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Formation of river cliffs is a necessary prelude for the development of ravines: A discussion

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Abstract

Genesis of ravines has not been fully understood, though the subject has been studied by several scholars, belonging to different disciplines. A consensus eludes as to which factors have created these eroded lands and which natural events or human activities have contributed to their formation. However, it has been accepted by most authors that ravines, called badlands in the West, have been crafted by innumerable ephemeral streams in which water flows only during rains for a short duration. There are different views on the spots of their origin and process of evolution. In the earliest stage of evolution, according to the widely popular Horton's theory, the number of rills is eroded by overland flows at a critical distance from the divide. Streams that developed during the period of investigation at the terrace along the bank of an old gully in the Yamuna ravines at the Gailana Research Centre do not support the rill concept of Horton's theory. Another noteworthy feature of these streams was that they did not have segmented channels in the beginning phase, as has been envisaged by Leopold and his co-workers in their theory of discontinuous gullies. It shows that neither Horton's rill theory nor the concept of discontinuous gullies of Leopold is valid in the study area. Deforestation and climatic changes of the mid-Holocene times are considered the main causes of ravine formation by many researchers. It is well-known that these were global events and they had affected large parts of the earth. But ravines have formed only an insignificant proportion of these lands. This fact is strong enough to reject the theory of deforestation and that of climatic change. Neotectonic events of uplifting have definitely played a significant role in creating badlands. These epeirogenic activities lowered the beds of the rivers and produced vertical cliffs on their banks which are essential for the evolution of ravines.

Keywords: *Ephemeral streams, cross-grading, gullies, River cliffs, badlands, neo-tectonism, belt of no-erosion*

Introduction

Ravines are areas of mini-drainage basins of ephemeral streams. These streams are very small in size rarely exceeding 2 Km of length in the Chambal and the Yamuna ravines. But they possess incredible erosive energy. By lateral and vertical corrasion, they have caused such a massive dissection of land along the banks of these rivers that the original ground exists only as narrow flat strips of land and sharp-edged crests of divides. In terms of drainage density, ravines are highly eroded lands. In the badlands of

