West Bengal, India. The modern concept of geomorphic threshold is applied here on gully erosion hazard to identify the critical slope of gully head (S) and upstream drainage area (A) with a core relationship of $S = aA^{b}$. Based on 118 gully heads we have statistically derived significant relationships between slope and drainage area ($r = 0.955$); overland flow ($Q$) and slope length ($L$; $r = 0.694$); relative shear stress ($	au$) and slope ($r = 0.915$); as well as overland flow detachment rate ($f$) and eroding force of overland flow ($F$; $r = 0.980$). The established $S$–$A$ critical relationship, as geomorphic threshold, is expressed as $S = 17.4194A^{0.2517}$, above which gully initiation occurred on the laterites. This equation can be used as a predictive model to locate the vulnerable un-trenched slopes (i.e. potential gully erosion locations) in other lateritic areas of West Bengal. The constant $b$ value (0.2517) and Montgomery-Dietrich envelope suggest a relative dominance of overland flow (52.51% of sample gully heads) in the erosion processes. The result of erosion model predicts an annual soil loss of 2.33–19.9 kg m$^{-2}$ year$^{-1}$ due to overland flow above the gully heads.

Keywords: Geomorphic threshold, gully, laterite, overland flow.

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Soil erosion is an issue where the adage ‘think globally, act locally’, is clearly applicable. Land degradation due to soil erosion is a momentous hazard in India1 and gully erosion (i.e. extreme form of accelerated soil erosion) already engulfs about 3.975 million ha of land in India2–4. It is estimated that soil erosion takes place at the rate of 16.35 tonne ha$^{-1}$ year$^{-1}$ in India, and about 29% of total eroded soil is lost permanently to sea and 10% is deposited in reservoirs5–8. Loss of soil is accelerated due to gully erosion which represents a major sediment producing process, generating between 10% and 95% of total sediment mass at catchment scale, whereas gully channels often occupy less than 5% of total catchment area9–11. A gully is defined as an

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ephemeral or permanent channel with minimum cross-section of 930 cm² (ref. 12). It is mentioned that a gully is relatively deep (>0.6 m), recently formed eroding channel (with ephemeral flow) on valley sides and on valley floors where no well-defined channel previously existed and it has steep sides, low width–depth ratio and stepped profile (presence of knick points), characteristically with a headcut (with plunge pool) at the upslope end, dominated by the processes of surface flow, piping and mass movement.13–17

Gully initiation by surface hydro-geomorphic processes has been recognized as a threshold phenomenon related to the size of the contribution drainage area and its slope.18–20 A geomorphic threshold is one that is inherent in the manner, within the geomorphic system, by changes in the morphology of the landform itself through time. It is a threshold of landform instability that is exceeded either by intrinsic change (e.g. slope steepness and soil cohesion) of the landform or by a progressive change of an external variable (e.g. extreme rainfall event, land-use conversion, climate change and neo-tectonic uplift).21–29 The significance of the geomorphic threshold concept for this study is that it makes us aware that abrupt erosional and depositional changes in the badlands can be inherent in the normal development of a landscape and that change in an external variable is not always required for a geomorphic threshold to be exceeded and for a significant geomorphic event to ensue. From the experimental studies in parts of Africa, Asia, Europe and North America, it is observed that maximum contributing drainage area above gully head is considered as the most influential positive factor to develop gully.25–29

The prime objective of this study is to investigate geomorphic threshold of permanent gullies and to estimate the responsible factors of erosion on the least explored lateritic terrain of West Bengal. It is hypothesized that the gullies over laterites develop when the geomorphic thresholds (extrinsic or intrinsic) are transgressed due to either a decrease in the resistance of materials (i.e. erodibility) or an increase in the erosivity of runoff or both.

