What is the best technique to estimate topographic thresholds of gully erosion? Insights from a case study on the permanent gullies of Rarh plain, India

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What is the best technique to estimate topographic thresholds of gully erosion? Insights from a case study on the permanent gullies of Rarh plain, India

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Abstract

The Rarh plain in the Lower Ganga Basin in India, best known for its lateritic landscape and gullied tracts, faces grave problems brought about by all types of soil erosion, of which gully erosion is the most conspicuous. The present study uses data collected through field measurements at 110 gully heads in ten sites of the Rarh plain, to first assess the applicability of various methods used to construct critical topographic threshold lines, and secondly, to characterise topographic threshold conditions of the permanent gullies in the Rarh plain as well as to identify main factors that promoted gully initiation in this region. It is concluded that thresholds defined though orthogonal regression are more apposite than manual fitting of threshold line or employing quantile or nonlinear regression techniques for the same. The critical topographic threshold conditions of gullying in the Rarh plain, expressed by the relationship $S=0.118A^{-0.111}$ between the gully head slope gradient (S) and upslope catchment area (A) can be used to map areas under risk of gully head development in the lateritic terrain, mainly in the deforestation fronts. The value of the exponent (0.111) suggests that subsurface processes and mass failures are the main processes of gully growth at present, and it is suspected that gully erosion in this region is not a recent phenomenon, judging by rather small gully head catchment areas as well as the low AS^2 range of 2–170 m^2. Although statistical evidence in favour of distinct site-specific thresholds is not found, results of this study indicate that gullies under eucalyptus stands have a significantly lower threshold than those in other land cover types. Gully erosion in this region was most likely triggered by massive changes in land cover and land use that commenced from the middle of 20th century and continued into the first few decades of 21st century. However, gullies observed under eucalyptus stands are much younger, judging by their larger upslope catchment areas compared to gullies found in other land covers. Albeit it is observed that the lateritic terrain of Rarh plain offers more resistance to gully incision than croplands or Mediterranean badlands, the threshold of gully head development is much lower than that of the primary laterites of the adjacent Chhotanagpur plateau fringe as well as other comparable soil types from around the world.

Key words: Gully erosion, topographic threshold, orthogonal regression, quantile regression, laterites, land cover change.

1. Introduction

For the tropical and semi-arid regions of our planet, soil erosion constitutes a serious hazard that promotes land degradation, affects soil productivity and therefore cripples agricultural activities (Lal, 2001; Morgan, 2005). India, a country of the monsoonal tropics, is also confronted with this environmental issue. Soil erosion by water is by far the most serious land degradation problem in India and has been estimated to occur at an average rate of 16.4 t ha^{-1} yr^{-1}, causing total soil losses of about 5 billion tonnes per year (Bhattacharyya *et al*., 2015). Although a meagre ca. 1% of Indian land is affected by gullying (Haigh, 1984; Kumar *et al*., 2020), gully erosion could still be a major contributor of regional soil losses, as gullies are known to contribute up to 94% of the total soil losses due to water erosion despite occupying very little area (ca. 1–5%) of any landscape (Poesen *et al.*, 2003; Poesen, 2018). Gullies, defined as erosional geomorphic features sculpted by sporadic yet concentrated and erosive runoff, are classified as ephemeral or permanent (Poesen *et al*., 2003; SSSA, 2008). Occurrence of ephemeral gullies is associated with agricultural landscapes, where they are obliterated periodically by deep tillage, land-levelling operation or natural deposition (Poesen *et al.*, 2003; Poesen, 2018). Permanent gullies, mostly found in rangelands or bare lands, are lasting features having clear-cut cross-sectional forms characterised by identifiable banks and prominent headcuts (Bull and Kirkby, 1997). Topographic attributes, such as slope length, steepness and curvature along with soil erodibility and land cover are most important factors of gully erosion (Valentin *et al*., 2005). Among these, the key role of land cover or land use change in gully initiation and development has been widely discussed. Devegetation by logging and burning, overgrazing, inappropriate ploughing, sudden change in cropping practice and road building all promote gully formation (Wells and Andriamihaja, 1993; Faulkner, 1995; Derose *et al*., 1998; Bork *et al*., 2001; Nyssen *et al.*, 2002; Podwojewski *et* *al*., 2002). Land use change is actually expected to have a greater impact on gully erosion than climate change (Valentin *et al*., 2005).

The concept of geomorphic threshold has been most widely employed for decades to assess gully initiation susceptibility and has garnered much importance in gully erosion research (Patton and Schumm, 1975; Begin and Schumm, 1979; Vandaele *et al.*, 1996; Torri and Poesen, 2014; Torri *et al*., 2018). Simply defined, a geomorphic threshold is the critical condition at which a landform undergoes abrupt changes. Such changes can either be engendered by some external factor (e.g. climate, human activity) that upsets the stability of a landform at an extrinsic threshold (e.g. rainfall, runoff hydraulics, land use and land cover), or due to changes at an intrinsic threshold, which can be the aftermath of a progressive change of the landform itself (e.g. weathering) (Schumm, 1979, 2004). The idea of critical process thresholds exists in various sub-fields of geomorphology (e.g. Horton, 1945; Schumm, 1956; Coates and Vitek, 1980; Phillips, 2006) and in gully erosion studies, the geomorphic threshold concept, popularly known as 'topographic threshold', as expounded by Patton and Schumm (1975) and refined by Begin and Schumm (1979) have been widely accepted and globally applied (Torri and Poesen, 2014). It is an efficient tool to identify susceptible points of gully initiation in a region (Prosser and Abernethy, 1996; Rutherfurd *et al*., 1997; Desmet *et al*., 1999; Nachtergaele *et al*., 2001; Dewitte *et al*., 2015) as well as recognise main factors promoting gully development therein (Vandekerckhove *et al*., 2000; Nyssen *et al*., 2002; Vanwalleghem *et al*., 2003).

An example of coupled criteria analysis, the main essence of this theory is the assumption that in a region of uniform geology, land use and climate, gully erosion is a threshold phenomenon that initiates when, for a given catchment area, a critical slope gradient has been exceeded or vice versa. The topographic threshold of gully initiation is given as an inverse relationship $S = aA^{-b}$, where S is the critical slope gradient for gully head development (m m^{-1}), A is gully head drainage area (ha) and a and b are environment-specific coefficients (Patton and Schumm, 1975; Begin and Schumm, 1979). Despite being a power-type equation, plotting the *S*-*A* points in a double logarithmic plot allows a straight line to be drawn through the lowest points. Such a line is representative of the critical *S*-*A* conditions for incipient gullying as it theoretically distinguishes between gullied and non-gullied parts of a landscape and also implies that no incision should occur in parts of the study area where *S*-*A* points plot below the line (Vandaele *et al*., 1996; Nyssen *et al*., 2002; Vanwalleghem *et al*., 2003). Gully head slope gradient and upslope drainage area were taken as surrogates of runoff energy and runoff volume respectively, because of practical constraints to obtain data on these variables (Patton and Schumm, 1975; Begin and Schumm, 1979; Vandaele *et al.*, 1996). In sum, this theory highlights that the process of gully formation is set in motion whenever runoff volume and energy (or flow shear stress in general) cross a critical threshold (Begin and Schumm, 1979; Vandekerckhove *et al*., 1998; Torri and Poesen, 2014).

The intercept a reflects the resistance of a particular site to gully development and is mainly dependent on land cover characteristics and soil properties, while the slope b is indicative of the dominant gully erosion process in operation (Montgomery and Dietrich, 1994; Torri and Poesen, 2014). Through analysis of about forty *S*–*A* relationships for overland flow induced gully-heads from various parts of the world, Torri and Poesen (2014) suggested that the coefficient b can be considered constant at 0.38 for gullies formed through overland flow. In line with this, Montgomery and Dietrich (1994) had earlier discovered b-values greater and less than 0.2 to be associated with erosion by overland flow and subsurface processes (incl. mass movements) respectively. This indicates that if gully development is significantly influenced by subsurface flow or landsliding, the negative trend of the *S*-*A* relationship is weakened and could even be positive (Montgomery and Dietrich, 1994; Vandekerckhove *et al.*, 2000). Torri and Poesen (2014) found clear influence of land cover on the coefficient *a*, with the lowest values observed for croplands, followed by that of rangelands, pastures and forests. This implies that a higher critical slope or contributing area would be necessary for gully initiation under forest or grasslands than in agricultural fields. Overall, the slope *b* is much less variable than the intercept *a* (Maugnard *et al.*, 2014).

A plethora of approaches have been conceived and applied to construct critical *S*-*A* threshold relationships. Patton and Schumm (1975), in their pioneering study obtained the threshold conditions of gully initiation in Colorado (USA) by manually drawing a line through the lowermost collinear points of an *S*-*A* point cloud and many have since followed suit (e.g. Begin and Schumm, 1979; Vandaele *et al.*, 1996; Desmet *et al.*, 1999; Nyssen *et al.*, 2002; Morgan and Mngomezulu, 2003; Dong *et al.*, 2013; Makanzu Imwangana *et al.*, 2014). Mathematically a straight line can be drawn through any two lowermost points of a scatter plot, which makes this approach evidently somewhat arbitrary and seriously sensitive to outliers, if such values are not detected and removed. Furthermore, multiple threshold lines may be drawn for one point cloud, which is bound to make interpretation or comparison quite difficult (Maugnard *et al.*, 2014). Overall, this approach is rather simplistic and has no real statistical grounding. Alternative techniques to obtain critical threshold lines have ranged from taking the lower limit of the 95% prediction interval of an orthogonal regression line (Vandekerckhove *et al.*, 1998), drawing a line through the lowermost points (ignoring extreme values) having the same slope as an orthogonal regression line (Vanwalleghem *et al.*, 2005), applying nonlinear regression techniques (Gómez Gutiérrez *et al.*, 2009) to using quantile regression for the least possible acceptable quantile value (Maugnard *et al.*, 2014). Both Vandekerckhove *et al.* (1998) and Vanwalleghem *et al.* (2005) suggested methods based on orthogonal regression to construct critical threshold lines. Orthogonal regression, also known as total least squares regression, minimises the deviations perpendicular to the best-fit line, rather than reducing the deviations vertically or horizontally like ordinary linear regression. The obtained best-fit line is the first principal component between the variables (Jackson, 1991; Leng *et al*., 2007). Even though the method itself is a statistical improvement over that of Patton and Schumm (1975), Vanwalleghem *et al.* (2005) either did not suggest or implement any statistical measure to identify and ignore possible outliers, and the threshold defined by Vandekerckhove *et al.* (1998) moves away downward from the point cloud when the sample size is small or correlation between the variables is weak (Maugnard *et al.*, 2014). Implementation of a nonlinear regression technique based on the *Levenberg-Marquardt* algorithm of Moré (1978) by Gómez Gutiérrez *et al.* (2009) has not received much favour in subsequent gully topographic threshold studies, although the latter authors claimed that the said algorithm ensures a high efficiency in determining the *a*, *b* coefficients. The quantile regression-based approach of Maugnard *et al.* (2014) is the latest endeavour to find a standardised method to estimate topographic threshold conditions of emergent gullying. Quantile regression enables estimation of conditional quantiles of a response variable and provides a more holistic view into the relationships between variables (Koenker and Bassett, 1978; Koenker, 1994). For a critical threshold line corresponding to 10% quantile, the probability of gully head development in areas that lie above that line in terms of *S*-*A* conditions is 90%.