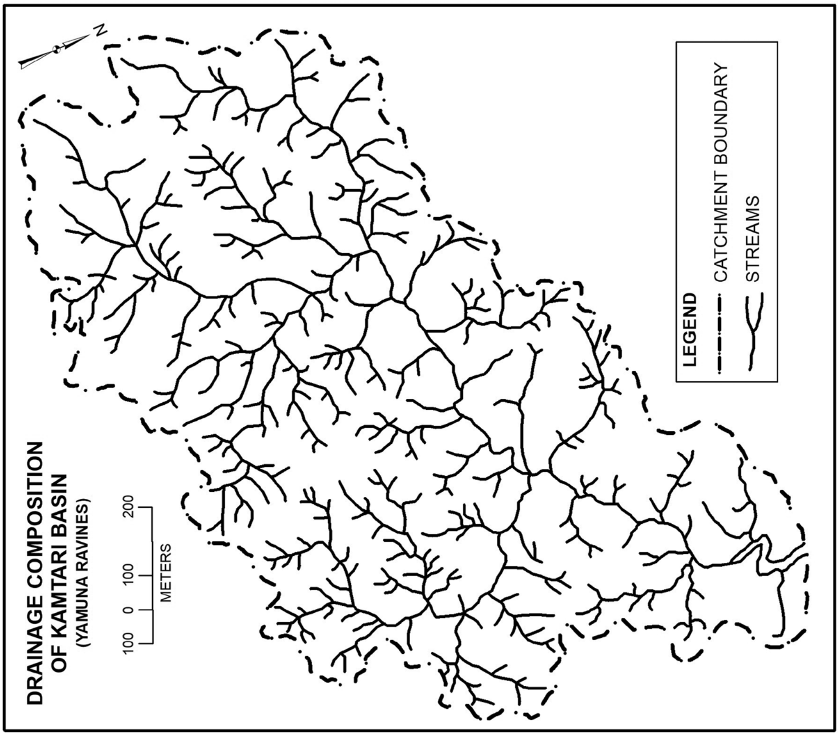

Fig. 1: Kamtari Basin, Yamuna ravines

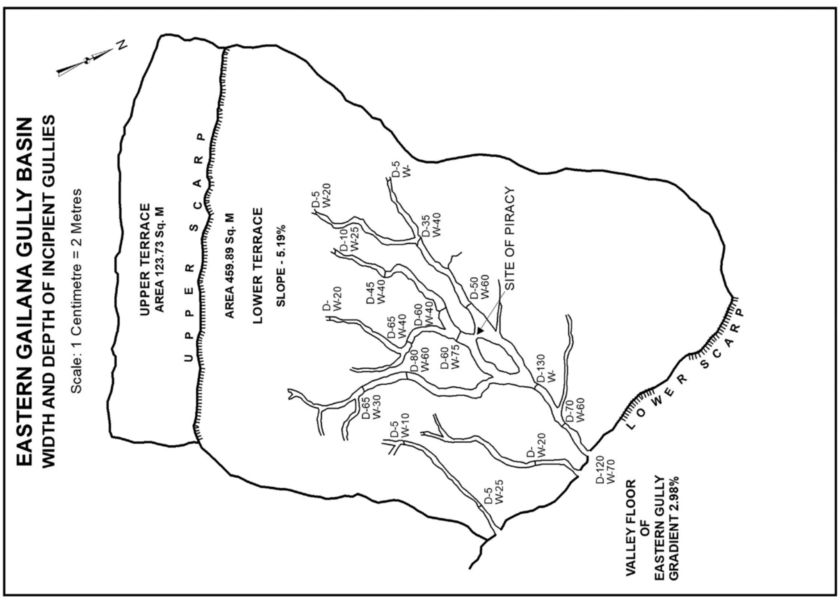

Fig. 2: Gailana Gully Basin, Yamuna ravines

Perth Amboy in the U.S.A., drainage density was found to be as high as 602 miles per square mile. In the Kamtari gully basin near a village of the same name in the Yamuna ravines, the drainage density of 27.24 miles per square mile is very low in comparison to the density of the Perth Amboy badlands. The reason for the low values of density is that a large number of small streams did not appear on the map of the Kamtari basin on account of its small scale (1 inch = 200 ft), while the map of Pert Amboy terrace was surveyed on the much larger scale of I inch = 10 ft with a contour interval of one foot.

From the genetic point of view, the ravines of the Chambal and the Yamuna rivers are polycyclic landscapes, containing landforms of at least two cycles of erosion. Terraces, found at different elevations in wide valleys of large gully streams, and the presence of nicks in the water courses of rivers and large gully streams are the confirming evidence of the multi-cyclic origin of these ravined lands. In the drainage networks of the region, tributaries join their master streams at acute angles suggesting a drainage system of dendritic pattern. The initial paths followed by the streams have been dictated by the regional and local slopes of the area.

Enormity of the problem

According to a report from the Indian Council of Agricultural Research, ravines in the country have already converted 3.975 million hectares into wasteland. Their continuing advance has taken a tall eight hundred hectares of agricultural land every year (Anonymous, 2016). To bring the ravine lands under plough again and save the adjoining areas from encroachment by headward advancing gullies is a big challenge for the country.

The ravine erosion problem is not confined to India alone. Several countries of the world like the U.S.A., Spain, Italy, Russia, Israel, and the U.K. are also affected by this problem. It is now being increasingly realized that more intensive research with a thrust on the genesis of ravines is needed, although valuable contributions have been made in this regard by scholars working in hydrology, geology, geomorphology, engineering, and geography. Some theories have also been formulated to explain the mechanism of their formation. The present study aims at evaluating the role of the responsible factors and theories that explain the genesis of ravines.

Database and Methodology

Data in the study have been obtained mainly by measurement from the maps of two drainage basins of the Yamuna ravines (Fig. 1 & 2). One of the two is the map of a drainage system of an old gully named Kamtari Basin where the streams are firmly established in their deep channels. The other is a basin of recent origin in which streams started emerging in the rainy season of the year of 2002. These streams are in the early stage of their evolution, still deepening their channels and enlarging their network. Direct measurements were also made in other parts of the study area where new streams were created or the old ones extended after a spell of heavy rains. In the selection of the sites of sample basins, random sampling was not used for two reasons. One, in morphology, the ravines are similar in the entire lower basin of the Yamuna and the Chambal. It is also a fact that the physical and cultural environment in the region is homogeneous permitting generalization for the whole region. Two, only those points were selected which were easily approachable by road.