The study area (about 176 sq. km) is situated between the adjoining region of western Rampurhat 1 block of Birbhum district, West Bengal and eastern Shikaripara block of Dumka district, Jharkhand (encompassed by 24°08’–24°14’N and 87°38’–87°44’E) (Figure 1). This geomorphic unit is recognized as an elevated interfluve of laterites (Rarh Bengal)23,31 between Brahmani (north) and Dwarka (south) rivers and is the eastern plateau fringe of Rajmahal Basalt Traps (~118 Ma)20. Elevation of this unit ranges from 20 to 80 m, having an average slope of 2.17° towards south-east. The in situ primary laterites (Pliocene to Early Pleistocene) and ex situ secondary laterites (Early to Late Pleistocene) are simultaneously found in this eastern fringe of Rajmahal Basalt Traps (Early Cretaceous)30 (Figure 2). The climate of this region is sub-humid and subtropical monsoon type, receiving mean annual rainfall of 1437 mm. The monsoon and cyclonic rainfall intensity of 21.51–25.51 mm h⁻¹ is the most powerful climate factor to develop these lateritic badlands. The thin ferruginous soil is loamy-skeletal and hypothermic (weak fine crumb and granular structure, 2–5 mm size of manganese nodules, >2 mm size of ferruginous nodules with goethite cortex, 30–80% coarse fragments) in nature, developing in the barren lateritic wastelands and forest areas with sparse bushy vegetation.

Base map of the study area is prepared from SOI (Survey of India) topographical sheet of 1:25,000 scale (72 P/12/NE and 72 P/16/NW, 1979–1980) using Erdas 9.1 and ArcGIS 9.3 software. The regional elevation information is collected from USGS (United States Geological Survey, earth explorer) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) data of 2011 having 30 m of spatial resolution. All the maps are geo-referenced in UTM (universal transverse mercator) projection with WGS-84 (world geodetic survey, 1984) datum. The locations of laterite exposures and gullies are mapped on the basis of field expeditions, toposheets, survey points of Gramin GPS (global positioning system, 2008) and visual interpretation of IRS LISS IV and IRS P6/7 LISS III (72 L/20/NE, 1991) and IRS P6/7 LISS III (72 L/20/NE, 1995) satellite images. The locations of permanent gullies are established in the field and marked on toposheets and Gramin GPS. Figure 1. a, Location of study area in India. b, Spatial distribution of elevation, location of permanent gullies, streams and reservoirs, and exposures of laterites in the study area.

Figure 1. a, Location of study area in India. b, Spatial distribution of elevation, location of permanent gullies, streams and reservoirs, and exposures of laterites in the study area.
Figure 2.  a, Collection of sediment at the base of gully head at Maluti, Jharkhand.  b, Barren lateritic upstream landscape of gully-head catchment at Bhatina, West Bengal.  c, downstream dissection of latites by deeply incised gully and expansion gully heads at Bhatina, West Bengal.

Figure 3.  Spatial extent of two gullies and sample locations of gully heads in the areas of (a) Maluti (24°09'45"N, 87°41'14"E) and (b) Bhatina (24°10'25"N, 87°42'33"E) (Google Earth imagery date: 13/01/2014).

Relative shear stress \( (\tau) \) is defined as
\[
\tau = A d / a.
\]

We have applied Montgomery–Dietrich (M–D) envelope \(^{20, 26}\) as a tool to predict and compare the exact active processes to initiate gully heads. To denote the critical tractive or eroding force required for overland flow to initiate a channel, Du Boy’s equation is applied here\(^{18, 35}\).

\[
F = wd \sin \theta,
\]

where \( F \) is the tractive or eroding force exerted on the slope by overland flow (gm cm\(^{-2}\)), \( w \) the specific weight of water, gm cm\(^{-3}\) (assumed constant), \( d \) the depth of flow in cm and \( \theta \) is the gradient of ground slope.

We have applied the revised Morgan Morgan Finney model (RMMF) to estimate annual overland flow and its annual detachment rate and transport capacity\(^{36–38}\). The critical values of parameter are collected from table values of RMMF model\(^{37}\). The details of equations used are summarized as follows.

\[
R_f = R(1 - PI) / \cos S,
\]

\[
R_e = 1000 MS BD EHD (E/E_0)^{0.6},
\]
To judge and validate the calculated $S$-$A$ relation (i.e. statistically fit or not), we have performed two statistical techniques, viz. (1) Student’s $t$ test of correlation coefficient ($r$), and (2) significance test of standard error of $b$ ($S_E$)\(^{39}\).