With so many options to choose from, selecting the most appropriate approach can be rather difficult. It is thus necessary to assess which, if any, of these methods could act as a global standard choice to obtain topographic threshold equations as well as have some guidelines on how to select the most suitable method to estimate critical *S*-*A* threshold conditions of gullying in a particular region. This study therefore aims, through a case study on the permanent gullies of Rarh plain, India, to (i) conduct a comparative assessment of the *S-A* threshold determination techniques, highlight their merits and demerits and also suggest some guidelines for choosing a suitable thresholding method; (ii) assess if any of the study sites in the Rarh plain are characterised by distinct topographic threshold conditions; and (iii) characterise gully dynamics in the Rarh plain by analysing estimated parameters of the *S-A* threshold vis-à-vis various geomorphic and land cover attributes of the gullied tracts and by comparing with topographic thresholds of gully head development established across the world. Permanent gullies of the Rarh plain in eastern India are considered in this study. Although the central and western Indian ravines (Fig. 1a) are much better known because of their areal expanse and incision depth (Haigh, 1984), extensive gully reclamation measures have been in place for a few decades now in the said regions (Dagar and Singh, 2018), thereby precluding investigations of the natural state of gullies at present. Furthermore, in terms of soil and terrain characteristics, the presence of gullies in the lateritic terrain of the Rarh plain is quite unique. The central and western Indian ravines have formed through prolonged erosion of naturally erodible soils (deep, unconsolidated fluvial sediments rich in swelling clays) in a topography that is conducive to gully development (Singh and Agnihotri, 1987), much unlike the Rarh plain where gullies have formed in a gentler lateritic terrain.

2. Study Area

The study area for this work comprises of ten sites located in the state of West Bengal in India between 22° 50′ – 24° 10′ *N* and 87° 12′ – 87° 42′ *E*, with the distance between the northernmost and southernmost study site being ca. 150 km (Fig. 1).

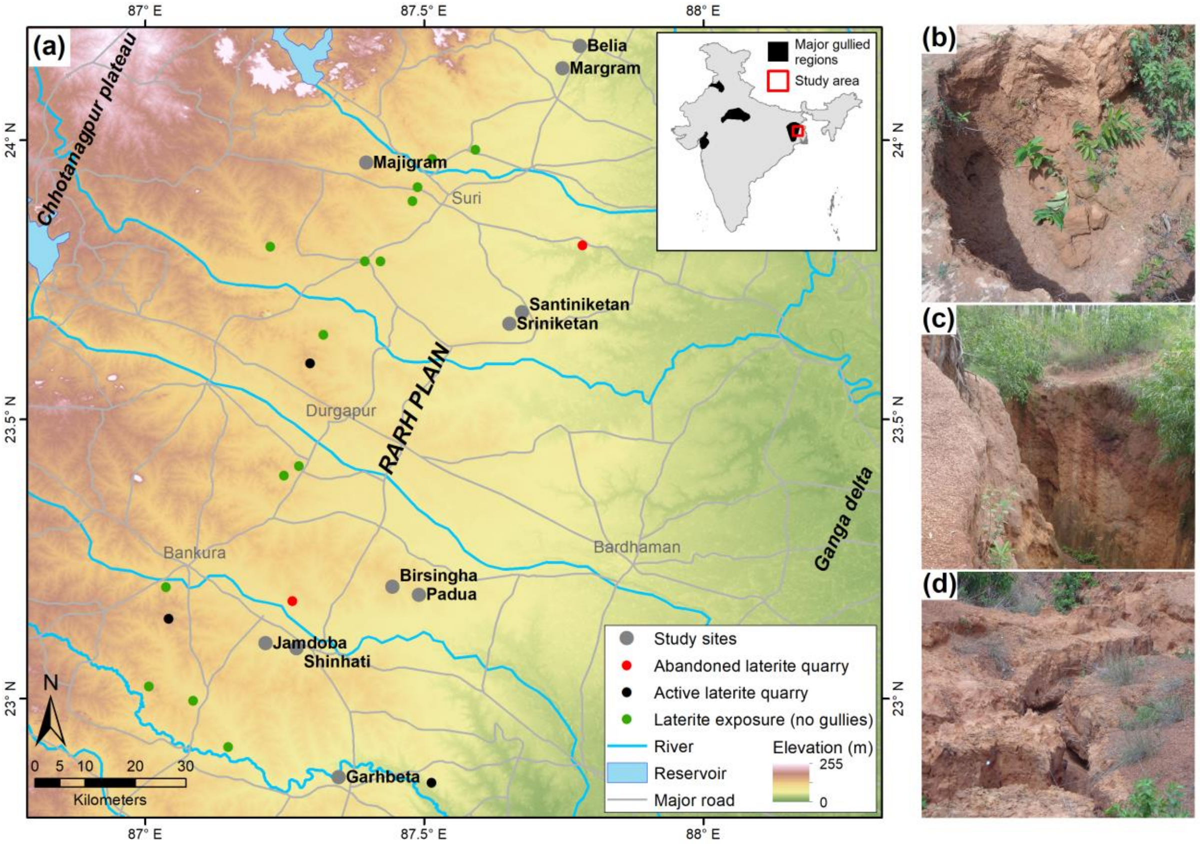

Fig. 1. (a) Location of the study sites in the Rarh plain, India; (b) top view of a surveyed gully head in Margram. Note the toppled soil chunks on the gully floor that are probably products of mass failures; (c) lateral view of a bank gully (ca. 3.5 m deep) in Santiniketan; (d) re-incised gully in Garhbeta (photographed from the gully head apex looking downslope at the gully floor).

The Rarh plain in the Lower Ganga basin in India is famous for the presence of deeply weathered laterites and derived lateritic soils and owes its name to their red colouration (Bagchi and Mukherjee, 1983). Located in the southern part of the state of West Bengal in India, it covers an area of ca. 7700 km^2 with elevation ranging between 50 m and 100 m a.s.l and an average slope of 3°–4° towards east and south-east (Bagchi and Mukherjee, 1983). Most of the 1040 km^2 of degraded land of West Bengal (NCA, 1976) lie in the Rarh plain and approximately 388 km^2 of lateritic terrain has experienced all forms of soil erosion that exceed the regional soil loss tolerance limit of 11.2 t ha^{-1} yr^{-1} (Sarkar *et al.*, 2005).

Geomorphologically, the Rarh region can be considered as an ideal pediplain, situated at a transitional zone between the higher Chhotanagpur plateau (>100 m a.s.l) to the west and the world's largest delta, formed by the rivers Ganga, Brahmaputra and Meghna (<50 m a.s.l) to the east, and dissected by a roughly parallel west to east flowing drainage system. Patches of lateritic terrain (exposures, gullied tracts and subtropical dry deciduous forests) are therefore found interspersed by rivers and floodplains roughly at every 30 km (Fig. 1a). Early Cretaceous basalt traps, Cambrian sandstones, polycyclic granites, granitoids and gneisses of the Archean comprise the lithology of the Chhotanagpur plateau and juxtapose the lateritic zone of Rarh Bengal to the west while Late Quaternary Alluvium is found to its east in the deltaic plains (Ghosh and Guchhait, 2020).

Laterites of West Bengal are the oldest soils found in the Ganga basin (Singh *et al*., 1998) and with an average thickness of 10–20 m, exist at two distinct levels: outcrops of high-level primary laterites (Paleocene to Mid-Pliocene) along parts of the Chhotanagpur plateau fringe and the reworked lower level secondary or detrital laterites (Middle to Late Pleistocene) in the interfluves throughout the Rarh plain (Bagchi and Mukherjee, 1983; Ghosh and Guchhait, 2020). The occurrence of laterites in the Indian subcontinent is related to the northward drift of the Indian plate from Gondwana towards Laurasia, which made it pass through a typical hot and humid equatorial climate conducive for lateritisation (Ghosh and Guchhait, 2020). Nonetheless, even the best developed laterites of India (Ultisols of Kerala) have not reached the stage of Oxisols, which is the equivalent of laterites in USDA Soil Taxonomy (Buol and Eswaran, 2000), although all the requirements conducive for their formation are fulfilled (Chandran *et al*., 2005).

Though all the gullies under investigation have developed in secondary laterites, not all laterite exposures of the Rarh plain are gullied (Fig. 1a), which already hints at the presence of topographic threshold conditions of gully erosion. Laterites found in the Rarh plain as well as in other parts of India are quarried for the extraction of building materials and many such quarries are observed throughout the Rarh plain (Fig. 1a). There is however no mention in available literature, or field evidence, that quarrying had triggered gully formation in the Rarh plain. Degraded woodland, barren laterite exposure with scattered trees or bushes are the main land cover types of the study sites (Fig. 2), all of which lie within the hot, dry-subhumid Chhotanagpur plateau and Garhjat hills agroecological subregion (Sehgal *et al*., 1996).

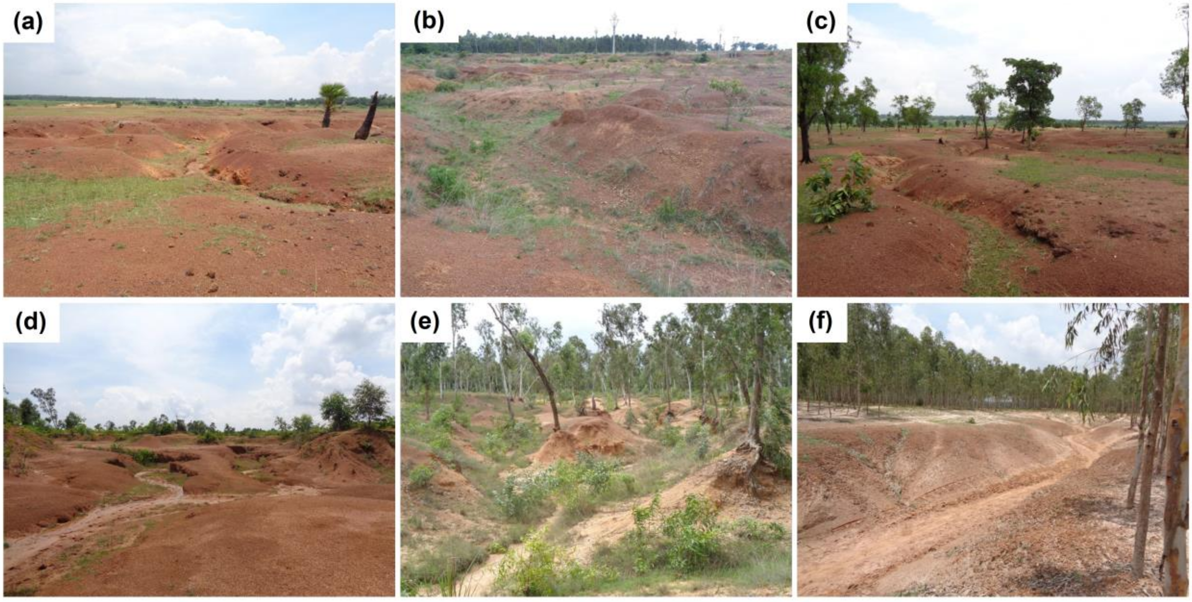

Fig. 2. Land cover types in the study sites: (a) bare (Majigram); (b) bare with patchy grass (Shinhati); (c) bare with sparse eucalyptus (Sriniketan); (d) bare with sparse plants (Birsingha); (e) earleaf acacia (Acacia auriculiformis) woodland (Santiniketan); (f) eucalyptus woodland (Padua).

According to the records of India Meteorological Department (IMD), the climate (*Aw*: Tropical hot and dry) of the Rarh plain is not very spatially variable; the north is slightly warmer (ca. <1° *C*) while the centrally located districts receive about 50–100 mm less rain on an annual basis, compared to the north and south. Maximum temperature during the summer (April–June) crosses 40° *C* and winter (December–February) temperature can be as low as 8°

C (Fig. 3). Annual potential evapotranspiration ranges between 1400 mm (December, January) and 1600 mm (May) (Ghosh and Guchhait, 2020). The total annual rainfall is around 1500 mm, 75–78% of which is received in the months of June to September, mainly from the monsoons, but also due to frequent thunderstorms, tropical cyclones and depressions.

