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Morphology and Origin of Valley-Side Gullies Formed along the Watersheds of Deccan Province, India and the Rangeland of Colorado, USA.

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Abstract

Gullies are the most ubiquitous geomorphic features on the Earth. These features are found along variety of climatic and topographic setups. The process of gullying is generally a combined result of fluvial erosion, piping, tunnel erosion and mass wasting and gives rise to dramatic landscapes all over the world. This paper deals with a few valley-side ephemeral gullies from the Western Upland Maharashtra from Deccan Province of India and a gully from a Rangeland of Colorado, USA. These are the areas with contrasting climate and lithological characteristics. It is an attempt to understand the origin of these gullies through the understanding of the morphological relationships that exist in them. On the basis of the sedimentological and morphological analysis and incorporation of a few radiometric dates it has been highlighted that gullying in both the environments owe their origin to the Holocene climate change events but their response to this climate change were different. In case of Deccan gullies, the arrival of a humid phase in the early Holocene induced intense erosion by gullies. Gullies were initiated along the pediment slopes as a result of this base-level drop. Once initiated, colluvium surfaces offered least resistance to the surface erosion and the gully network expanded. In the case of Colorado Gully the mechanisms were different as there is hundred fold contrast in the erosion thresholds between bare soil and full herbaceous cover. The initiation of the gullies along this grass-carpeted surface began following a sudden humid phase in the mid-Holocene after a long drought cycle, which generated a conditional instability and reduced the erosional resistance of these surfaces.

Key words: *Gullying, colluvium, Rangeland, sedimentology, herbaceous cover, Holocene*

Introduction

Gully development is cited as an example of equifinality in geomorphology, as a range of different processes and triggering mechanisms can apparently generate similar forms (Schumm, 1999).

A gully is a narrow channel worn on the earth by the action of water, especially a miniature valley, resulting from a heavy downpour of rain (Fairbridge 1968). According to Schumm et. al. (1984) and Bradford and Piest (1980), a gully is an incised, steep sided channel with an eroded headcut and slumping sidewall. Gully erosion is most commonly triggered by fluvial erosion following natural and anthropogenic disturbances or as a response to changes in climate and tectonic forcing and base-level drop (Istanbulluoglu 2005). Gullies are initiated or enlarged by floods in virtually all the morphogenetic regions. They are known to occur on the footslopes and pediments. They occur over alluvium or colluvium and in a variety of environments.

Headward growth and widening of many gully systems are attributed to gravitational mass-wasting processes of over steepened sidewalls. Soil saturation, groundwater sapping, and tension crack development also contribute to their instability (Istanbulluoglu 2005). Gullies are analogous to the large river systems except in scale; and represent the river system in the juvenile stage. They develop rapidly that facilitate monitoring and the geomorphic processes involved are relatively simple and easy to understand. These reasons provide this landscape to have acclaimed remarkable scientific attention all over the globe.

Gully erosion is usually attributed to changes in external and internal factors in the basin. External factors determine the magnitude of flow shear stress or stream power acting on the soil surface. These include tectonic uplift and base-level lowering, climate forcing and natural and anthropogenic watershed disturbances (Istanbulluoglu 2005). Internal factors arise from the characteristic behaviour of the erosion processes itself, such as feedbacks between topographic change, runoff generation and erosive power of overland flow (Bull 1997). However the distinction between internal and external factors is not clear-cut in many situations.

The geomorphic literature is replete with studies on gullies and badlands. Over the decades, the investigations have evolved from the studies of morphology employing traditional methodologies to the process studies and then to the calculation of erosion and network expansion rates using remote sensing, LIDAR and IKONOS data with the GIS tools. 'The initiation of gullies is the result of unwise utilization of land' was the conclusion of the work carried out by Wells and Andriamihaja (1993). The rate of erosion was detected by employing collector, erosion pins and profilometer techniques by Sirvent et. al. (1997). The first micro-topographic studies which used laser profilometers, with a resolution better than 1 cm was reported by Sole-Benet et. al. in 1997. Vandekerckhove et. al. (1998) reported topographical thresholds for ephemeral gully initiation in intensively cultivated areas of the Mediterranean. Farifteh and Robert (1999) and Casali et. al. (1999) studied gully erosion and effects of slope on the headcuts. Gully erosion modelling and landscape response was attempted by Sidorchuka (2003) in a small catchment of Swaziland. Gully incision was the key factor in desertification on the Negev highlands of Israel according to Avni (2005). The origin of the infamous biancane and calanchi badlands in southern Italy was determined by Farifteh and Soeters (2006). Badland erosion was simulated with KINEROS2 by Martínez-Carreras et. al. (2007) in Eastern Pyrenees. The simulation was done to validate whether there is any delay between sediment production, caused by intense summer rainstorms, and sediment transport, occasioned by the main floods produced by large precipitation events following wet antecedent conditions. The results demonstrated the capacity of KINEROS2 to simulate badland erosion, although it showed limited robustness. The role of base-level changes and its response to the erosion and stabilisation sequences in El Cautivo badlands of SE Spain was reported by Alexander et. al. (2008). Long-term development of Holocene and Pleistocene gullies was established by Panin et. al. (2009) in the Protva River basin in Central Russia. A new methodology for predicting the quantity and location of sediment delivery was developed and tested via a case study in the Pacific Northwest USA by Barber and Mahler (2010). Ryan et. al. (2010) made a comparison of gully erosion using airborne and ground-based LIDAR on Santa Cruz Island, California. Stefano and Ferro (2010) applied the dimensional analysis and the self-similarity theory to estimate rill and gully erosion in Sicily. A multidisciplinary study on Lavaka formation in Central Highlands, Madagascar was carried out by Raveloson et. al. (2012). Capra et. al. (2012) made measurements of ephemeral gullies carried out at event scale since 1999, in a small basin located in Sicily (Italy), to quantify soil loss attributed to ephemeral gully erosion.