Student’s $t = r\sqrt{(N - 2)}/\sqrt{(1 - r^2)}, \tag{11}$

where $r$ is Pearson product moment correlation coefficient, $N$ the total samples and $N - 2$ the degree of freedom.

$$S_E = b\sqrt{(1 - r^2)}/N, \tag{12}$$

where the confidence limit of calculated $S_E$ of $b$ is ($b \pm 1.96S_E$).

The performance of the model is validated by the value of efficiency coefficient (EC)\(^{40}\) and is applied successfully in the soil erosion research\(^{41,42}\).

$$EC = 1 - \sum(Q_{obs} - Q_{pred})^2/(Q_{obs} - Q_{obs}')^2. \tag{13}$$

In the above equation $Q_{obs}$ is the measured value, $Q_{pred}$ the calculated value and $Q_{obs}'$ is the mean of measured value.

The upstream slopes above gully heads (Table 1) are negatively correlated ($r = -0.55$) with upstream drainage areas which are used as surrogate for the volume of run-off yield in the study area. A significant line is fitted through the lower-most scatter points for study sites which are incised to form gully heads. This empirical trend line ($S = 17.419A^{-0.2517}$, with $R^2$ of 0.52) provides an approximation to $S$-$A$ threshold relationship for gully incision (Figure 4). Any site (un-trenched or trenched by gullies) lying above this critical line is more prone to gully erosion on this terrain of laterites. It is derived that the mean critical threshold slope for the initiation of gullies is 2.34\(^\circ\). The high value of $a$ (i.e. 17.419) signifies the initiation of gullies by high volume of overland flow and small landslides in study sites. The negative value of $b$ (i.e. $-0.2517$) and in general, $b > 0.2$ is considered, to identify the dominancy of overland flow erosion over sub-surface processes in the study area\(^{25-28}\).

Development of numerous gullies on laterites reflects the geomorphic instability in the landform itself, when the critical hydro-geomorphic situation crosses the

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**Table 1.** Summary of parametric values of selected variables of gully erosion (i.e. major determinants of geomorphic thresholds) in study area

<table>
<thead>
<tr>
<th>Slope length (L)</th>
<th>Slope gradient (S)</th>
<th>Drainage area (A)</th>
<th>Overland flow eroding force (F)</th>
<th>Upstream overland flow range (Q)</th>
<th>Detachment of lateritic surface by overland flow (H)</th>
<th>Transport capacity by overland flow (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range (m)</td>
<td>Mean (°)</td>
<td>Range (m(^2))</td>
<td>Low (Nm(^{-2}))</td>
<td>High (mm)</td>
<td>Low (kg m(^{-2}) year(^{-1}))</td>
<td>High (kg m(^{-2}) year(^{-1}))</td>
</tr>
<tr>
<td>24.63 to 200.3 m</td>
<td>71.72 m</td>
<td>457.08 m(^2)</td>
<td>0.58 to</td>
<td>560.58 to</td>
<td>2.33 to</td>
<td>8.8 to</td>
</tr>
</tbody>
</table>

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**Figure 4.** Establishing critical slope–area threshold relation ($S = 17.419A^{-0.2517}$) for the gullies of lateritic terrain on the basis of intrinsic thresholds $S$ (m\(^2\)) and $A$ (m\(^2\)).

$$R_0 = R/R_{in}, \tag{6}$$

$$Q = R_f \exp (-R_c/R_0) (L/10)^{0.1}, \tag{7}$$

where $R_f$ is effective rainfall, $R$ the mean annual rainfall, $R_0$ ratio of mean rainfall to rainy days, $P_I$ the permanent interception by vegetation cover on slope, $S$ the slope, $R_c$ the soil moisture storage capacity, $MS$ the soil moisture content at field capacity, $BD$ the bulk density of top soils, $EHD$ the effective hydrological depth, $Q$ the ratio of actual to potential evapotranspiration and $L$ is the slope length, $E_o/E_0$ the ratio of actual to potential evapotranspiration, $R_n$ is the number of rainy days in a year (Table 3).