Each major climatic and geologic event of the past brings about some changes in the morphology of landforms of a region. Extensive traversing of the area was done in order to find evidences of such changes. Existing theories and models were supported or rejected in light of these evidences.

Identified factors

Important factors generally held responsible for the formation of ravines include depletion of natural vegetation, climatic change, neo-tectonism, and ill-conceived farming practices.

Depletion of vegetation

The devastating dust bowls of the 1930s which swept away the fertile soil from the vast areas of the Prairie plains of America made scientists believe that vegetation offers the best protection against erosion by winds and water and that its removal from the ground surface initiates soil erosion which finally ends up in the formation of badlands or ravines. The development of badlands in the grass-carpeted Pawnee plains in Western Colorado (U.S.A.) shatters this myth. It may be a mere coincidence that in many areas of the U.S.A., badland topography has developed in areas where vegetal cover was destroyed either due to natural events or human activity. For instance, in the Duck-Town Copper basin of the Tennessee River, badlands developed over an extensive tract of 27.1 Km^2 where the natural vegetation was destroyed by the release of toxic fumes from a smelting plant. According to Schumm (1956), this is the largest badland topography in the humid climate of America. He discovered another area in the country where an eroded landscape emerged because its vegetation was destroyed by volcanic dust. These instances supported the deforestation theory of the development of badlands. Schumm (1956) for example argued that surfaces without vegetation have no protection against erosion where fluvial forces carved out channels easily. Jacks and Whyte (1955) in their world survey of erosion held deforestation being the principal cause of ravine formation in India. This view received strong support from the authors of the model of discontinuous gullies (Leopold, et.al, 1964) and Gram (1984) who state that gullies originate in swales and shallow depressions of the ground where severe depletion of vegetation has occurred on account of deforestation, overgrazing, or by any other human activity of extractive nature. Deforestation theory became popular among researchers after the mid-1950s (Kual, 1961; Roy *et al*, 1969; Tejwani, *et al* 1960; Bali, 1967; Bhusan, et.al., 2002; Joshi, *et al*, 2013). However, this opinion of scholars seems to be purely speculative and unsupported by robust evidence. Had the destruction of vegetal cover been the principal cause of ravine formation, the Indo-Gangetic plains of the country would be ravine lands, because forests and all other types of natural vegetation were wiped out from these plains when agriculture was introduced in the area. In removing the vegetation to get land for farming, a brutal method of *slash and burn* was used. But ravines actually developed along the banks of a few rivers only in an area that is an insignificant fraction of the 700,000 km^2 area of the Indo-Gangetic plain. It is inexplicable as to why ravines did not develop in the entire deforested lands leading to a belief that removal of vegetation is not an important factor in the evolution of ravines. Sharma (1976, 1979, 1990, and 2009) for instance considered deforestation as a causal factor of ravine formation but finally, he rejected this theory because he could not find sufficient evidence in support of this general view.

Maximum damage to natural vegetation has been done by wildfires. The U.S.A. is perhaps the worst affected by wild blazes. In 1871, a wildfire destroyed forests from 3.8 million hectares of land in the Michigan and Wisconsin states. In January 2021, a forest fire destroyed large areas in Uttarakhand, Himachal Pradesh, and Nagaland. As a matter of fact, wild blazes destroy jungles, mostly in the Himalayan states of our country almost every year. After every incident of forest fire, the ground remains virtually exposed for several years during which the erosive agents of denudation are expected to create badlands in these lands in a relatively short period. But eroded landscapes have not evolved in these fire-affected areas. It suggests that the complete removal or depletion of vegetation is not the sole cause of badland evolution.