Study of gullies requires data with very high resolution since the landsurface process is operating on a fine scale. Use of advanced techniques to generate such high resolution data to generate DEMs became evident in the past few years. Digital elevation models (DEMs) obtained by photogrammetry using detailed aerial photographs reaching resolutions of up to 1 m, which allowed close analysis of drainage systems and the detection of some changes in landforms and denudation rates, have been conducted by several investigators in the last decade (eg. Alexander et. al. 2008). Airborne LIDAR measures typically a few points per square meter, thus provide DEMs of one-metre resolution (eg, Bretar et. al. 2009 and Thommeret et. al. 2010). Current terrestrial laser scan equipment can measure terrain topography with a nominal resolution of about 5 mm. It maps landforms more quickly and accurately than any other topographic method, with the advantage that it is possible to map hillslopes at a distance, without introducing any physical disturbances so making the detailed erosion study possible (Gallart et. al. 2012).

In the last 20 years, a growing number of studies have explored the influence of erosion processes on vegetation establishment, describing erosion as an ecological driver that affects vegetation composition, structure and spatial pattern (Bochet et al. 2009).

An emerging technique to investigate erosion rates is the study of exhumed roots which are possible in badlands sufficiently humid to allow the growth of woody vegetation. Such studies have been carried out by Corona et. al. (2011), Saez et. al. (2011) and Bollati et. al. (2012). "Thirty years of studies on badlands, from physical to vegetational approaches. A succinct review" by Galart. et.al. (2012) is the most recent and exclusive review of the articles on gullies.

Mechanism of gully and ravine erosion, gully development, reclamation and management have been widely studied by Indian geomorphologists, soil scientists, and agriculture scientists and reported in many national journals. Bulk of the literature on ravines and gully erosion are from the Northern Plain of India, especially of the extensive and classic badlands of Chambal. A comprehensive review of studies and researches on ravine erosion and reclamation in India by Indian geoscientists has been presented by Haigh (1984). Dearth of literature from the Deccan Volcanic Province is not very astonishing, considering the lack of sedimentary reservoirs in the Deccan Trap Terrain. However Kale et. al. (1994) reported morphology and origin of valley sides gullies, Western Upland Maharashtra. Joshi and Kale (1995) studied contribution of sidewall erosion in gully development. Pleistocene colluviation and the Holocene gullies of the Western Deccan have been studied by Joshi and Kale (1997). Joshi (2000) investigated the development of badlands in two localities in Bhima Basin. Joshi (2006) evaluated morphological adjustments of gullies on the anthropogenic interference in the landscape. Rill and gully erosion risk of lateritic terrain in South-Western Birbhum District, West Bengal, India was reported by Jha and Kapat (2009).

This paper is an attempt to evaluate the oft quoted statement "Gully formation is an example of equifinality in geomorphology, since a range of different processes and triggering mechanisms have known to generate this landform", by applying the concept to a few gullies formed in Western Upland Maharashtra and comparing them with one, formed in the rangeland of Colorado, USA.

The Study Area

Four small watersheds in the semi-arid areas of Western Upland Maharashtra, India have been chosen for the study. The area is underlain by Cretaceous-Eocene basalts of various types. Annual rainfall ranges between 500 and 800 mm with rains during four monsoon season, followed by a long dry spell. Gullies and badlands are observed on thick colluvial deposits in the foothill zones. The deposits are wedge shaped and generally becoming thicker away from the Hillslopes. Late Quaternary valley-fill deposits are also subjected to gully development throughout the Western Deccan Trap Region. Natural vegetation is generally absent except for few Acacia plants.

The first site is Chandanapuri which is a watershed located within Pravara Valley (Godavari Basin), Maharashtra where best developed valley-side gully systems can be seen. The average elevation of the place is 880 m ASL. Semi-arid conditions prevail over the region with an annual average rainfall of 500 mm. Natural vegetation is almost absent with the exception of scattered acacia vegetation on the slopes. The foothill / pediment zone is thickly covered with colluvium and the surface is deeply dissected by gullies to form a badland. The gullies are wide, deep and continuous but have been disturbed considerably by human activities.

Alephata is a small pediment-slope gully system in Kukdi Basin (Bhima Basin), India which is characterized by highly sinuous channels and flat-topped interfluves. The average height of the place is 853 m ASL. Slopes are gentler compared to the previous site. This site is just 40 km south of the Chandanapuri site and hence falls in the same semi-arid tract. The average annual rainfall is 530 mm. This is one of the rare localities where piping and tunnel erosion is observed. Gullies are V-shaped and are cut into sandy-silts and silty-clays below a thick indurated semi-caliche. Gullies start with a headcut formed into underlying rocky pediment and there are many within-gully headcuts. Natural vegetation is completely absent. This is the second site in Deccan.

Wai-Pasarni site is also a small pediment-slope gully system in Krishna Basin, India. The geomorphic settings and gully systems between Alephata site and this site are very similar except that this site does not display piping and tunneling. Rainfall in this site is fairly higher than the three other sites due to the influence of wet Western Ghat zone and the amount is approximately 800 mm a year. The altitude of the place is 972 m ASL. Vegetation is very sparse. Gullies are sinuous and V-shaped, cut into colluvium and smooth rounded inter-gully spurs.

The fourth site in Deccan is Pashan-Baner which is located very close to Pune which is also a small pediment-slope gully system, in Mula-Mutha Basin (Bhima Basin). The average elevation of the area is 660 m ASL. Gullies are sinuous and V-shaped and inter-gully areas are flat and smooth. The up-gully heads are cut into the foothill slopes in bedrock. The thickness of colluvium is less in this locality but gully systems resemble the previous two localities.