In RMMF net flow erosion is derived from the minimum value between annual rate of soil particle detachment by overland flow (H) and annual transporting capacity of overland flow (G) (if $H < G$ then net annual erosion is $H$ and vice versa).

$$H = ZQ^{1.5}\sin S(1 - GC)10^{-3}, \tag{8}$$

$$Z = 1/COH, \tag{9}$$

$$G = CQ\sin S 10^{-3}, \tag{10}$$

where $Z$ is soil erodibility constant, GC the ground cover, COH the soil cohesion and $C$ the crop cover factor.
threshold limit, i.e. $S^b > T$ (T is the threshold value, i.e. 17.42 for this study site). It is estimated that critical drainage area for the slope of 2.34° is about 2908 sq. m to initiate gully. Here we have compared our result of $S$–$A$ threshold relation with results of various studies conducted in different environments (Figure 5). It is found that our $S$–$A$ critical line of threshold is placed below other lines, signifying a minimum geomorphic threshold to gully incision in this tropical sub-humid monsoon climate and other geographical conditions.

We have checked and validated the calculated $S$–$A$ relation using eqs (11) and (12). The null hypothesis ($H_0$) is that there is no significant correlation between the two variables. For 116 degree of freedom ($N-2$) the tabulated $t$ value is 3.29 in 0.001 significance level (two-tailed), but our calculated $t$ value (7.09) is much greater than tabulated $t$. This result reflects the rejection of $H_0$ and acceptance of alternative hypothesis which favours a significant and core inter-relation between $S$ and $A$ in the geomorphic system of gully erosion. The calculated confidence limit of $S_b$ of $b$ (0.271–0.232) does not enclose zero (i.e. zero gradient). It shows that the power regression ($S = 17.419 A^{-0.2517}$) is certainly significant at 5% level. Therefore, this $S$–$A$ threshold equation of channel initiation is valid statistically and can be applied in other erosion prone lateritic areas of Rarh Bengal.

Through inserting the values of drainage area ($Q_{obs}$) in the equation of $S = 17.419 A^{-0.2517}$, the predicted slope values ($Q_{pred}$) of each gully are calculated. The mean slope of sample gullies ($Q_{obs}$) is 4.6°. EC (eq. (13)) is estimated in case of slope prediction and its value is greater than 0.63 (greater than 0.5) which is generally interpreted that this model performs satisfactorily. Therefore, this model is validated in the study area. For the experiment, $S$–$A$ model is applied in 82 gully heads of Masra–Jutla area (24°06’37” to 24°08’15”N, 87°39’38” to 87°41’14”E) and Bolpur–Santiniketan area (23°40’47” to 23°41’46”N, 87°39’47” to 87°40’36”E) of Birbhum district. In this badlands of laterites, we derived two distinct threshold equations of $S = 14.368 A^{-0.236}$ ($R^2$ of 0.44) for Masra–Jutla area and $S = 112.48 A^{-0.472}$ ($R^2$ of 0.85) for Bolpur–Santiniketan area respectively. In both cases, the dominancy of overland flow erosion is identified from significant $b$ value (i.e. >0.2). In these two regions we have found that the value of EC varies from 0.54 to 0.77, depicting a good performance of $S$–$A$ model.

From $b$ value (i.e. 0.2717) we have found the relative dominance of Hortonian overland flow in the gully erosion. A theoretical division of the landscape into process regimes in terms of log $S$ (X axis) and log $A$ (Y axis) signifies different geomorphic thresholds to gully erosion and the resultant threshold line is popularized as Montgomery–Dietrich (M–D) envelope of $A$–$S$ threshold. From M–D envelope, we have classified gully heads on the basis of erosion dominancy (Figure 6). In this study area, 52.51% and 27.96% of gullies are affected by overland flow erosion ($S = 1.23^\circ$–5.24° and $A = 2129.05–10513.90$ sq. m) and landslide erosion ($S = 5.20^\circ–9.51^\circ$ and $A = 457.08–5702.5$ sq. m) respectively (Table 2).

By adding appropriate values of $S$ and $A$ for each sample site in the slope-area threshold relation ($\tau = S^b / A$) for each experimental sites, with increasing value of $S$, the magnitude of $\tau$ steadily increases with a linear relation of $\tau = 0.32675 + 0.4352 (R^2$ of 0.838). This signifies that to develop gully head, the increasing slope provides more kinetic energy to flow which generates more shear stress on the lateritic surface (Figure 7).