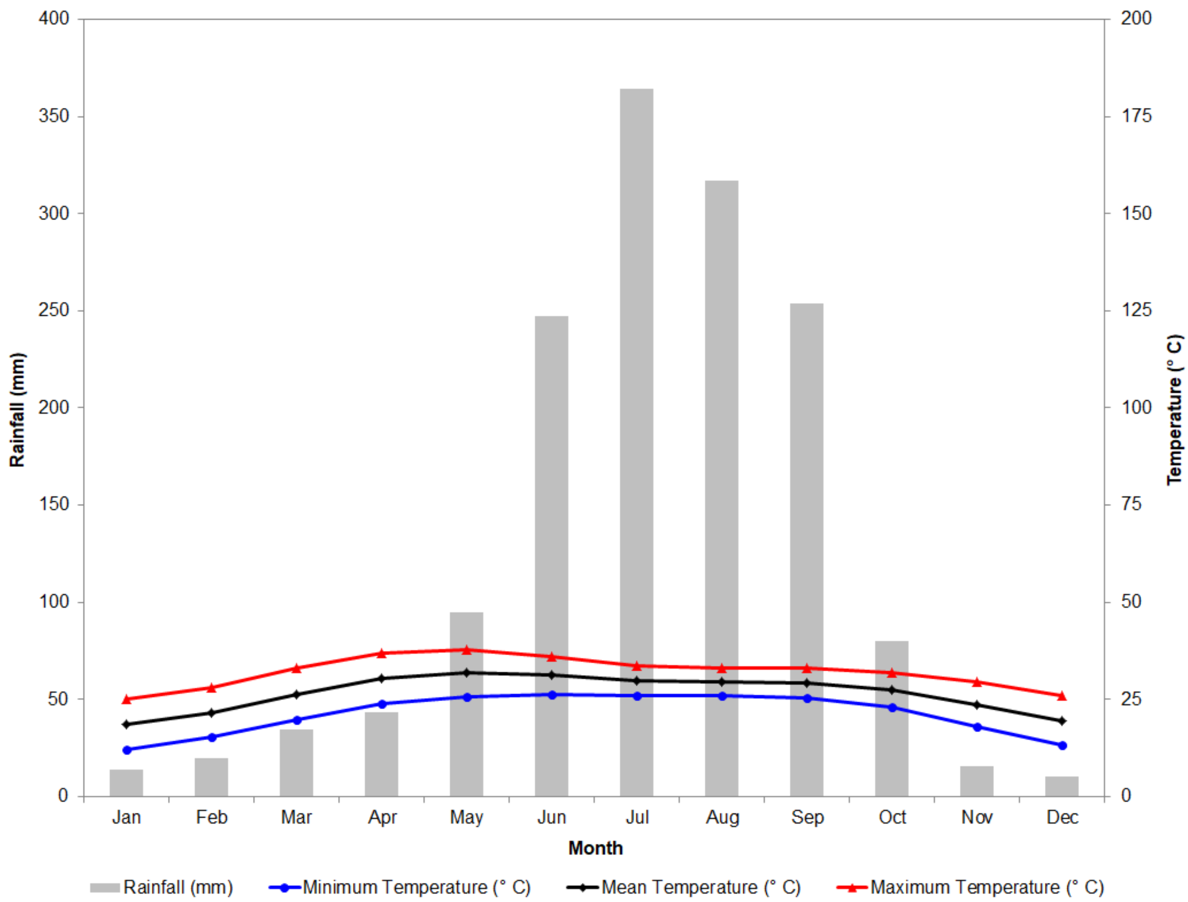

Fig. 3. Mean monthly rainfall and minimum, maximum and mean monthly temperatures in Rarh plain during 1980–2019. Source: Sriniketan and Bankura weather stations, IMD

3. Materials and Methods

Before the field work, a pre-selection of 130 gully heads was made through inspection of high resolution imagery in OpenStreetMap (https://www.openstreetmap.org/), based on the possibility to appropriately trace their upslope catchment areas during the ensuing fieldwork.

Therefore, digitated (Nyssen *et al*., 2002), rilled-abrupt (Oostwoud Wijdenes *et al*., 1999) or artificially created gully heads (e.g. at a drain outlet) were not considered. The chosen gully head points were directly imported as point shapefiles into QGIS 2.18 from OpenStreetMap and then exported as .KMZ files, which provides the possibility to visualise the gully head points in the Google Earth app in an Android smartphone. Important for the field survey, it ensured greater efficiency and saved a lot of time. Field survey included recording gully head slope gradients and delineating gully head catchment areas and was followed by necessary geospatial and statistical analyses.

3.1 Data collection

The study sites were visited and slope gradients and upslope drainage areas of pre-mapped gully heads were recorded in the month of August, 2019. 110 of the selected 130 gully heads could be surveyed and the number of gully heads surveyed per site varied between 5 and 18 (See Table 1).

An Android smartphone was really the main tool for the field work, as it helped immensely in navigating to the study sites, most of which are located far away from major roads, and then navigating to the pre-selected gully heads. The Rocklogger app (Turner-Jones, 2016) was used to record the slope gradients and coordinates at the gully heads as well as water divides while delineating the catchments, which was important for the calculation of the upslope contributing areas. The accuracy of the smartphone GPS is comparable to the accuracy of a standard handheld GPS device which is ca. 3 m and it has been reported that for dip angles (slope gradients) less than 40°, the Rocklogger app records with quite high accuracy, although it is important for the user to remember to calibrate the app as per instructions provided on start-up before commencing the measurements (Steiner, 2017).

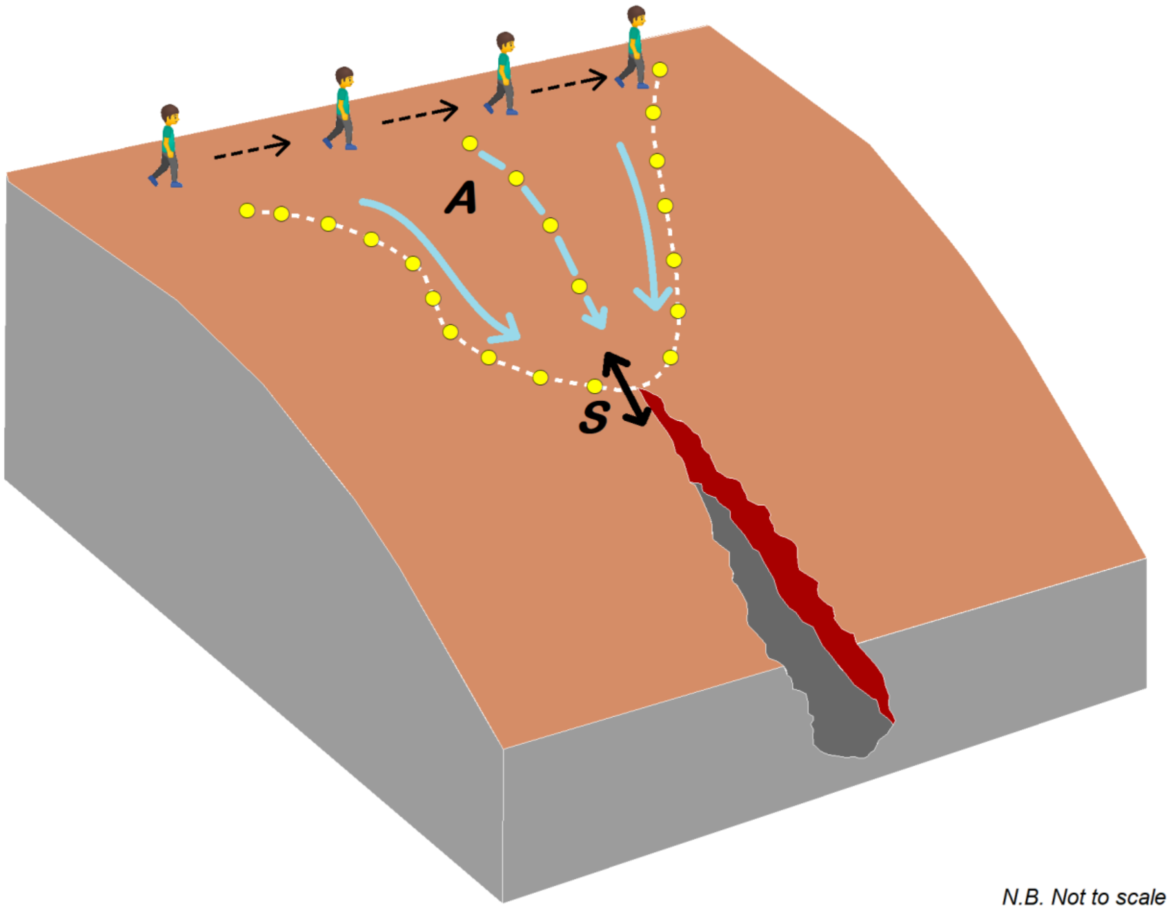

Fig. 4. Indicative illustration of field survey technique. Gully head catchment area (*A*) (white dashed line) delimited using downslope trajectories of plastic balls (yellow dots) dropped by the surveyor from one side of the gully head to another. Blue arrows indicate possible runoff directions towards the gully head. *S* is the local slope gradient of the soil surface, measured 5 m upslope and 5 m downslope of the gully head.

With regards to the manner in which gully head slope is measured, different authors have done it differently and most do not mention how (Nyssen *et al.*, 2002). While Patton and Schumm (1975) measured the steepest slope gradient along the gully, Vandaele *et al.* (1996) did so just above the gully head. A more robust method is to measure slope gradient over a distance of 10 m parallel to the gully, with 5 m being upslope of the gully head and 5 m downslope (Rutherfurd *et al*., 1997; Nyssen *et al.*, 2002), which is how it was done during the field survey (Fig. 4).

Delineation of gully head catchments was way more challenging and time consuming; even more so because it was dry during the fieldwork and drainage area delimitation is easiest after rainfall (Nyssen *et al*., 2002). However, it was done by using the position of microtopographical features (e.g. traces of water flow pathways) and different small landscape elements (e.g. furrows, ditches etc.) as an advantage, wherever possible. For majority of gully head catchments, this was not possible and downslope movement of dropped plastic balls (diameter 10 cm) was tracked to identify possible water flow pathways and demarcate gully head catchment limits (Fig. 4). It was possible to demarcate entire gully head catchments in all the sites except Jamdoba, where only the lower 80–100 m of the catchment boundary on both sides could be identified in the field, due to catchments being comparatively larger and because of the presence of low vegetation. Entire gully head catchments of the aforementioned site were then drawn in ArcMap 10.5 using an ALOS PALSAR DEM, which has the best horizontal resolution (12.5 m) amongst all freely available gridded elevation datasets. Finally, gully head catchment areas were calculated.

3.2 Data analyses

Equations corresponding to mean threshold lines were derived for each of the study sites and the corresponding correlation coefficients (r_c) and significance levels (p) were comparatively assessed. Since the coefficients (a, b) are expected to be constant within the same population of gully heads (Nyssen *et al*., 2002), i.e. within each site, differences in a and b between the study sites were assessed for statistical significance to discern whether or not any of the study sites are characterised by distinct topographic threshold conditions. Furthermore, any possible effect of land cover, planform curvatures or shapes of gully head catchments on the *S-A* threshold was tested. Land cover was assessed during the fieldwork and dominant planform curvature of gully head catchments was determined from an ALOS PALSAR DEM. Shapes of gully head catchments were quantified by calculating the elongation ratio, which is the ratio of the diameter of a circle having the same area as the catchment under consideration to its maximum length (Schumm, 1956). Four catchment shape classes can be identified using the elongation ratio, viz. circular (>0.9), oval (0.8–0.9), less elongated (0.7–0.8) and elongated (<0.7). Parametric statistical tests could not be performed because of non-normality of coefficient *a* and *b* with respect to classes of the grouping variables. Hence, Kruskal-Wallis rank-sum tests were conducted along with pairwise Wilcoxon rank-sum (Bonferroni-adjusted) post-hoc tests (Zar, 2010), wherever applicable, to evaluate the significance of differences.