The location map of these four sites is demonstrated in Fig.1 (see page 119). One gully from each of these sites has been selected for the present investigation (Fig.2 see page 120). In the further sections, these gullies will be referred to as "Deccan Gullies"

Pawnee Grassland is a vast Rangeland in Western Colorado, between South Platte River and Wyoming state line in United States of America (Fig.3 see page 120). This extensive flatland was formed during late Cretaceous- early Tertiary Laramide uplift of Rockies. Silt, sand and gravels carried eastward from mountains were deposited across an extensive fluvial surface, forming a vast ramp tilting down to the east (Ostercamp et. al. 1987). The Fox Hill sandstone and the Laramide Formation preserve Cretaceous sedimentation (Scott 1978). Three main Paleogene and Neogene sedimentation cycles are preserved in Oligocene White River Group, the Miocene Arikaree Formation and Pliocene Ogalla Formations. These Cretaceous, Paleogene and Neogene sediments have undergone minimal subsequent erosion except in places such as Colorado Piedmonts. Tributary streams to the South Platte River have eroded progressively headward into an escarpment known as Chalk Bluffs which parallels the Colorado-Wyoming border. In the process these tributaries have captured eastward flowing channels. The Chalk Bluffs are capped by Miocene sandstone and conglomerates that are more resistant to erosion than the underlying White River Group. The White River Group includes fluvial and eolian sandstones, siltstone and shales. Most of these sediments are soft, densely fractured and readily erodible (Trimble 1993). **Pawnee National Grassland** was established after 1930 dust bowl in response to severe erosion from the agricultural lands. At present the area within the grassland is a mosaic of lands owned by federal government, state government and private individuals. The region is characterized by highland continental climate, dominated by Westerly winds. Annual precipitation ranges between 300 and 380 mm. Average summer temp is 21^0C with highest reaching 38^0C and winter average is -2^0C with lowest reaching the value of $- 34^0$C. Relative humidity is low throughout the year. Vegetation is mainly central shortgrass ecoregion and shortgrass steppe type. Grazing of domestic cattle is the main land use of the region at present. Deeply incised ephemeral channels and badland topography commonly form where rocks of White River Group are exposed or close to the surface in this rangeland. One such gully was surveyed from this locality. The site from where this gully has been surveyed is also known as Pawnee Buttes because of two distinct buttes in that locality (Fig.. 4 see page 121). The average altitude of the surface is 1600 m ASL.

Stratigraphical and textural characteristics of the sediments

For Deccan gullies, gully walls and exposures in wells and along road-cuts were investigated for evaluating the stratigraphical characteristics of the colluvial deposits. Several sections were examined at each site to generate a composite profile showing downstream variation in the lithosections using Miall's (1978) lithocode system to identify the facies. Slight modifications have been made to suit the present sites. Fig. 5 presents generalized lithostratigraphical logs of all the four Deccan sites. By and large, there is predominance of sandy-silts in all the sections. In Ale Phata, Wai and Pashan the percentage of finer sediments is high. Chandanapuri area displays coarser sediments with gravels and boulders. In the coarse facies, imbrications are weak and there are lenses of gravel and sand. Horizontal and inclined stratification, as well as cutandfill structures are observed in channel facies. Both normal and inverse grading is observed. The fine-grained units are generally massive and structure less. Calcium carbonate nodules and bedded calcretes are conspicuous throughout the sequences.

In Chandanapuri, deposits that are close to the foothills consist of angular to sub-rounded clasts of basalts, ranging in size from sand-sized grains to boulders, set in a matrix of pale-yellow-brown sandy-silts with considerable amount of defused carbonate. The fine-grained units are generally massive and structureless. Massive matrix supported gravels and crudely bedded gravels (Gms, Gm) are more frequently observed near the foothills. Near the streams, the units reveal a predominance of sandy and gravelly facies, with horizontal, trough and cross-bedded stratification. Thickness of the deposit exceeds 20 m at places. At Ale, the deposits show the predominance of sandy-silty material (Sm, Sh) with occasional pebbles. Bedded calcrete is a common feature. Top layers are slightly indurated (Fig. 6). Clay layers are present at frequent intervals which promote sapping, and surface depressions are produced on the gully walls and on the surface of the deposits. There is not much significant variation between the middle reach and downslope facies. Bedded calcium carbonate, associated with sandy-silts predominate Pashan deposits. Coarse gravel facies (G) are near absent, except for occasionally embedded cobbles or pebbles in sandy-silty units. Top soil is common. Mesolithic artifacts have been collected from the surface of these deposits. Observations at Wai reveal that near the foothill zones, the deposits are thinner, with a predominance of silty-sandy facies, whereas colluvium becomes thicker downslope, with alternate Sm and Sh layers (Fig. 5 and Fig. 6).

For Pawnee Gully, five litho-sections have been studied from the source till the confluence where this gully meets the main gully near the buttes. Facies are silty-sandy, massively structured and do not show any stratification. Gravel lenses are found only in the sections very close to the foothills otherwise the deposits show very little variations in vertical stratification (Fig. 7a, 7b and Fig. 8) (see page 122 for fig 8). Buried soils could be found at some sections that may indicate the antiquity of the deposits. Deposits reveal true characteristics of alluvium as against the colluvial sediments of Deccan gullies.

Textural analysis of a few samples from Deccan and Pawnee are displayed in Fig. 9. Percentage of silt varies between 18 and 47 and that of sand between 13 and