At present, all the cultivable lands of our country are being used for growing a variety of crops by farmers who do not have any formal training in farming. Soil conservation scientists in the country believe that these farming practices are faulty and accelerate the rate of soil erosion which leads to ravine formation. Along the bank of the Yamuna and the Chambal, the authors of the paper have met several farmers who own lands on both ravine-ravaged sides as well as on the opposite side of the river bereft of ravines. It is unlikely that the farmer is wise on the ravine-free side of the river armed with erosion-resisting practices and is unwise on the other side by following faulty techniques and allowing fluvial forces to convert his fields into an eroded landscape. Evidently, neither deforestation nor unscientific farming practices are the major factors in ravine formation.

Climatic change

Climates have changed in the past. During the recent ice age, a large part of the northern hemisphere was covered with thick sheets of ice. The Ice Age ended with the retreat of the ice sheet to the present position around the North Pole. The Holocene Age that followed was a period of warm conditions. Two climatic events in this period have been associated with the evolution of ravines according to some writers. In the first phase, the world experienced hot and dry conditions engendering severe depletion of vegetation. Ground surfaces devoid of the protective cover of vegetation became vulnerable to erosional forces. Thereafter arrived a wet phase with heavy rains over large areas of the world. Daniel (1994) is of the view that the badlands of the Pawnee Grasslands in Western Colorado (U.S.A.) owe their origin to the arrival of this wet phase of the climate. In India, stronger monsoonal rains were received for several hundreds of years. From the study of the drainage basin of the Pravara River: a tributary of the Godavari River, Joshi (1994) concluded that heavy downpours were responsible for the birth of ravines in the area. A few years later, the same basin was studied by the author in collaboration with Nagare (Joshi and Nagare, 1913) to contradict her earlier findings by attributing neotectonics as the major player in the evolution of ravines that rejected the theory of climatic change as the trigger. They concluded that; the climatic change of the mid-Holocene, like all major climatic events, was a global phenomenon that affected large parts of the earth and that, its impact cannot be so selective to create badlands only in a few areas of the earth's surface.

Fig. 3: A tall cliff on the right bank of Yamuna at Bateshwar, Bah Tehsil, Agra district

Fig. 4: Cliff-less banks of Yamuna at Rohn Kalan, Raipur village, near Agra

There is a stronger ground to disapprove of the climatic concept. According to Overpack and his co-workers (1996), Indian monsoons became exceptionally strong twice during the past Twenty thousand years. The first episode of heavy rains took place about thirteen thousand ago and remained active for a short period of 500 years. About 9.5 thousand ago (Overpack *et al.* 1996), India experienced another phase of heavy rains that ended about 5.5 thousand years ago. If ravines owe their origin to these two phases of heavy rains, the process of formation of ravines in India would begin some 13000 years ago and would be intensified during the second phase of abnormally heavy rains. On this basis, the age of the ravines would be about 13000 years. But there is little evidence to support that badlands are so old in the country or in any other part of the world. Most researchers conclude that these eroded lands are not older than a few hundred years. According to Habib (1963) eminent historian of India, the Chambal ravines belong to the pre-Mughal period, which means that the process of ravine formation must have begun sometime during the 13th or 14th century. Two western earth scientists, Jacks and Whyte (1955) discovered that Yamuna River has lowered its bed by 60 ft. near the Etawah city of U.P. during the last 500 years. As a consequence, cliffs of almost the same height were formed on the bank of the river here and other parts of the river basin. The presence of cliffs is essential for the formation of ravines. It means that the process of ravine formation started about 500 years ago when cliffs appeared on river banks. Misra *et al.* (1994) have also concluded that ravines are only a few centuries old. It is thus clear that the process of formation did not start 13000 thousand years ago and it is unrelated to the arrival of the wet phase of the mid-Holocene times.

Neotectonic movements

Indian geologists are of the view that neotectonic movements, which commenced about 1,000 years ago have played a dominant role in the evolution of ravines (Singh, 2005, Agarwal *et al*, 2002). Surface evidences like incised rivers, vertical river cliffs, preferential alignments of water courses, uplifted earth blocks, abrupt changes in the river courses, two-storied terraces along gully banks, etc., suggest that neotectonic movements were stronger in the entire trans-Yamuna plains. This cannot be a mere coincidence that the deepest ravines of the country have developed in this region. This fact lends support to the neotectonic theory.