In order to identify the most suitable method to construct a critical topographic threshold line, procedures as suggested by Patton and Schumm (1975), Vandekerckhove *et al.* (1998) and Vanwalleghem *et al.* (2005) were strictly followed, whereas some optimisations were necessary to implement the techniques suggested by Gómez Gutiérrez *et al.* (2009) and Maugnard *et al.* (2014). Although Gómez Gutiérrez *et al.* (2009) mentioned that they used a nonlinear regression technique, i.e. *Levenberg-Marquardt* algorithm (Moré, 1978), they did not provide any details as to how they chose the starting values or how many iterations were run. Furthermore, there was no information on how they obtained their critical threshold lines, viz. lower 95% prediction interval limit or a line through the lowermost points with the same slope as the best-fit line. Therefore, in this case, a best-fit equation was first obtained by running the same algorithm and then two threshold lines were fitted; one being the lower 95% prediction interval limit and another being simply a translation of the best-fit line through the lowermost points. Starting values of the regression parameters (*a* = 0.09; *b* = 0.06) were chosen intuitively judging by the values of *a*, *b* coefficients as obtained through the other methods. 15 iterations were supposed to be completed, although the solutions converged after 12 runs as the defined limit (10^{-10}) of difference between sum-of-squares of successive iterations was reached. Maugnard *et al.* (2014) estimated the two regression coefficients and their corresponding 90% confidence interval limits across a range of quantiles (0.01–0.50 with 0.01 increments) using the rank score test method coined by Koenker (1994) and then chose the lowest quantile for which the confidence intervals of both regression parameters were estimated with acceptable precision to construct a critical topographic threshold line, but did not clearly state the criteria for deeming the confidence intervals of the regression parameters corresponding to a certain quantile as acceptable. In this study, following a similar line of thought, confidence intervals of both regression parameters for 50 quantiles between 0.01 and 0.5 were estimated and the quantile value with the narrowest confidence interval was chosen, which happened to be the 0.4 or 40% quantile for both *a* and *b* (Fig. 5).

The constructed critical threshold lines were comparatively assessed to highlight probable merits and demerits of each method. Ultimately, the critical threshold line obtained by implementing the most appropriate technique was graphically compared with (parameters of) threshold relationships established for gullied regions across the world. This aided in further assessment of the characteristics of the gullied tracts of the Rarh plain. All statistical analyses were performed in the RStudio IDE of R statistical programming language (R Core Team, 2020).

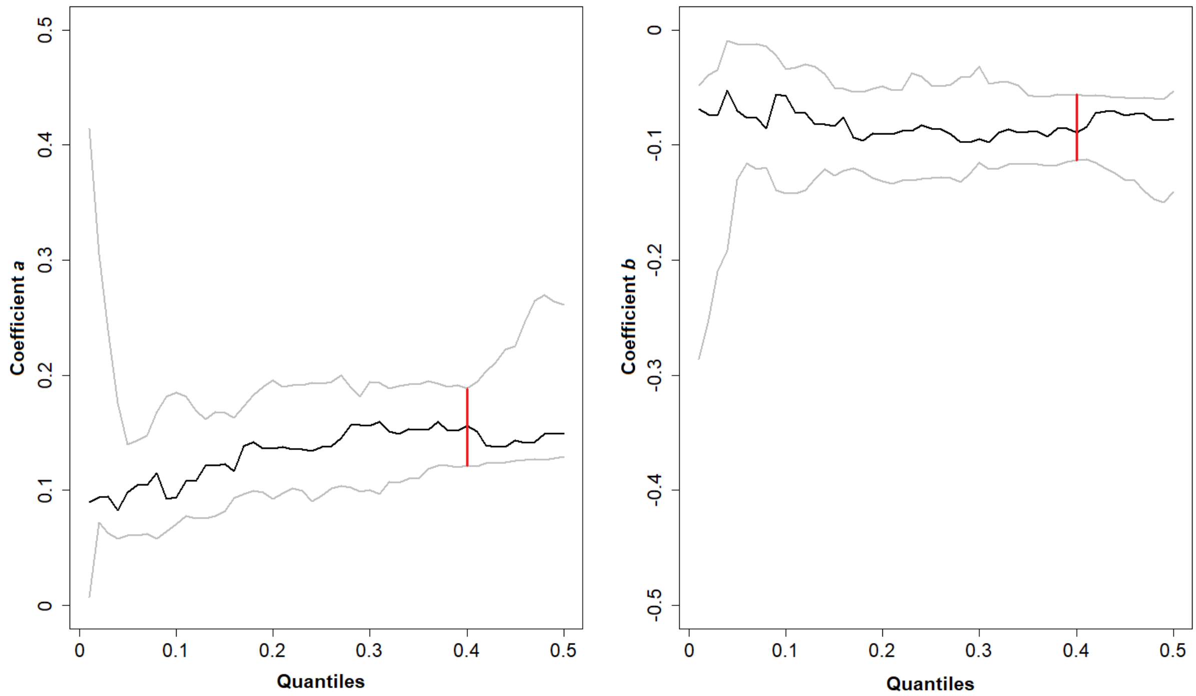

Fig. 5. Estimates of *a* (left) and *b* (right) coefficients of the topographic threshold across quantiles (black lines) and their 90% confidence intervals (grey lines). Red vertical lines indicate the quantile with the narrowest 90% confidence interval, i.e. the 0.4 quantile.

4. Results

4.1 Salient descriptive statistics

Catchment areas of the 110 surveyed gully heads range from 299.5 m^2 (Santiniketan) to 38,092.1 m^2 (Jamdoba), with a mean of 5836.1 m^2 and a standard deviation of 7674.5 m^2. Measured gully head slopes range from 0.045 m m^{-1} (Jamdoba) to 0.169 m m^{-1} (Garhbeta), with a mean of 0.088 m m^{-1} and a standard deviation of 0.027 m m^{-1}. On average, the largest gully head catchment areas are found in Jamdoba (mean: 21,265.4 m^2) and steepest gully head slopes in Garhbeta (mean: 0.13 m m^{-1}). However, Margram and Shinhati are characterised by the largest ranges in catchment area (SD: 12,966.7 m^2) and slope (SD: 0.029 m m^{-1}) respectively. Overall, there is larger variation in upslope catchment areas (CV: 131.5%) than in gully head slopes (CV: 30.7%).

With regards to different land cover types, gully head catchments under eucalyptus woodland are characterised by the largest areas on average (12,837.5 m^2) by far and the largest standard deviation (10,394.6 m^2) as well. Upslope drainage areas having patchy occurrences of grass are most common (n = 37). These have the largest *S*-values (mean: 0.111 m m^{-1}) as well as the highest standard deviation (0.029 m m^{-1}) thereof. However, if all gully head catchments under eucalyptus are considered, their average area (10,942.6 m^2) is more than three times than that of catchments without eucalyptus (2918.0 m^2). On the contrary, average value of *S* in catchments with eucalyptus stands (0.069 m m^{-1}) is less than those without (0.098 m m^{-1}).

4.2 Gully topographic threshold characteristics in the Rarh plain

The values of *S* and *A* were plotted on double logarithmic graphs for the study sites, land cover types, planform curvature classes and shape classes of gully head catchment areas (Fig. 7) and equations of mean threshold lines were obtained for each of the sites through orthogonal regression analyses (Table 1). The study site of Padua was the largest in terms of area and gullies were surveyed from lower and higher landscape positions (Fig. 6). Consequently, it was observed that the surveyed gully heads concentrated in two distinct scatters in the *S*-*A* plot. So much so that a mean threshold line would simply go through between the two scatters where no gullies were present. Therefore the data for Padua was subdivided into $Padua_1$ and $Padua_2$ and separate mean threshold lines were fitted.

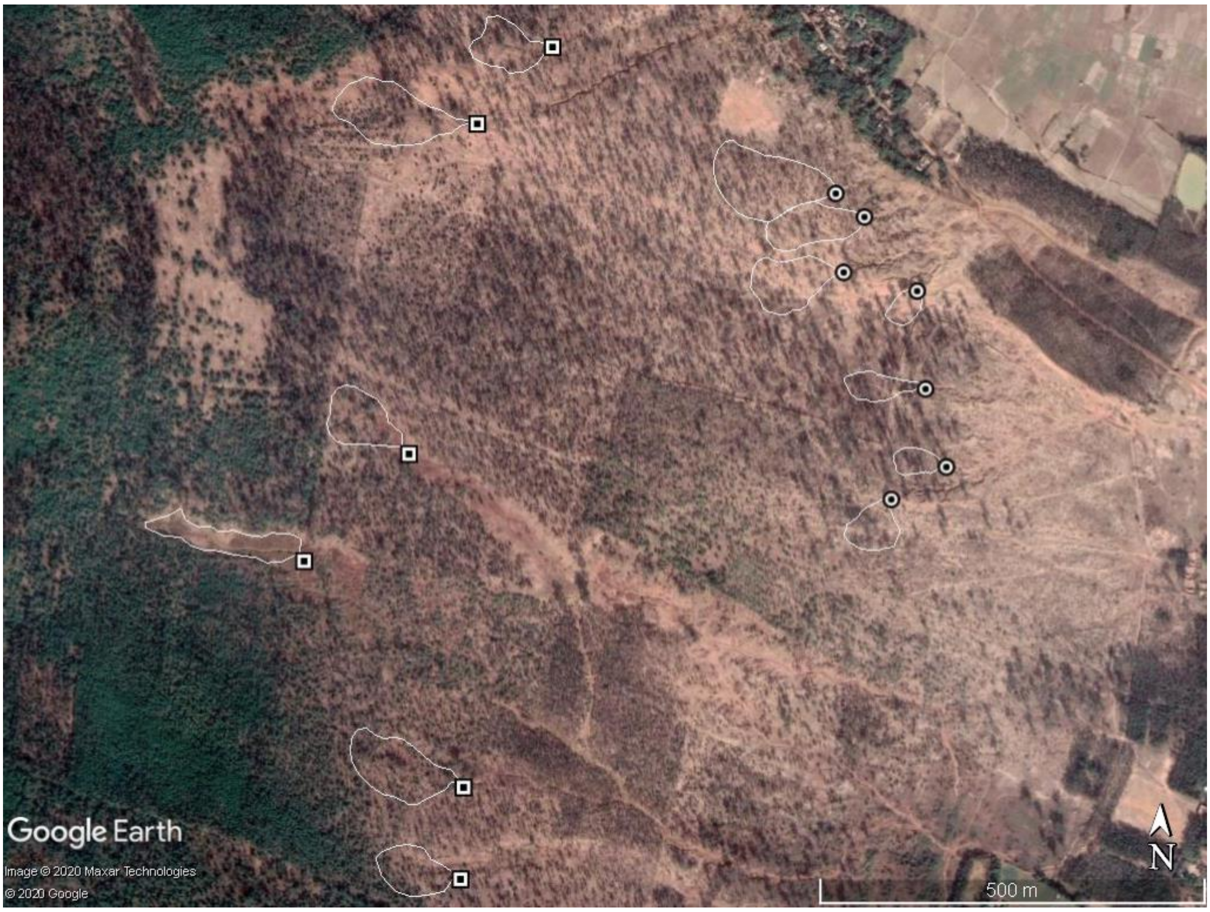

Fig. 6. Surveyed gully heads and their upslope catchments at Padua. Square points are classed as $Padua_1$ and circular points as $Padua_2$