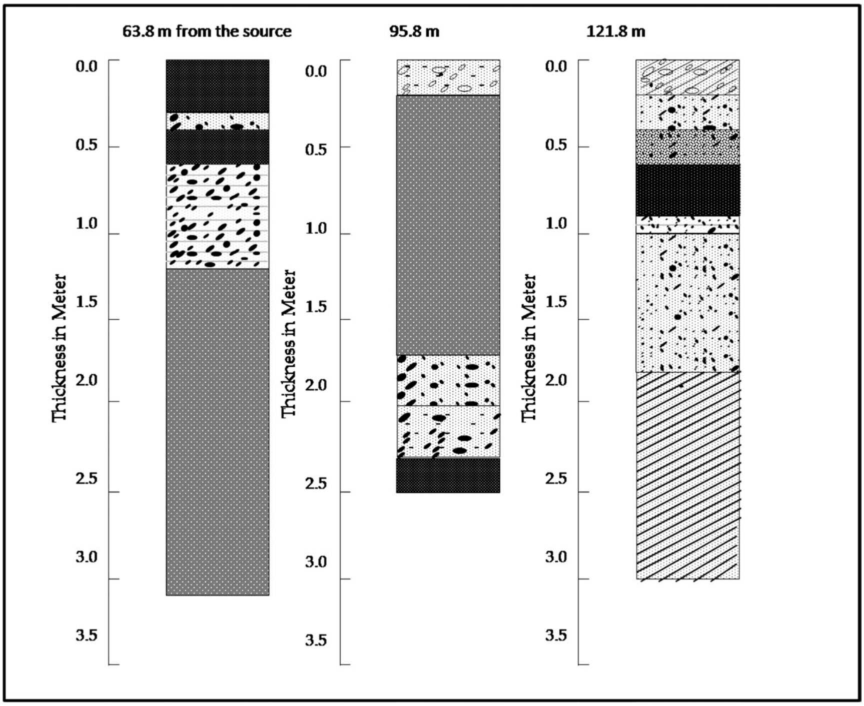

Fig. 5

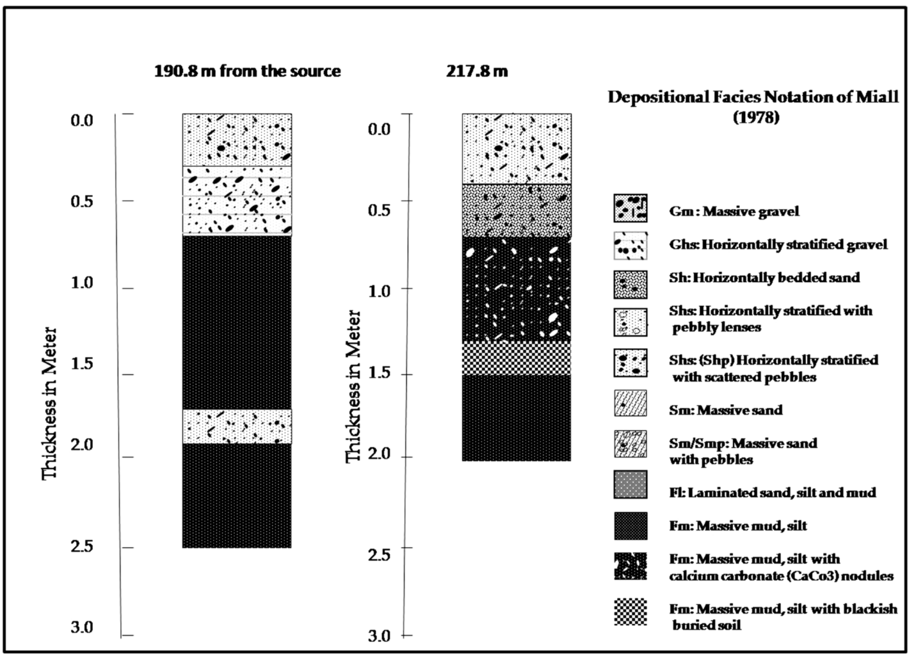

Fig. 7a and b : Lithostratigraphical characteristic of Pawnee sediments

58 in Deccan sediments. The colluvium at all the four sites reveals similarity in terms of its appearance, texture and topographic location. This could imply similarity in the depositional processes at all the four sites and other parts of the upland region and perhaps suggest its origin during the Pleistocene environment.

Sediment below 4 phi is very low (<5%) from all the samples analyzed from Pawnee, as compared to Deccan sediments. Silt and sand are almost of equal percentage here. This is contrary to what had been expected from these deposits. Percentage of finer sediments was expected to be more from the Pawnee sediments than the Deccan gullies when they were observed in the field. Though the stratigraphical characteristics of the sediments displayed the alluvial nature of the deposits beyond any doubts, it appears that these sediments were deposited in an environment with the depositing agents having higher energy than the former.

Longitudinal Profile Analysis

Longitudinal profiles of the gullies have been measured in the field using a Dumpy Level. The profiles are concavo-convex with several minor breaks along the profiles. The logarithmic profiles of these gullies are presented in Fig. 10. By and large, they reveal the characteristics of youthful energy delivery all along the streams. Ale, Pashan and Pawnee gullies are very identical in appearance while Chandanapuri and Wai gullies are similar in characteristics. The logarithmic profiles of all these gullies imply that they are all in the above-grade condition. Hack's Stream gradient Index (SL) of all these gully profiles has been calculated as follows (Hack 1973);

$$\mathbf{SL = h1 - h2 / lnL2 - lnL1}$$

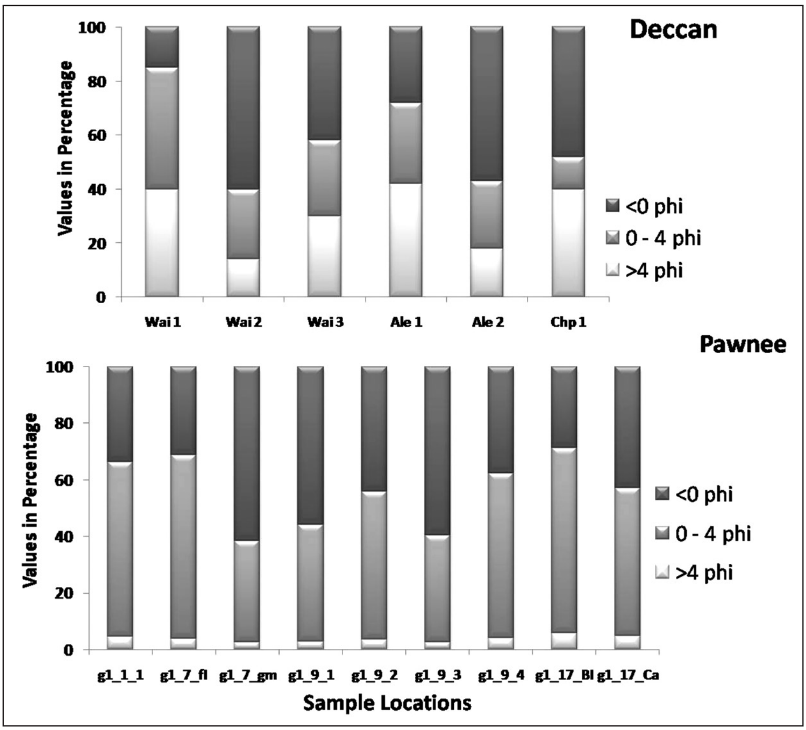

Fig. 9 : Textural characteristics of the sediments for both Deccan and Pawnee sediments

Where as:

1. SL is Hack's Stream Gradient Index
2. *h1* is the height of first point
3. *h2* is the height of second point
4. *L1* is distance from source of first point
5. *L2* is distance from the source of second point

** ln is the natural log

The results are presented in Table 1. SL value of Pawnee Gully is the lowest amongst them, suggesting that this has nearly reached the base-level. All the Deccan gullies are exhibiting marked concavity in the profile which indicates base-level control of the gullies. This is not observed in case of Pawnee gully.