Uplifting and faulting, the two main activities of neotectonism influenced ravine formation. Rise in the source region of the Yamuna and the Chambal, which occurred at least twice in their life history, steepened their bed gradient and thereby renewed their eroding energy. The same function was performed by faulting. Activation of the Mathura-Moradabad fault, caused by the up-throwing of the north-western block presently known as Delhi Ridge made the slope gradient of the Yamuna steeper in the downstream area. It rejuvenated the river. The formation of ravines along the bank of the river is the direct outcome of this incident (Fig. 3).

On the basis of the presence of vertical cliffs on the banks of the rivers, geologists of the country agree that uplifting and faulting have caused deep entrenchment of all the rivers of the region. Surprisingly, however, there are long segments of Yamuna River where the river has not been entrenched at all affected by uplifting and faulting. For instance, in the east of Agra city, near the Rahn Kalan Raipur village, there is no sign of incision of the river course. No cliff exists on any of its banks in about 10-kilometer length. Here, the river flows in an open wide valley virtually with flat banks (Fig. 4). Gently sloping alluvial plains stretch endlessly from the river on both sides. It is not believable that a river will be entrenched in one part and remain un-trenched in its immediate neighboring area. Another anomaly exists in the 70-kilometer stretch of the river from Mathura to Agra where evidence of entrenchment exists only on one side of the river in the form of cliffs while the other side has no cliff.

Relevance of Horton's theory

Horton's theory is perhaps the best available explanation of the evolution of erosional streams and their drainage basins where he explains how streams originate and create badlands through their erosive action. According to him, overland flow is non-erosive near the divide because of the small volume. As it moves downward, its volume is progressively increasing by the addition of the runoff from the downslope areas of the catchment. At some distance from the divide, it acquires enough volume to start cutting rills. This distance is called critical distance and the area in which rills are created is a rill zone. The area around the divide, where the channels are not eroded by the runoff is "a belt of no erosion". The presence of a dense network of rills on the side of an abandoned brick kiln from its top to the bottom does not support Horton's concept of a "belt of no erosion". It also negates his argument that runoff has to travel a certain distance from the divide to get the required depth and volume to erode channels.

According to Horton's theoretical model, there are three erosional zones in a drainage basin: the zone of sheet erosion, the Zone of rill erosion, and the gullied zone. In the Chambal and the Yamuna ravines, rill zones are not seen in the upper catchments of the streams. The adjoining alluvial uplands of the ravine belts constitute the upper catchment of the principal streams in the region. Master streams and many tributaries originate in these alluvial plains which are divided into small agricultural fields, having 30-40 cm high earthen boundaries. At the margin of the ravine belt, field boundaries are made higher to check the advance of upward-moving gullies from the adjoining ravine belt. During heavy storms, accumulated rainwater in these fields, often, breaches the lower boundaries at weak patches like cracks or holes. Moving with great force towards the points of breaches, this water invariably erodes long gullies in the fields. A 10.05-meter-long gully with a depth varying from 0.31 meter to 1.67 meters was created by the rains of a single day on July 5 in the year 1972 in a Bajra (millet) field at the bank of master stream of Chambal ravines in Nandgaon village in Bah *tehsil* of Agra district. Contrary to Horton's theory, no rill was seen in the upslope part of the field. The development of cracks in field boundaries during hot summers is a common phenomenon in the region. In other parts of the region also, where new gullies came into existence during the period of investigation, no rill zone was created in the upper areas of these gully basins. The present is the key to the past. Hence, it may be presumed that ravines along the banks of the Yamuna and the Chambal have been produced by streams, which might have originated in this manner in the agricultural plains which once extended up to the river banks.

A drainage system has evolved on a terrace along a 1.27-meter-high vertical bank of an old gully in the Yamuna ravines at the experimental site of Gailana village during the period from 2002 to 2005. The terrace is a small uncultivated piece of land, with an area of just 459.89 meters2 and a gentle slope of 5.19 percent. After the first few monsoonal rains of the year 2002, small depressions of irregular shape appeared on the ground. In subsequent rains, these impressions were enlarged. Water overflowed from the upper depression to the lower one. Finally, they took the form of streams. Within two years, a third-order drainage network evolved which had nine first-order streams and two second-order streams as its tributaries. All the first-order streams had scarps of mild heights of 5 to 9 cm at their heads. The master stream joined the old gully at its east-facing vertical bank. By the year 2005, all the streams of the drainage system were fully established in permanent channels.