Table 1. No. of observations (*n*), coefficients *a* and *b*, correlation coefficient (r_c) and significance level (*p*) of *S*-*A* relationship of gullies in each study site

Site	*n*	*a*	*b*	r_c	*p*
Belia	10	0.1	-0.032	-0.426	0.551
Margram	5	0.093	-0.029	-0.933	0.001*
Majigram	17	0.045	0.069	0.375	0.124
Santiniketan	6	0.157	-0.054	-0.819	0.008*
Sriniketan	7	0.109	-0.036	-0.300	0.552
$Padua_1$	6	0.186	-0.088	-0.895	0.002*

Padua$_2$	7	0.057	-0.001	0.013	0.983
Birsingha	7	0.05	0.033	0.012	0.782
Shinhati	12	0.123	-0.041	0.095	0.778
Jamdoba	15	0.088	-0.035	-0.205	0.540
Garhbeta	18	0.084	0.059	0.212	0.181

Except in Margram, Santiniketan and Padua$_1$, the site-wise relationship between *S* and *A* are rather weak and insignificant at the 5% or 10% level. Site-specific values of the intercept *a* are not too different and the exponent *b* has remarkably similar values as well, with few of them (Majigram, Birsingha and Garhbeta) even being positive. Upon testing for differences in values of *a* and *b* between the study sites, it was found that none of them is uniquely different from the rest at any acceptable alpha-levels, thereby statistically indicating towards absence of distinct topographic threshold conditions in any of the study sites.

Subdividing the dataset based on land cover/ vegetation type did not lead to any appreciable increase in the strength or significance of the *S*-*A* relationship at all. Unsurprisingly, no significant or explicable bearing of the various land cover types on values of coefficient *a* was detected, though it was noticed that mean *a*-value for gullies with presence of eucalyptus in their upslope contributing area was significantly lower ($p = 0.002$) in comparison to gully head catchments without eucalyptus. No statistically significant effect of planform curvature or shape of upslope catchments on the *S*-*A* relationship was found.

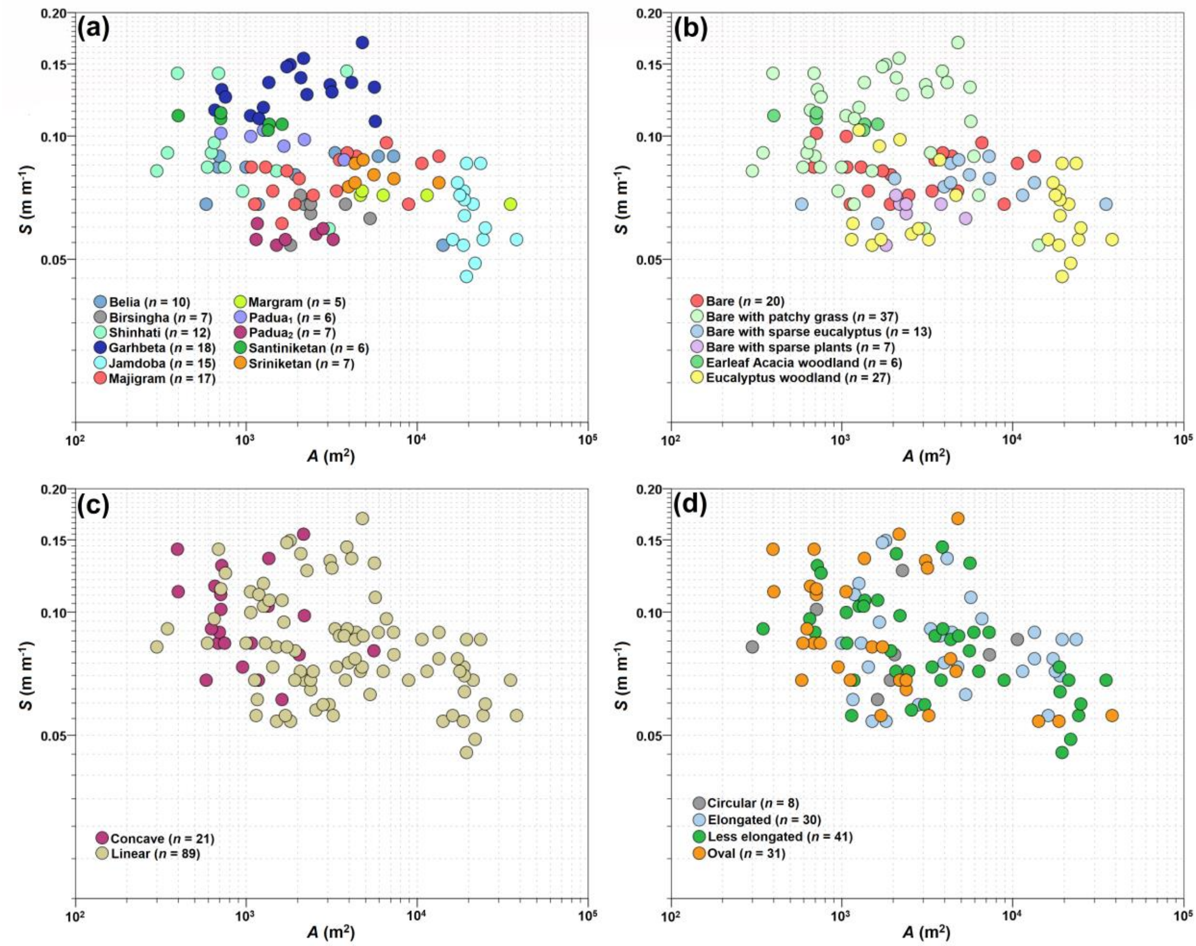

Fig. 7. Grouped *S*-*A* scatter plots for (a) study sites and (b) land covers, (c) dominant plan curvature and (d) shapes of gully head catchments.

4.3 Comparison of thresholding techniques

Seven critical threshold lines were constructed using the four discussed techniques (Fig. 8) and the regression coefficients of each are tabulated (Table 2). A strict adherence to the Patton and Schumm (1975) method yields two threshold lines that are very different from one another in terms of intercept and slope. Threshold lines obtained by applying the techniques of Vandekerckhove *et al.* (1998) and Vanwalleghem *et al.* (2005) are fairly similar, with only a difference of 0.006 in their intercepts. Using nonlinear regression (Gómez Gutiérrez *et al.*, 2009), the difference in intercepts between the lower 95% prediction interval limit and the line through the lowermost points was even smaller (0.005). Though the 90% confidence intervals of both coefficients *a* and *b* were narrowest for the 40% quantile, the resulting regression line is evidently not a "critical threshold" line and it severely underpredicts the *S*-*A* conditions of permanent gullies in the Rarh plain.

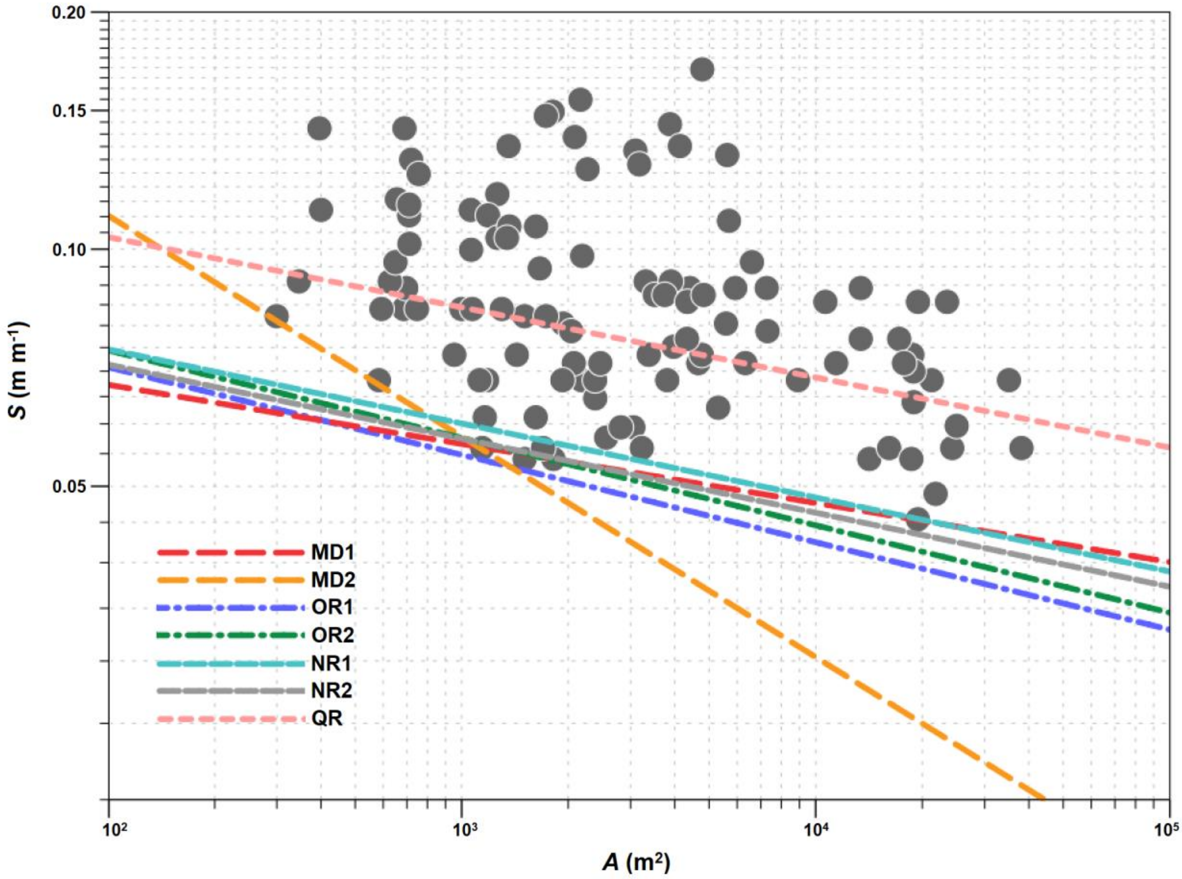

Fig. 8. Critical topographic threshold lines constructed by different techniques. Legend codes correspond to the codes in Table 2.

Table 2. Coefficients *a* and *b* of a critical topographic threshold obtained by different methods. Codes correspond to the legend codes of Fig. 8.