Morphological Characteristics of the Gullies

The bankful width (w), depth (d) and gradient of these gullies at various sections were measured in the field. Standard statistical procedures were employed to determine the interrelationships of various channel and sediment parameters.

The morphological relationships reveal moderate correlations between distance from source (as a surrogate for discharge) on one hand and bankfull width (r2 = 0.19-0.92), depth (r2 = 0.02-0.91), form ratio (r2 = 0.03-0.67), and gradient (r2 = 0.31-0.92) on the other. Fig. 11 shows the correlation diagram which illustrates that in general, the width, depth and form ratio increase downgully, whereas the gradient decreases downgully. All the four Deccan gullies follow identical pattern, whereas Pawnee Gully is showing an opposite trend. Depth and gradient is increasing with distance. Intermediate diameter of the largest clast (a measure of flow competence) exhibits an inverse relation with distance in case of Deccan gullies, whereas Pawnee sediments show little variations. The link suggests a general down-gully adjustment in the channel morphology and implies a balance of form and processes at least for Deccan gullies and these gullies mature by increasing their width, form ratio and sinuosity and by reducing their depth and gradient. Form ratios of all these gullies are relatively low, representing a deep cross-section, which indicates high hydraulic efficiency. As flow depth rises in these narrow channels, flow velocity, stream power and shear stress all increase to immensely increase erosional capabilities of these channels. Gully size and gradient relation is depicted in Fig. 12. The diagram shows a distinct 'S' shaped plot and it does not exhibit a steady decrease in channel gradient with an increase in width. This suggests non-systematic changes in channel morphology. The trend does not support the oft-quoted opinion that river channel gradient decreases as width increases. Numerous within-gully head cuts and man-induced alterations along the gullies may have caused the deviations in the relationships, where ever they are found.

Table 1 : SL Index values of the gully profiles.

No.	Gully	Average SL index value
1	Ale	18
2	Chandanapuri	14
3	Pashan	13
4	Wai	14
5	Pawnee	4

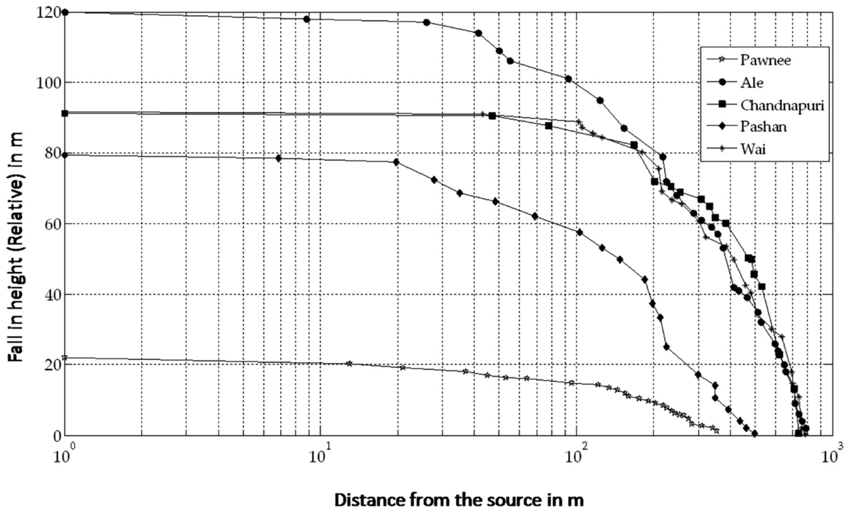

Fig. 10 : Longitudinal gully profiles of Deccan and Pawnee

Processes of Gully Development:

The gullies under review in Deccan Province of India are believed to have been formed following the Holocene base-level shift, though the present morphological characteristics have been largely modified by the present hydrological conditions (Joshi and Kale 1997). Field observation and analysis of the sediment and morphometric parameters also assist this finding. In common with the rest of the inter-tropical regions, the Deccan experienced climatic changes during the late Quaternary Period (Kale and Rajaguru 1987). In western India, variations in precipitation, rather than temperature changes, have been deduced. Geomorphological and sedimentological evidence of climates drier than those at present, with episodic and flash floods and stronger winds, have been inferred for the study area by earlier workers (Kale and Rajaguru, 1987). Alternate wet and dry periods at the end of Pleistocene Period saw the initiation of the colluviation on the pediment slopes and gullying occurred as a response to the following Holocene wet phase (Joshi and Kale 1997).

Absence of vegetation generates widespread Hurtonian run-off after heavy rains, inducing rilling and gullying. Gully development was also favored by high silt content and their proximity to steeply sloping barren hills. However, there are two generally accepted thresholds for rills and gully developments on loamy soils, such as, 20-30 for rills and 120-160 for gullies. Permanent gullies do not develop on slopes between 20 and 30 (Savat and Ploy 1982). These gullies have been developed on pediment slopes of less than 30. This raises the question of the importance of surface wash as the predominant process involved in gullying in these sites. Absence of pipes, sink holes and seep caves also suggest that sub-surface flow also has not been involved in their development. Strengthening of the monsoon in early-mid Holocene induced the main rivers to incise.