Using eqs (4)–(7), we found that 118 catchments of gully heads yield an annual overland flow of 560.68–693.45 mm on laterites terrain which have the least growth of tropical deciduous vegetation cover and ample portion of bare crust soils (Table 3). The calculated mean overland flow of 619.51 mm is found to be sufficient to instigate rill and gully on critical slope angle and length. Du Boy’s eq. (3) shows that the exerted eroding force of overland flow (measured mean depth of overland flow is 0.0025 m) ranges from 0.58 to 5.32 N m$^{-2}$ above the gully heads. Here the slope–length ratio ($S$–$L$) is found to be an important geomorphic variable of fluvial erosion to denote relative dominancy of high slope with low length.
Figure 6. The diagram showing $S$ (in $^\circ$)–$A$ (in m$^2$) scatter plot in $M$–$D$ envelope (i.e. red curve) to depict erosion dominant gullies in the study area.

Table 2. Distribution of gully heads in respect of dominant erosion process using M–D envelope

<table>
<thead>
<tr>
<th>Dominant gully erosion process</th>
<th>Percentage of gully heads</th>
<th>Slope range ($^\circ$)</th>
<th>Area range (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overland flow erosion</td>
<td>52.51</td>
<td>1.2–5.2</td>
<td>2129.1 to 10513.9</td>
</tr>
<tr>
<td>Seepage erosion</td>
<td>15.25</td>
<td>2.2–4.6</td>
<td>685.5 to 3843.7</td>
</tr>
<tr>
<td>Landslide erosion</td>
<td>27.96</td>
<td>5.2–9.5</td>
<td>457.1 to 5702.5</td>
</tr>
<tr>
<td>Diffusive erosion</td>
<td>4.28</td>
<td>4.4–5.3</td>
<td>483.2 to 879.9</td>
</tr>
</tbody>
</table>

Table 3. Important parameters with typical values used in RMMF model and other equations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter code</th>
<th>Typical value and range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean annual rainfall</td>
<td>R</td>
<td>1437 mm</td>
</tr>
<tr>
<td>Number of average rainy days</td>
<td>Rn</td>
<td>191 days</td>
</tr>
<tr>
<td>Soil moisture storage capacity</td>
<td>Rc</td>
<td>7.736</td>
</tr>
<tr>
<td>Permanent interception by vegetation cover on slope</td>
<td>PI</td>
<td>0 to 1</td>
</tr>
<tr>
<td>Crop cover management factor</td>
<td>C</td>
<td>1</td>
</tr>
<tr>
<td>Soil moisture content at field capacity (wt%)</td>
<td>MS</td>
<td>0.4</td>
</tr>
<tr>
<td>Bulk density of top lateritic soil (Mg m$^{-3}$)</td>
<td>BD</td>
<td>1.73</td>
</tr>
<tr>
<td>Effective hydrological depth of soil (m)</td>
<td>EHD</td>
<td>0.05</td>
</tr>
<tr>
<td>Ratio of actual to potential evapotranspiration</td>
<td>$E/E_o$</td>
<td>0.05</td>
</tr>
<tr>
<td>Cohesion of surface soil</td>
<td>COH</td>
<td>5</td>
</tr>
<tr>
<td>Mean flow depth of overland flow (m)</td>
<td>d</td>
<td>0.0025</td>
</tr>
<tr>
<td>Specific weight of water (kN m$^{-3}$)</td>
<td>w</td>
<td>9.807</td>
</tr>
</tbody>
</table>

Table 4. Validated and significant equations of gully erosion system in the study area