Code	Method	*a*	*b*	Proposed by
MD1	Manual drawing: line through lowest collinear points	0.095	-0.075	Patton and Schumm (1975)
MD2	Manual drawing: line through	0.4	-0.28	Patton and Schumm (1975)

	lowest collinear points			
OR1	Orthogonal regression: lower 95% prediction interval limit	0.118	-0.111	Vandekerckhove *et al*. (1998)
OR2	Orthogonal regression: Line through lowest collinear points keeping slope constant	0.124	-0.111	Vanwalleghem *et al.* (2005)
NR1	Nonlinear regression: lower 95% prediction interval limit	0.115	-0.094	Gómez Gutiérrez *et al.* (2009)
NR2	Nonlinear regression: Line through lowest collinear points keeping slope constant	0.11	-0.094	Gómez Gutiérrez *et al.* (2009)
QR	Quantile regression: For quantile with narrowest confidence interval ($\tau = 0.4$)	0.156	-0.089	Maugnard *et al.* (2014)

5. Discussion

5.1 What is the best method to estimate gully topographic thresholds?

Maugnard *et al.* (2014), using a fictitious dataset, argued that the thresholding method of Patton and Schumm (1975), i.e. to draw a line through the lowest points, can give rise to multiple lines for one *S*-*A* dataset. Results of this study explicitly confirm their suspicion. Moreover, the drawn lines $S = 0.095A^{-0.075}$ (MD1) and $S = 0.4A^{-0.28}$ (MD2) are so starkly dissimilar that on judging the thresholds solely by the equations without a visual assessment of the *S*-*A* scatter would lead someone to conclude that the lines represent topographic thresholds of gully erosion in different regions. A situation such as this is bound to cause a lot of confusion for the researcher as (s)he has no objective means to identify the line that actually represents the critical topographical conditions of gully erosion in a particular region, as both of them have been drawn as per definition of Patton and Schumm (1975). Furthermore, threshold lines drawn in this manner would also be very sensitive to odd outlying values (Maugnard *et al*., 2014). Due to all these reasons, there exists a lot of uncertainty about estimating the critical topographic thresholds using the method of Patton and Schumm (1975). However, in rare occasions such as when an *S-A* scatter tends to be more vertically oriented (e.g. Makanzu Imwangana *et al.*, 2014) or when any of the other approaches fails to capture the topographic threshold conditions, this is the only method to construct critical threshold lines. However, even in such instances, it is paramount to detect and ignore outliers before manually drawing a threshold line.

Lines OR1 and OR2 are both related to a best-fit orthogonal regression line $S = 0.205A^{-0.111}$. OR1 is the lower 95% prediction interval limit (Vandekerckhove *et al.*, 1998) and line OR2 is drawn through the lowest points with the same slope (b = -0.111) as the mean threshold line (Vanwalleghem *et al*., 2005). The difference in intercept a (0.006) between these two lines is negligible in this study, but could increase if the method of Vanwalleghem *et al.*, (2005) is applied in datasets with outliers, because the value of intercept a is directly dependent on the position of the lowermost points (Maugnard *et al.*, 2014). The approach of Vandekerckhove *et al.* (1998) has probably been the most frequently employed in critical topographic threshold estimation after that of Patton and Schumm (1975) and understandably so. In combination with obtaining the mean threshold line by means of total least squares minimisation, taking its lower 95% prediction interval as the critical threshold is statistically sound and also allows the researcher to explicitly state the gully initiation probability in areas that plot above the critical threshold line, i.e. 97.5%. However, for small datasets, it can result in overprediction of topographic conditions vulnerable to gullying as it tends to move downward from a visually expected threshold line (Maugnard *et al.*, 2014). In such cases, the method of Vanwalleghem *et al.* (2005) is indeed a better choice. Again, possible outliers must be inspected and ignored if necessary.

The best-fit line obtained by running the *Levenberg-Marquardt* algorithm (Moré, 1978) is $S = 0.186A^{-0.094}$ and the derived threshold lines are $S = 0.115A^{-0.094}$ (NR1: lower 95% prediction interval line) and $S = 0.11A^{-0.094}$ (NR2: line through the lowest points keeping the slope constant). Much like that of orthogonal regression, there is negligible difference in the intercepts of the equations, and both lines seem to capture well the critical topographic conditions of gullying in the Rarh plain. In fact, results obtained by using the aforementioned algorithm in this study is much better than that of Gómez Gutiérrez *et al.* (2009), where the threshold lines clearly overpredict critical *S*-*A* conditions of gullying in their study area. Notwithstanding the quality of obtained results, it is not recommended to resort to nonlinear regression in order to estimate critical topographic threshold conditions, as it is simply not necessary. Moreover, it is impossible to know beforehand the starting values of the regression coefficients, which has to be fed into the algorithm before running it. In this study, there were some references to assume these starting values and even then, it was a matter of intuitive choice.

Maugnard *et al.* (2014) recommended using quantile regression to construct topographic threshold lines, stating that it is more statistically grounded than the other methods in practice and robust to outliers. They used the most extreme (lowest) quantile for which the 90% confidence intervals for both regression parameters were possible to be estimated with acceptable precision, but did not explicitly state the criteria for such an assessment. Following a similar logic, regression was performed for the quantile with the narrowest confidence intervals. The 0.4 quantile has the narrowest intervals for both *a*, *b* coefficients in this study, but the regression line $S = 0.156A^{-0.089}$ underpredicts critical topographic threshold conditions by a large margin, and is evidently inappropriate to use further. While the argument of Maugnard *et al.* (2014), that thresholds obtained by following the methods of Vandekerckhove *et al.* (1998) and Vanwalleghem *et al.* (2005) would reflect the mean statistical weight of all the data points rather than the weight of the points at the lower boundary of the scatter plot because they rely on orthogonal regression, is statistically valid, it is also important to understand that estimation of topographic threshold conditions of gullying is not a statistical curve-fitting exercise. The motive is merely to find a line passing through the lowermost points of an *S*-*A* scatter; a line that distinguishes between the stable and unstable or gullied parts of a landscape. While it is recommended to estimate a range of quantiles and their confidence intervals and then choose a quantile to perform regression analysis (Cade and Noon, 2003), the statistical basis for making a selection of the lowest possible quantile with 'acceptable precision' as suggested by Maugnard *et al.* (2014) is unclear. It is however quite evident that this was not based on selecting the quantile with narrowest confidence intervals of both *a* and *b*. Also, both regression parameters are not automatically supposed to have the narrowest confidence interval limits for the same quantile (Cade and Noon, 2003). However, Maugnard *et al.* (2014) did not provide any guideline on a possible course of action in case the two regression parameters have different quantiles with the narrowest confidence intervals. In sum, the method of Maugnard *et al.* (2014) does not represent much of a step forward. They even admitted that dataset characteristics have a strong influence on the quantile value that can be used for regression and that minimum 50 data points would be required, which is way more than what most researchers estimating topographic thresholds of gully erosion base their analysis on. As such, a regression line for an arbitrarily chosen low quantile ($\tau = 0.01$) will always pass through the lowermost points, but at the same time will also be seriously sensitive to outliers, as illustrated by inserting an imaginary outlying point in the *S*-*A* plot of this study (Fig. 9). This might seem contradictory to common statistical knowledge, as one of the strengths of quantile regression as opposed to ordinary least squares regression is robustness to outliers (John and Nduka, 2009), but this argument only holds when there are sufficient number of data points under a targeted quantile (Fig. 9). One, therefore, can choose to perform quantile regression on a lowest possible quantile, such as 0.01, to estimate topographic threshold of gully initiation in a region without taking into account the confidence intervals of the *a*, *b* coefficients for different quantiles. However, a regression line for such a low quantile will not automatically be resistant to possible outliers, just like the other methods discussed before. Consequently, detection and removal of such data points is essential before an analysis. However, presence of an outlier has negligible effect on the lower 95% prediction interval limit of an orthogonal regression line (Fig. 9), further highlighting the applicability of this method in estimating critical topographic threshold conditions of gully erosion.

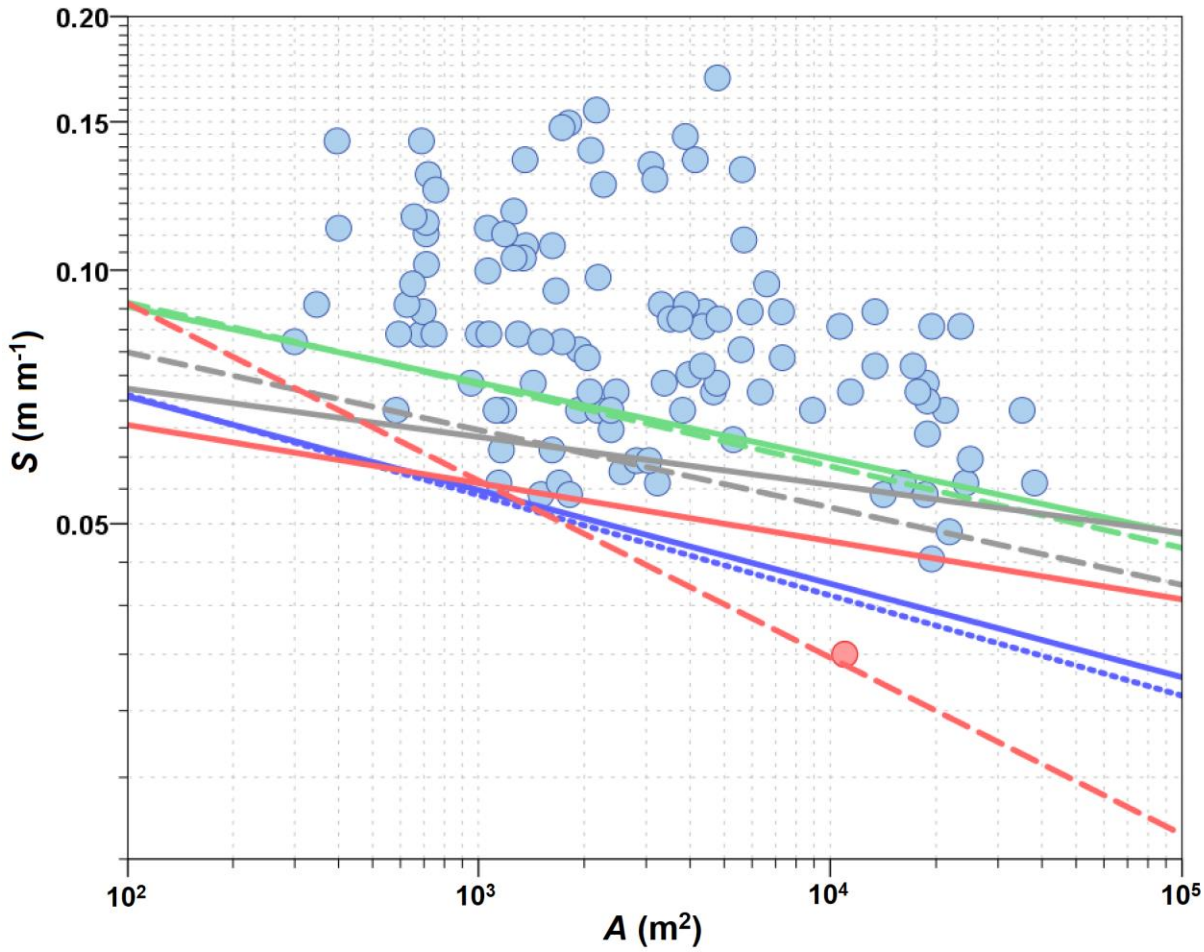

Fig. 9. Effect of a fictional outlier (point in red) on the orientation of quantile regression lines (dashed lines) compared to quantile regression lines without any effect of the outlier (solid lines). Red lines correspond to 0.01 quantile, Grey lines to 0.1 quantile and green lines to 0.2 quantile. Effect of the outlying point is only eliminated from the 0.2 quantile. For sake of comparison, the lower 95% confidence interval line of orthogonal regression ignoring the outlier (solid blue line) and considering the outlier (dotted blue line) are also plotted.