A noteworthy feature of this drainage system was that rills did not appear in the upper part of the catchment before the birth of the streams (Bhan, 2005). This fact was also noticed in all the agricultural fields on the margin of ravine belts in which the birth of several new gullies takes place during each rainy season. Leopold et.al. (1964) have also discovered areas on the ravined hill slopes in the semi-arid regions of New Mexico where the surface flows did not create rills. Studies conducted in the southwest regions of the U.S.A. have shown that gullies or arroyos do not result from the enlargement of rills (Morgan, 1979). These surface evidences do not lend support to some concepts of Horton's theory. However, the rill concept has been supported by Schumm (1956) in his study of badlands of the Perth Amboy terrace revealing that a number of rills developed on the slope in front of a cliff in the initial stage. All these rills, according to him, have their origin at some point near or at the base of the cliff, from where they move upward. Some of these rills succeed in crossing the top edge of the cliff and land themselves on the surface of the adjoining upland. The most aggressively eroding rill among them degrade a deeper channel than its less active neighbour and becomes the permanent stream exactly in a manner envisaged by Horton. Thus, he approves Horton's mechanism of stream evolution though he differs with Horton's view that the action of the runoff is related to the increase in discharge at increasing distances from the divide. In his opinion, neither distance nor increased discharge downward from the divide modifies the action of the runoff. He explains that the continual addition of sediment load in the runoff from the downslope areas reduces its eroding and transporting energy.

Role of river cliffs

A visit to any ravine land in the world reveals three facts very boldly. One, river cliff is the most dominant landform of this landscape. Two, ravines are present in every segment of a river, where it has a cliff on its bank. The dimensions of ephemeral streams and their erosive power are directly correlated with the heights of the cliffs. Long streams cut deeper gullies, where cliffs are high, are shorter and have carved out shallow valleys in areas of low cliffs. The spatial spread of ravines also varies in direct proportion to the heights of the cliff. For instance, there is a consistent increase in the height of the Yamuna cliffs from the southern outskirt of Mathura city downward up to Agra city. The same pattern of progressive increase is seen in the size of the ravined area. In the area of low cliffs near Mathura, gullies are shallow, and the width of the ravine belt is only tens of meters. Around Agra, where the cliffs have attained elevations up to 6 meters, the depth of gullies has a range of 4-5 meters. In the region, the ravine is much wider. In Bah tehsil of Agra district, Yamuna and the Chambal have towering cliffs. The cliffs of the Yamuna at Bateshwer and Rudmuli village are higher than 30 meters. Ravines have also attained the most fearsome form and awesome size in this zone. This is the highly dissected part of the Yamuna basin where gully depths of 15 to 20 meters are not uncommon. Even at the points of origin, gully streams have great depths, measuring 8 to 12 meters in this area.

In the plains behind the northern side of the Yamuna from the neighborhood of Mathura city up to Dyal Bagh suburb of Agra, there is no rill or gully development, while on the other side of the river, the uplands behind the cliff have a dense network of gullies

Fig. 5: Ravine-free plains opposite severely gullied side of Yamuna (Gailana Village, Agra)

Fig. 6: A fast eroding gully along the livestock trail, Yamuna ravines Gailana village

(Fig. 5). In the neighborhood of village Rahn Kalan at a distance of about of 10 km from Agra, gullies are absent from the sides of the river. In this segment, Yamuna River has no cliff on any of its banks. In contrast, in the plains in the downstream region of the river, ravine erosion has occurred at a massive scale. Lithologically, geologically, climatically, and culturally, the gullies and the un-gullied areas on both sides of the river are amazingly homogeneous. All the factors that have been held responsible for the origin of gully streams by many researchers are present in this stretch of the Yamuna uplands. According to Horton, for example, a runoff requires a minimum thickness, and a rainfall of sufficient intensity to erode channels. A minimum depth of 5 mm of runoff is required to enable it to erode channels (Kirkby *et al*, 1980). According to Hudson (1971), a rainfall of the intensity of 25 mm per hour is needed to generate the required volume runoff. Morgan (1971) is of the opinion that an intensity of 10 mm per hour is enough for the development of rills and gullies in British conditions.