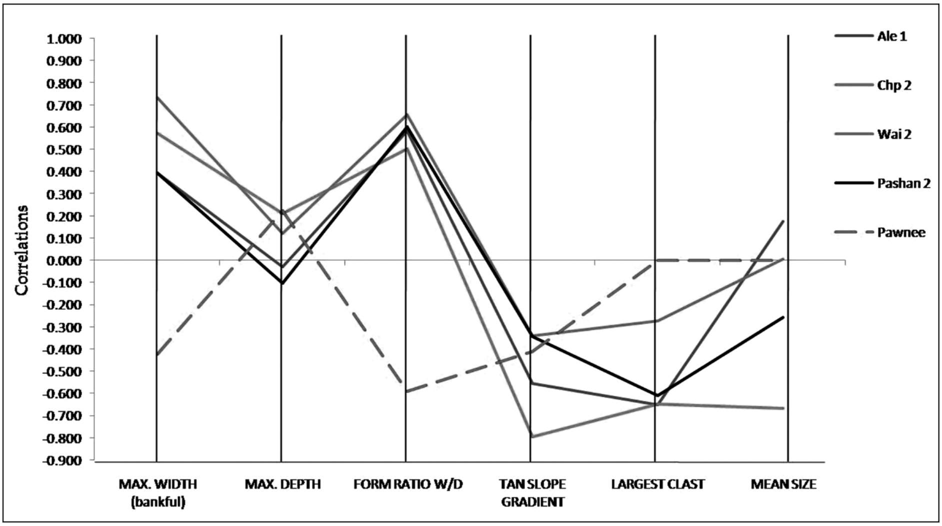

Fig. 11 : Correlation diagram (Distance Vs other variables) for both Deccan and Pawnee gullies

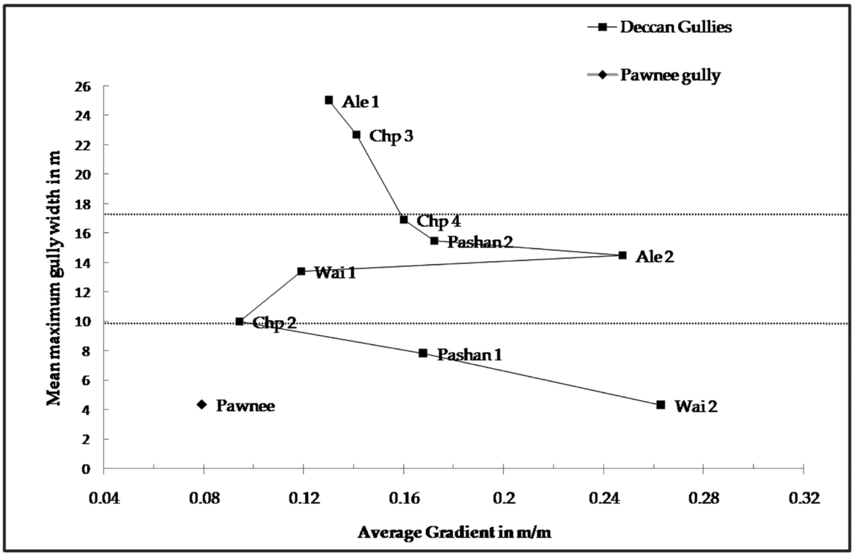

Fig 12 - Gully size and gradient relation for both Deccan and Pawnee gullies

Hillslopes and pediments responded after a huge time lag. Vegetation-free friable colluvium provided low shear stress to erosional forces of increased surface wash and rapidly lowering base-level and gullies were initiated in these foothill zones. Gullies developed and expanded by headward erosion and incised rapidly. Incision along the meandering courses by eroding the outer banks leads to channel widening. The characteristic V-shaped channels, high gradient and depth favors efficient energy concentration in the channel during monsoons and gullies incise and cut through friable colluvial material without much difficulty. The absence of overbank deposits clearly suggests that gullies increase their flow capacity by deepening their channels and altering their morphology and there is no time lag for channel response to high flows. These gullies enlarge during the high flows to accommodate excess discharge and therefore no overbank discharge occurs. The morphological characteristics of the gullies are analogous to large systems, on a different scale.

Pawnee revealed similarity in the morphological parameters with Deccan gullies in many respects and differed in some. On the basis of the analysis of a single gully, it is difficult to conclusively determine the origin but on the basis of the general understanding of the region, coupled with the behavior of the gully in comparison with the other Deccan counterparts, the gully forming mechanisms in Grasslands of Colorado (Pawnee) has been presented as below;

Erosion resistance of a soil or bedrock is in terms of a threshold shear stress, which is expressed as;

$$D_C \propto \tau^{\alpha} - \tau_C^{\alpha}$$

Where;

Dc represents the detachment capacity

τ is the bed shear stress

α is a parameter that depends on the derivation of this equation

$\alpha = 1$ for a linear shear stress model (Howard and Kerby 1983)

and $\alpha = 3/2$ for a unit stream-power model

(Whipple and Tucker 1999, Moore and Burch 1986)

In the present context, $\alpha = 1$ for a linear shear stress model (Howard and Kerby 1983) has been employed.

The thick vegetation carpet all over Prairies of North America offers a strong erosion resistance to surface erosion. In the presence of vegetation, some portion of the applied fluid shear stress will be expended on plants rather than on the soil directly; this effect is especially pronounced when grasses are flattened by overland flow, forming a barrier between the flow and the soil surface (Foster1982). The erosion threshold will also reflect both intrinsic soil cohesion and effective cohesion imparted by roots. Therefore the threshold value required to overcome these grass covered surfaces is several magnitudes higher than bare surfaces. This hundredfold contrast in erosion threshold between bare soil and full herbaceous cover implies a significant role for vegetation as a mediator of channel formation and development in these regions.

A great deal has been written on arroyo networks formed in these rangelands, particularly those in the Western United States that focused on the understanding of the triggering factors and overgrazing has been considered as one of the most important triggering factors (Antevs 1952, Graf 1988). Under the natural conditions, initiation of gullies on these grasslands doesn't owe their origin directly to overland flow, but to a conditional instability that is established under certain conditions which can overcome the strong erosion threshold provided by the grass carpets.

The following three conditions seemed to have been responsible for the gully formation in these areas.

1. A resistant vegetation layer overlying an erodible substrate, which sets up a conditional instability through which erosional perturbations can grow by positive feedback (Tucker et. al. 2006).
2. Summer thunderstorms, which can with reasonable frequency (3–5 yr) generate boundary shear stresses high enough to penetrate the highly resistant vegetation armor, but only within erosional hot spots where hydraulic forces are amplified by channel constriction and locally steep gradients (Tucker et. al. 2006).
3. Moderate to high substrate cohesion which prevented a growing erosional perturbation from being rapidly dissipated by bank collapse and channel widening.
4. A high volume fraction of fine-grained erodible material.