<table>
<thead>
<tr>
<th>Relation between variables</th>
<th>a</th>
<th>b</th>
<th>Established equation</th>
<th>r</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$–$A$ (threshold relation)</td>
<td>17.419</td>
<td>$-0.2517$</td>
<td>$S = 17.419.4^{0.2517}$</td>
<td>$-0.550$</td>
<td>0.518</td>
</tr>
<tr>
<td>$r$–$S$</td>
<td>0.4352</td>
<td>0.3267</td>
<td>$r = 0.3267S + 0.4352$</td>
<td>0.915</td>
<td>0.838</td>
</tr>
<tr>
<td>$F$–$L$</td>
<td>4.9511</td>
<td>$-0.7219$</td>
<td>$F = -0.41\log L + 2.464$</td>
<td>$-0.320$</td>
<td>0.487</td>
</tr>
<tr>
<td>$Q$–$SL$</td>
<td>539.63</td>
<td>$-0.0498$</td>
<td>$Q = 539.63SL^{0.0498}$</td>
<td>0.694</td>
<td>0.633</td>
</tr>
<tr>
<td>$H$–$F$</td>
<td>0.6242</td>
<td>3.8266</td>
<td>$H = 3.8266F^{0.6242}$</td>
<td>0.980</td>
<td>0.975</td>
</tr>
</tbody>
</table>

(i.e. high $S$–$L$ value) in the gully erosion. There is significant negative correlation of $-0.694$ (significant relation, tested by Student’s $t$) between $S$–$L$ and annual overland flow. The deep gully heads with depth of 2.11–3.72 m have high $S$–$L$ value of 0.21–0.45, which means that these deep gullies of laterites are formed due to high angle of slope with relatively low slope length and an average of 560 mm overland flow erosion. Basically, high
$S-L$ with large catchment is the most vulnerable site of gully erosion. Here, overland flow is empirically related with $S-L$, developing a trend line of $Q = 539.63 \, S - L^{0.6498}$ ($R^2$ of 0.6537) (Figure 7). Slope length is found to be related with eroding force of overland flow ($F$), forming a critical trend line of $F = -0.7219 \, \log S + 4.9511$ (Figure 8).

Interestingly, when 28 un-trenched slope facets are plotted on the scatter diagram, the slopes are found to be of critical erosion potentiality, because these points are located high above the trend line. Thus, these slopes on laterites needed special attention to avoid initial rill and gully formation. These vulnerable slopes vary in length from 72.2 to 221.6 m and in angle from 5.1° to 13.57° (Figure 9). The only safety factor of these sites is that the lateritic terrain is covered widely by bushes, grasses, few tropical deciduous trees (mainly *Sal*) and *Acacia* plantation.

Detachment by rain splash and rill erosion above the gully heads are the major sources of sediment for gully catchment and transporting sediment downslope by runoff which is estimated by RMMF model. The analysis of RMMF model reveals that $G$ is very high on this terrain, ranging from 8.8 to 72.3 kg m$^{-2}$ year$^{-1}$, but the present $H$ ranges from only 2.33 to 19.9 kg m$^{-2}$ year$^{-1}$, i.e. the annual rate of flow erosion in the sample catchments. Here soil erosion exceeded the general permissible limit (11.20 t ha$^{-1}$ year$^{-1}$). It is observed that with increasing $F$, the value of $H$ also steadily increases in the slopes. This positive linear relation is depicted as $H = 3.8266 \, F + 0.6242$ ($R^2$ of 0.9752), having significant correlation coefficient of 0.98 (tested by Student’s $t$, Figure 10). Since the calculated confidence limit of $S_t$ of $b$ (0.645 to 0.602) is not zero, this relation is therefore statistically valid for the lateritic region. Catchments with high values of $F$ annually yield high amount of sediment (>8 kg m$^{-2}$ year$^{-1}$) due to overland flow erosion. We have developed five important empirical equations (i.e. statistically viable) of geomorphic system in the lateritic region to depict the role of thresholds in gully erosion (Table 4).

Determination of significant geomorphic intrinsic and extrinsic thresholds (viz. slope, drainage area and overland flow) is considered practically and statistically validated approach to study gully erosion processes by cause and effect analysis. Under the influence of extrinsic threshold ($Q$), the instability of gully erosion system is finally triggered by the intrinsic threshold ($A$ and $S$) which already exists within the system. In the study sites, gullies are formed by deepening of rills and slumping of side slopes through the shearing effect of concentrated overland flow, increase in pore-water pressure and decrease in soil strength along seepage lines close to the streams. Gully development in the vicinity of concentrated flow is...
facilitated in the lateritic sediments with predominantly coarse-textured upper horizon (i.e. secondary duricrust of loose ferruginous nodules) abruptly overlying a compact, less permeable underlying mottle clay and kaolinite pallid zone (B horizon).


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