Overall, it can be concluded from this comparative analysis that no single method can be identified as a global standard to construct topographic thresholds of gully erosion. Each method has its set of merits and demerits. However, it is best not to follow the approach of Patton and Schumm (1975) unless absolutely necessary, because of its arbitrariness. Similarly, applying a nonlinear regression like Gómez Gutiérrez *et al.* (2009) is also not recommended, because it is just not necessary to employ nonlinear regression in situations where linear regression analysis is sufficient, even if the former is possible. In this study, the lower 95% prediction interval limit of the orthogonal regression line ($S = 0.118A^{-0.111}$) is taken as representative of the critical *S*-*A* conditions of the permanent gullies in the Rarh plain and it is recommended to use any of the two methods relying on orthogonal regression (Vandekerckhove *et al.*, 1998, or Vanwalleghem *et al.*, 2005) to fit critical threshold lines of gully initiation. The fact that orthogonal regression considers errors in both variables and does not imply any specific role of any one (Jackson, 1991; Carroll and Ruppert, 1996; Leng *et al.*, 2007) is consistent with the idea of topographic threshold estimation, with the variables *S* and *A* being inter-dependent and in most cases measured with errors. Quantile regression as employed by Maugnard *et al.* (2014) cannot be accepted as a global standard to model critical *S*-*A* conditions of incipient gullying. Moreover, it is not necessary to put so much effort in estimating the confidence intervals of the regression parameters across a range of quantiles and then proceeding to construct critical topographic threshold lines when methods based on orthogonal regression are already more effortless and pertinent alternatives. Quantile regression, however, can aid in examining if the *S*-*A* relationship differs markedly over various quantiles, which is simply not possible to perform through ordinary linear or orthogonal regression (Koenker and Bassett, 1978; Cade and Noon, 2003). Since the whole idea of topographic threshold analysis rests on evaluating aspects of the *S*-*A* relationship with respect to possible effects of factors such as land cover, soil properties, climate or land management measures, it might be interesting to fit several quantile regression lines to an *S*-*A* scatter plot and analyse them with reference to (changes in the) mentioned factors.

5.2 Gully topographic threshold characteristics in the Rarh plain

Results of this study confirm that the various gullied tracts of the Rarh plain as examined in the present work are not characterised by distinct topographic thresholds of gully erosion. This finding is in line with what is expected, as all the gullied catchments have developed in secondary laterites at similar landscape positions (valley-side gullied catchments) and have largely similar land cover characteristics. The line $S = 0.118A^{-0.111}$ is representative of the critical topographic threshold conditions of gully erosion in the secondary laterite areas of the Rarh plain and imply that laterite exposures that plot below are not at risk of incision. This is a plausible explanation for the presence of many non-gullied laterite exposures in the Rarh plain (See Fig. 1a). However, since many environmental factors exercise control over a topographic threshold of gullying, it does not necessarily mean that all areas that plot above the line are bound to be incised (Patton and Schumm, 1975). Major disturbances brought about by land cover changes or intense rainstorms would still be required to initiate gullying in areas made susceptible by runoff convergence and connectivity (Gómez Gutiérrez *et al*., 2009; Muñoz-Robles *et al.*, 2010; Goñi, 2018).

The exponent value of -0.111 is indicative of inert gully dynamics (Yibeltal *et al*., 2019), and according to Montgomery and Dietrich (1994), is also suggestive of a relative dominance of subsurface processes and resulting mass failures as processes of gully head retreat in the Rarh plain at present. Though there is large variation in gully head catchment sizes between the study sites, the minimum catchment size encountered is about 300 m^2 and the average gully head catchment area in 8 out of the 10 study sites is less than 0.5 ha. The AS^2 range for gullies of the Rarh plain (2–170 m^2) is markedly smaller than the range of 500–4000 m^2 that Montgomery and Dietrich (1992) found in semi-arid California or the ranges of values found by Wu and Cheng (2005) and Dong *et al.* (2013) in China, respectively for gullies in the Loess Plateau (41–814 m^2) and Yuanmou Dry-hot valley (4–758 m^2). As the gullies considered in this study are permanent features with subsurface processes like piping and associated mass failures likely to be the dominant gully growth processes at present, it can safely be assumed that their upslope catchment areas have decreased strongly over time due to prolonged gully head retreat induced by surface runoff. However, in order to identify the main gully erosion process (overland flow erosion/ seepage erosion/ diffusive erosion/ landsliding) at each gully head in the Rarh plain, it is recommended to employ the Montgomery-Dietrich envelope (Montgomery and Dietrich, 1994; Moeyersons, 2003) in future studies.

Gully genesis and long-term dynamics has been best studied through analysis of historical ground-based or aerial photographs with respect to present conditions (e.g. Frankl *et al.*, 2019). Unavailability of such resources in the public domain in India makes it difficult to trace the formation of gullies in this region back in time or discern the causes of gully development. The only available long-term documentary records on the regional geography of West Bengal are the West Bengal district gazetteers (O'Malley, 1906), but even these are insufficient to pinpoint exact times of gully formation in this region. It is however most likely that gullies started to appear as vast stretches of land, which were under thick forest cover till ca. 1850–1870, started being cleared away to generate revenue through timber production by the British East India Company and also to make way for agriculture, build roads and railways through this region (O' Malley, 1906; Roy Mukherjee, 1995; Pattnaik and Dutta, 1997). However, the newly created agricultural lands were subsequently found to be yielding little and were thus abandoned and left as wastelands, promoting soil erosion (Pattnaik and Dutta, 1997). Roy Mukherjee (1995) cites over-grazing and over-exploitation of forest resources by the tribal communities of this region as well as deliberate burning of forests in order to prepare land for agriculture as main causes formation of 'ravines', but no specific information was provided on when these might have started to form. Although it is entirely possible for many of the gullied catchments of this region to be over a century old, in which case it is natural for their gully head drainage areas to be small and consequently for the gullies to be stabilised, it is impossible to know which ones. For example, the much larger gully head catchment areas in Margram (mean: 1.3 ha) and Jamdoba (mean: 2 ha) compared to the other sites indicate that gullies in these areas have formed more recently. Overall, with the effect of major land cover changes on incipient gullying being very well known (Faulkner, 1995; Bork *et al*., 2001; Poesen *et al*., 2003; Poesen, 2018), it is quite likely that such land cover changes in the 19th and early 20th century had triggered gully formation in parts of the Rarh plain.

A statistical test revealed that gullies having eucalyptus stands in their upslope catchment areas have a significantly lower value of coefficient *a* than gullies under other land cover types. This finding, along with a field observation on the sparseness to absence of ground vegetation in the eucalyptus woodlands, points directly to eucalyptus' allelopathic influence on the environment, hindering development of other plant species (Zhang and Fu, 2009; Chu *et al*., 2014) as well as their role in inducing soil erosion in general (Valentin *et al*., 2005) and gully erosion in particular (Nyssen *et al*., 2006). The fact that eucalyptus is not an indigenous species of the forests of this region and is only found in plantations (Roy Mukherjee, 1995) provides a suitable explanation of the results of the statistical test, that planting eucalyptus in barren lands because of their assumed beneficial ecological effects (Pohjonen and Pukkala, 1990) actually worsens the situation by inhibiting growth of ground vegetation, aiding in formation of soil crust due to direct raindrop impact on soil (Valentin *et al.*, 2005) and promoting gully erosion, which is captured by the low threshold value compared to gully head catchments without eucalyptus trees. As planting eucalyptus as part of afforestation schemes in the Rarh plain and surroundings started only in 1962 (Roy Mukherjee, 1995), the gullies under eucalyptus are much younger, and consequently their upslope catchment areas are much larger compared to gully head catchments elsewhere. Also found in plantations in the Rarh plain, is earleaf acacia (Acacia auriculiformis), which is locally called *sonajhuri* or *akashmoni* (Roy Mukherjee, 1995; Banerjee, 2007). Results of this study confirm that, much unlike eucalyptus, earleaf acacia woodlands (Santiniketan site), with dense grass and other understory vegetal cover, provides maximum resistance against gully erosion.

Landscape plan curvature is often considered in gully erosion studies as it controls flow convergence, which is of paramount importance in emergent gullying (Vandaele *et al*., 1997; Vandekerckhove *et al*., 1998). Furthermore, catchment shape has been historically examined in morphometric studies as one of the main controls of hydrological connectivity, runoff intensity and soil erosion (Horton, 1945; Schumm, 1956). However, in this study, these parameters were observed to have no considerable bearing on the *S*-*A* distribution of the gullies. It could be due to the fact that most of the studied gullies have consumed their upslope catchments over time, thereby leaving no signature of the effects of upslope plan curvature or catchment shape on the present *S*-*A* distribution. Contrarily, it could also mean that land cover type and change are the main factors of gully erosion in the Rarh plain. This conclusion aligns well with observations of Vandekerckhove *et al.* (2000) or Gao (2013), whereby they noted that vegetation type and cover are the most important factors determining the topographic threshold in non-agricultural lands.

Finally, the topographic threshold of the permanent gullies in the Rarh plain was graphically compared with topographic thresholds of gullies estimated for different regions around the world having similar soil types and/or land cover as the gullied tracts of the Rarh plain (Fig. 10; Table 3). Compared to gullies developed in similar soil types, the secondary laterites of the Rarh plain plot totally above the Australian red kandosols (Muñoz-Robles *et al*., 2010) and partially above the ferralsols of Tanzania (Achten *et al*., 2008), but below acrisols of Ethiopia (Yibeltal *et al*., 2019), saprolite of Swaziland (Morgan and Mngomezulu, 2003), ferrallitic soils of Rwanda (Moeyersons, 2003), dry red soils of China (Dong *et al*., 2013) and primary laterites of the Chhotanagpur plateau (Ghosh and Guchhait, 2016). The permanent gullies developed in the primary laterites of the adjacent Chhotanagpur plateau fringe are characterised by a much higher critical threshold relationship $S = 0.31A^{-0.25}$ (Ghosh and Guchhait, 2016). As the coefficient *a* is considered to be a measure of landscape resistivity to entrenchment, it is plainly understood that primary laterite outcrops of the Chhotanagpur plateau are considerably less prone to gully erosion than the secondary laterites of the Rarh plain. The value of *b*, as derived by Ghosh and Guchhait (2016), indicates that overland flow is the main agent of gully development in primary laterites. This is in line with what is expected, as primary laterites are inherently harder and more erosion-resistant, making action of subsurface processes impossible or negligible in effect (Ghosh and Guchhait, 2020). Primary laterites of the Chhotanagpur plateau region have one of the highest topographic thresholds for gully erosion in the world (Fig. 10). Considering studies that were done in regions having similar land cover/ use (rangelands, bare lands etc.), all except two have higher critical *S-A* thresholds than the Rarh plain.

Overall, gullies of the Rarh plain have quite different topographic threshold characteristics than gullies developed in similar soil types in other regions around the world (Fig. 11). Although the secondary laterite areas are more resistant against gullying compared to Mediterranean badlands (Torri *et al*., 2018), the value of coefficient *a* for the Rarh plain is only slightly larger than the average value of *a* found for ephemeral gullies in croplands (0.08) and is much smaller than those of rangelands and pastures (0.194) or forests and grasslands (0.535) around the world, and the value of coefficient *b* is considerably lower for all the compared cases (Fig. 11).