The observed process dynamics implies that long-term rates of valley incision should be especially sensitive to climatic oscillations between episodes of drought and warm-season convective rainfall. In the context of the American West, the greatest susceptibility to channel incision occurred when the return of convective summer rain marks the end of a significant drought cycle. The middle Holocene (ca. 5–7 ka) has historically been considered a maximum in summer monsoon rainfall during that period. This period saw more vigorous behavior during the early-middle Holocene (as well as near the Pleistocene-Holocene boundary and the late Holocene Neoglacial. These arroyo systems are very sensitive to climate variability and are zones of concentrated geomorphic activity. Alternating episodes of drought damages vegetation and potentially reduce erosional resistance by an order of magnitude and intense summer convective storm activity generates high boundary shear stresses, which provides a plausible mechanism for a climate-driven initiation of these channels and acceleration in denudation rates in these regions.

Conclusion

The nature of gully development and enlargement is complex and a general model doesn't seem to apply in all the environments. Based on the field observations, data analysis and general understanding of the areas under review, it appears that gullying in both the environments were initiated as a response to Holocene climate change. Several proxy evidences suggest these findings. However, their response to this climate change differed widely. In case of Deccan gullies, strengthening monsoon in the early Holocene induced incision of the main channels and a general base-level fall. Gullying along the pediment slopes occurred as a result of this base-level drop. Once initiated, there was very little resistance from the loose, bare colluvium surfaces and the gully network expanded. In case of Pawnee Gully, a sudden humid phase in the mid-Holocene after a long draught cycle generated a conditional instability and reduced the erosional resistance of these grass- covered surfaces and induced gullying. It is also broadly consistent with dating of Holocene channel fills in the study areas (Arnold 2006, Arnold et. al. 2006). Long-term multiple measurements can provide data required to assist further understanding and to quantify gullies in terms of gully mechanics and morphology.

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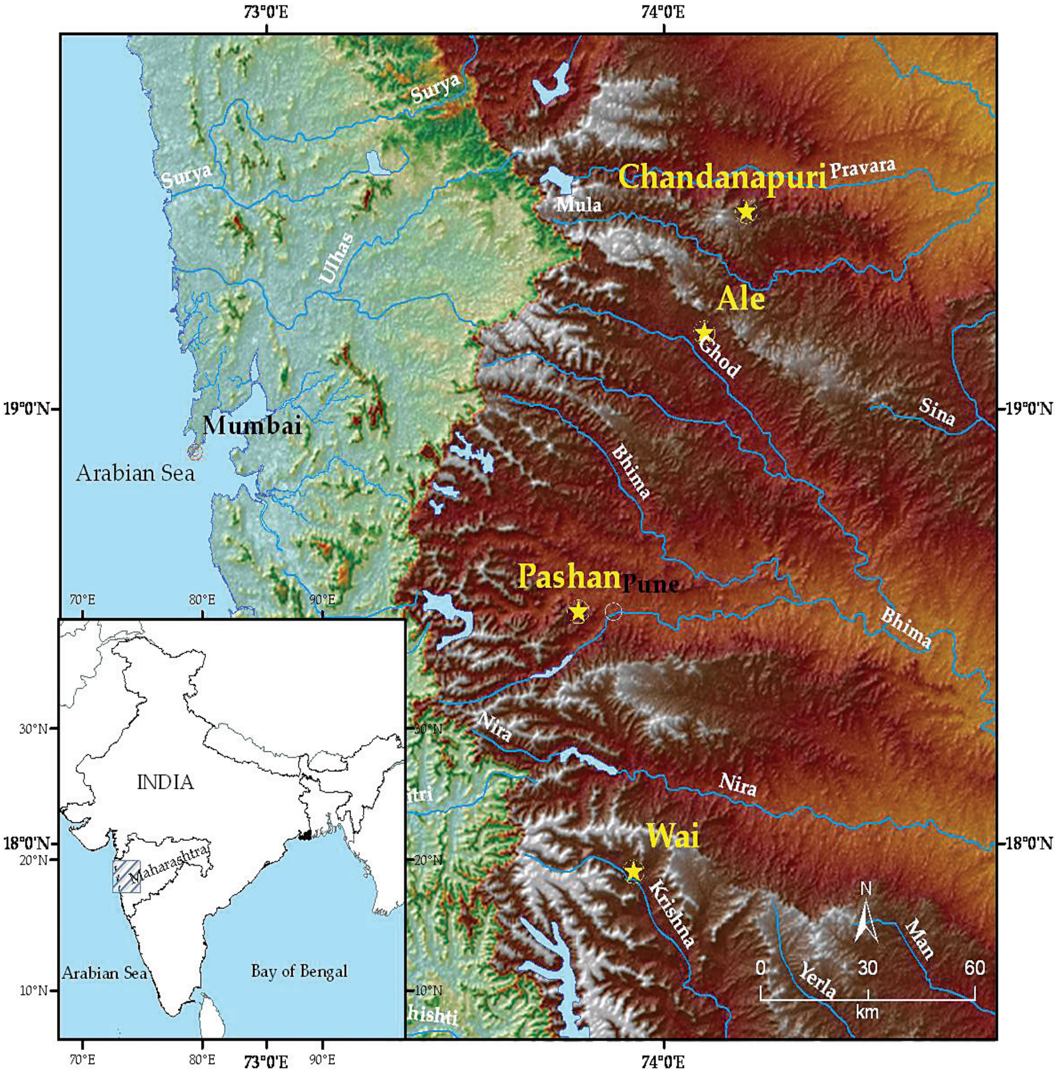

Fig. 1 See page 107 for text

Fig. 2 See page 107 for text

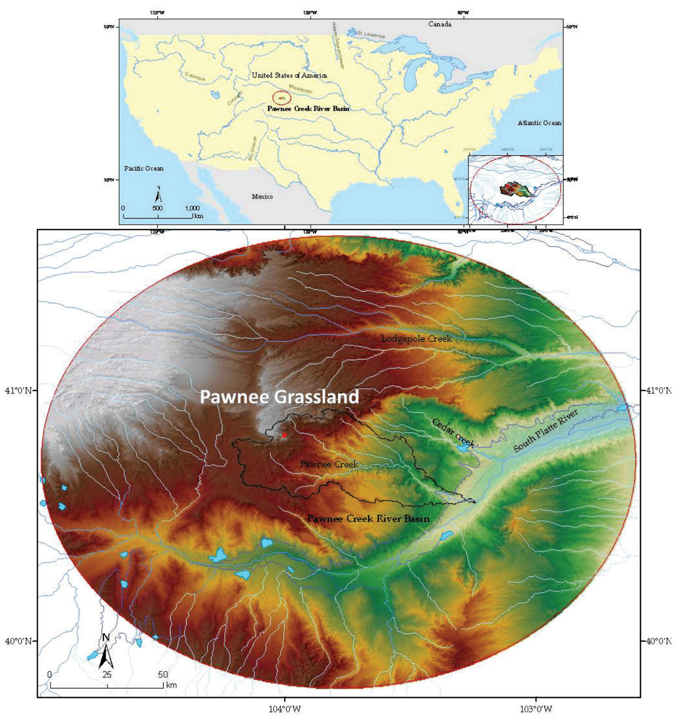

Fig. 3 See page 107 for text

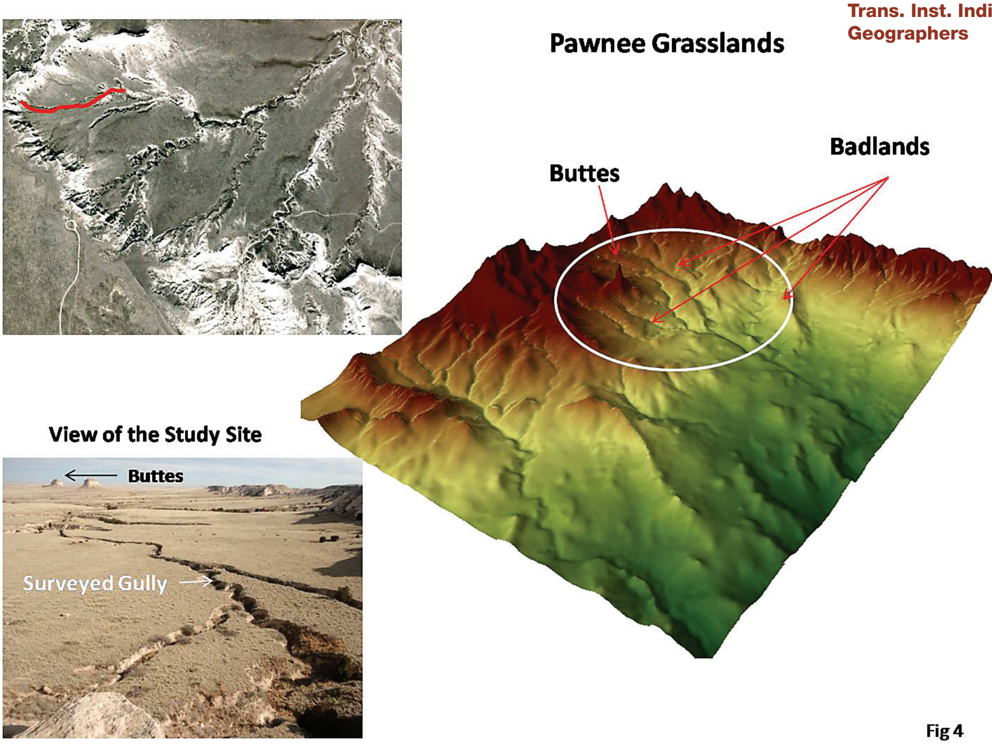

Fig. 4 See page 107 for text

Fig. 6 See page 108 for text

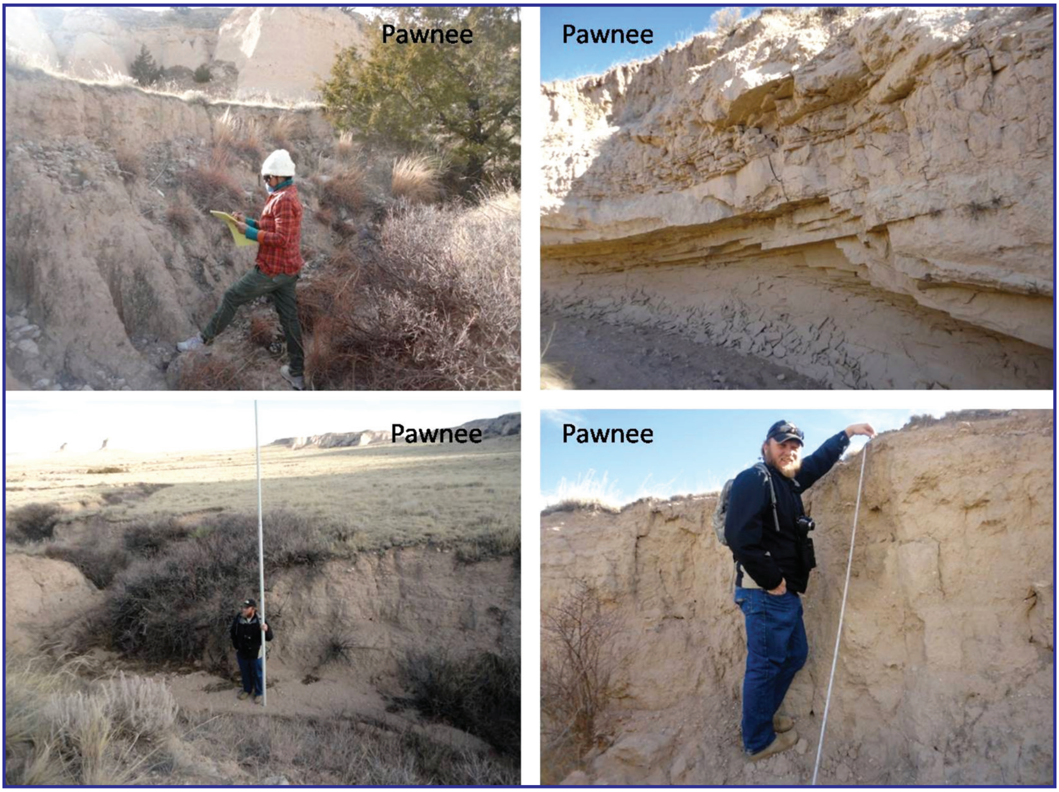

Fig. 8 See page 108 for text