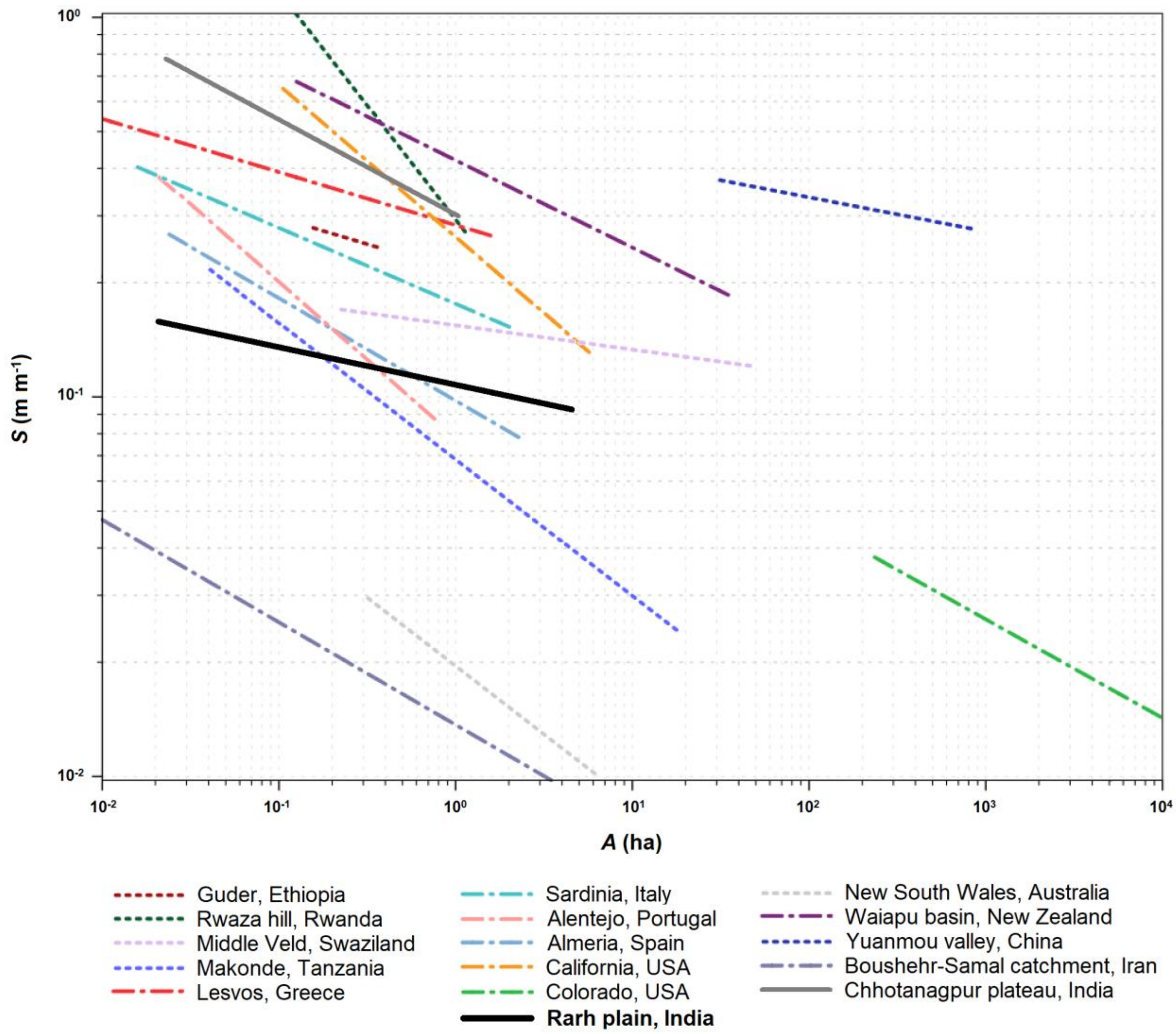

Fig. 10 – Topographic threshold of permanent gullies in the secondary laterites of Rarh plain (black solid line) compared to topographic thresholds of permanent gullies in the primary laterites of Chhotanagpur plateau (grey solid line), areas having similar soil types (all dotted lines) and comparable land cover (all dash-dot lines). See Table 3 for details and references.

Table 3 Values of parameters *a* and *b* of topographic thresholds of gully erosion in different regions as compared in Fig. 10

Country	Region	*a*	*b*	Source

Ethiopia	Guder	0.219	-0.139	Yibeltal *et al*. (2019)
Rwanda	Rwaza hill	0.3	-0.6	Moeyersons (2003)
Swaziland	Middle Veld	0.158	-0.064	Morgan and Mngomezulu (2003)
Tanzania	Makonde	0.07	-0.36	Achten *et al*. (2008)
Greece	Lesvos	0.29	-0.14	Vandekerckhove *et al*. (2000)
Italy	Sardinia	0.18	-0.2	Zucca *et al*. (2006)
Portugal	Alentejo	0.08	-0.41	Vandekerckhove *et al*. (2000)
Spain	Almeria	0.1	-0.27	Vandekerckhove *et al*. (2000)
USA	California	0.27	-0.4	Montgomery and Dietrich (1988)
USA	Colorado	0.16	-0.26	Patton and Schumm (1975)
Australia	New South Wales	0.02	-0.36	Muñoz-Robles *et al*. (2010)
New Zealand	Waiapu basin	0.43	-0.23	Parkner *et al*. (2006)
China	Yuanmou Dry-hot valley	0.52	-0.09	Dong *et al*. (2013)
Iran	Boushehr-Samal catchment	0.044	-0.18	Nazari Samani *et al*. (2009)
India	Chhotanagpur plateau	0.31	-0.25	Ghosh and Guchhait (2016)
India	**Rarh plain**	**0.118**	**-0.111**	**This study**

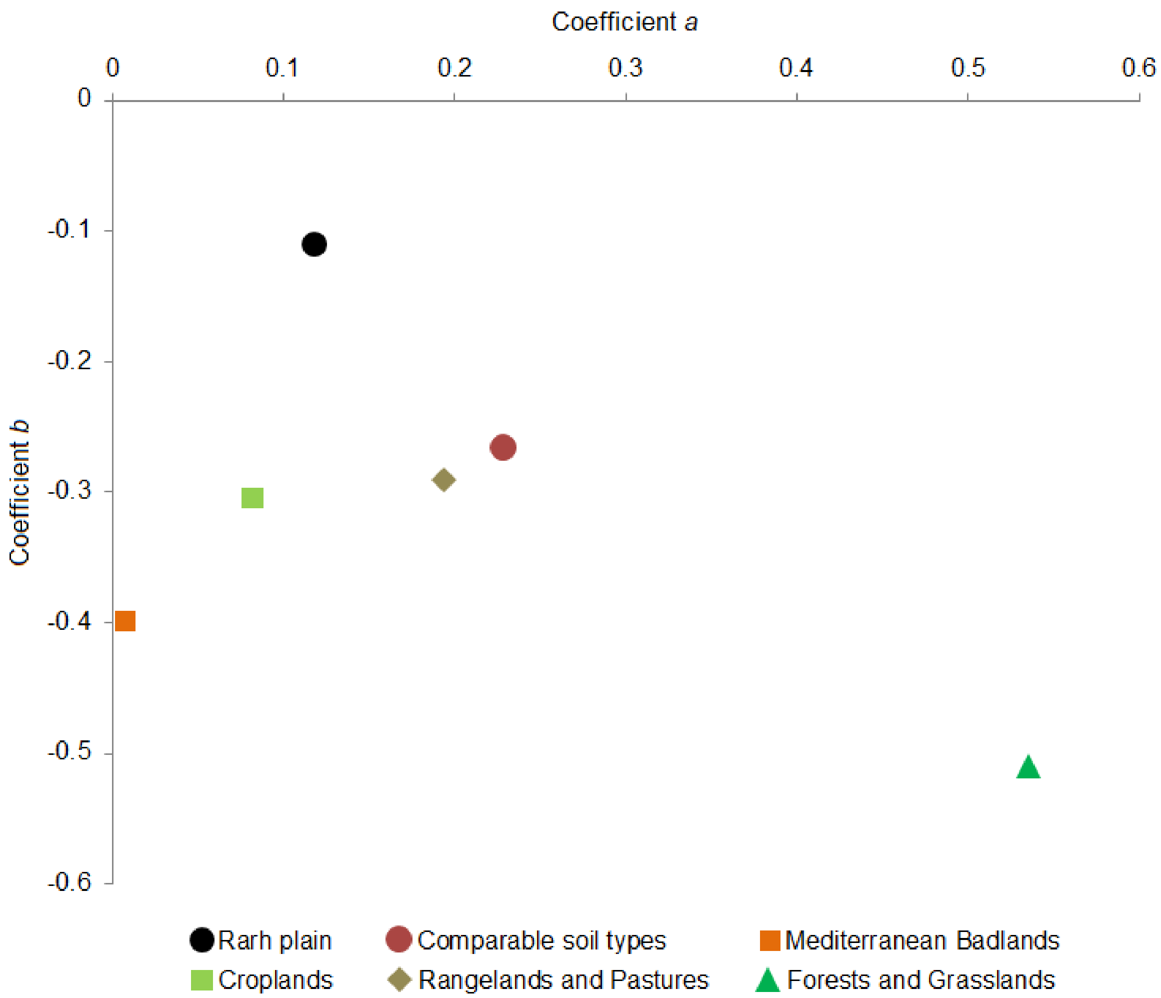

Fig. 11. Comparison of coefficients *a* and *b* of the topographic threshold of Rarh plain with that of other environments (Source: Torri and Poesen, 2014, Torri *et al*., 2018)

Table 4 Values of parameters *a* and *b* of topographic thresholds of gully erosion in different environments as compared in Fig. 11

Environment	*a*	*b*
Mediterranean Badlands	0.008	-0.4
Similar soil types	0.23	-0.27
Croplands	0.08	-0.3
Rangelands and Pastures	0.19	-0.29

Forests and Grasslands	0.53	-0.51

Source: Torri *et al*. (2018) [Mediterranean Badlands]; Moeyersons (2003), Morgan and Mngomezulu (2003), Achten *et al*. (2008), Muñoz-Robles *et al*. (2010), Dong *et al*. (2013), Ghosh and Guchhait (2016) and Yibeltal *et al*. (2019) [Similar soil types]; Torri and Poesen (2014) [Croplands, Forests and Grasslands]; Moeyersons (2003), Morgan and Mngomezulu (2003), Dong *et al*. (2013), Torri and Poesen (2014), Ghosh and Guchhait (2016) and Yibeltal *et al*. (2019) [Rangelands and Pastures]

6. Conclusion

A review of previous studies dealing with topographic thresholds of gully erosion revealed that many different methods have been used to model critical topographic conditions of gullying since Patton and Schumm (1975) started it. However, it was observed that often a chosen technique was applied without any justification. This study assessed the various methods that have been used so far to estimate critical topographic thresholds of gully erosion, highlighted the advantages and disadvantages of each of them after a thorough comparative analysis, and concluded that the two techniques based on orthogonal regression, suggested by Vandekerckhove *et al.* (1998) and Vanwalleghem *et al*. (2005) are most appropriate. However, notwithstanding the technique being used, it is paramount to conduct a thorough exploratory data analysis to detect and ignore outliers before proceeding to fit a critical threshold line through an *S-A* point cloud. That said, the method of Vandekerckhove *et al.* (1998) was found to be relatively robust to outliers and should be the preferred choice in gully topographic threshold studies. Albeit it is not recommended to use quantile regression to fit critical threshold lines, it can be very useful to discern if there are significant differences in the *S-A* relationship across quantiles and assess the same with respect to changes in environmental factors that are known to exercise utmost control on gully initiation.

The critical threshold line for the permanent gullies of the Rarh plain, $S = 0.118A^{-0.111}$ can be applied to locate areas of germinal instability in the lateritic exposures of the Rarh plain, mainly in the deforestation fronts, therefore enabling preventive conservation to be practised through appropriate management measures. Contrary to popular belief and governmental action in this area, whereby it is believed that eucalyptus afforestation as part of social forestry schemes is beneficial, results of this study tend to suggest otherwise; planting eucalyptus trees in barren lateritic outcrops is likely to do more harm than good. Unsurprisingly, topographic threshold of permanent gullies in the primary laterites of the adjacent Chhotanagpur plateau is much higher than that of the Rarh plain and one of the highest worldwide, thereby highlighting the resistance of 'typical' primary laterites. Results of this study indicate that many of the gullied tracts of the Rarh plain have reached a state of (quasi-)stabilisation and that subsurface processes and associated mass failures are main gully growth processes at present. Further studies are however recommended to decipher evolutionary history and recent dynamics of the gullies of Rarh plain and Chhotanagpur plateau.

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