Monsoonal rains are described as torrential for their high intensities generating runoff which has volume and thickness more than what is required for the evolution of ravines. There is only one factor that is absent in the un-gullied sections of Yamuna plains. It is none but the cliff. It proves that the presence of river cliffs is essential for the evolution of ravine landscapes. Cliffs activate the fluvial forces to commence the massive task of land dissection which finally results in the evolution of ravines along river banks. In the absence of the cliffs, these forces become passive agents of denudation, unable to cause channelized erosion. This is the reason why ravines have not evolved in any part of the world where rivers sans cliffs along their banks. Schumm (1956) has derived the same conclusion from his study of the badlands of Perth Amboy. He states in his concluding remark that for the evolution of badland topography, upland must have a cliff or a very steep slope front on its side, facing the river. From all this evidence, it may be inferred that the formation of river cliffs is a necessary prelude to the evolution of a ravine landscape.

At the experimental site of Gailana and other parts of the study area, it was discovered that all the new streams had one point of their origin and they carved out a single continuous channel. None of them commenced their journey from the number of depressions of the ground in segmented channels, as conceived by Leopold *et al* (1964). The theory of discontinuous gullies by the authors, no doubt, became very popular among the researchers but it is not substantiated by surface evidences in the Chambal and the Yamuna ravines. Depressions of varying sizes and shapes do exist in all parts of the study area and fresh gully streams have commenced from there in some cases, but they scarcely correspond to Leopold's model. Spoon-shaped cavities at river banks are invariably created providing easy access to the river to the villagers and their cattle. Gullies originate at such points, if there is a sufficient supply of rainwater from the background area. Such gullies follow human or animal trails in their upward journey and grow relatively faster (Fig. 6). Most favorable locations for the evolution of a stream are those where village drains make a cut at the edge of the steep bank of some river or gully. It was discovered that gullies of the Chambal and the Yamuna basins which have developed at the terminal points of village drains, degrade their beds deeper and extend their lengths at great speed.

Water, falling from a drain in Pinahat town has not only created a very deep gully but it has exposed the foundation of houses, located at its side to lateral and vertical corrosion. The quantity of water, running in the drain is very small most of the year. During heavy rains, water falls from them in profuse quantities at high speed. This is the reason that great erosion occurs at times whenever a heavy storm hits the area.

Conclusion

Genesis of ravines is a complicated subject in fluvial geomorphology. Earth scientists' researchers have different opinions in this regard. However, they agree that these eroded lands are the result of the corrasion caused by ephemeral streams. Where these streams originate in a watershed and which natural events or human activities influence or promote their eroding power is still contested. According to Horton's theory, points of origin of streams lie in an area at a critical distance from the divide below the "belt of no erosion". In his opinion, the formation of the rills is the first stage of the evolution of streams. At the Gailana research centre, it was observed that a third-order stream system emerged at the terrace on the bank of a deep gully in the Yamuna ravines without any rill development in the upper catchment. Leopold and his co-workers also do not favor the rill concept. They also do not agree with Horton regarding his view on the origin of streams. The findings of the present study do not support the discontinuous theory. In the Chambal and the Yamuna ravines, all the newly developed streams had continuous channels. From the study of Perth Amboy badlands, Schumm has concluded that a stream originates at the base of river cliffs in the form of a rill. Moving upward it jumps over the adjoining upland and takes the form of a stream. During the period of investigation, no stream was found to have evolved from the base of any cliff in the study area. These evidences and observations disapprove of Horton's concept of a "belt of no erosion". They also negate his view that runoff is non-erosive around the divide.

Forest cover was wiped out from vast areas of the earth's surface by forest fires and also by humans to get lands for cultivation in early times. The climatic change of the mid-Holocene times also affected large parts of the world. The fact that these lands are largely un-ravined proves that these global events are not the cause of ravine formation. Ravines developed only in those parts of these plains where rivers have cliffs on their banks. It proves that cliff is essential for the evolution of ravines. It is a widely accepted fact that cliffs in the region have been produced by the neotectonics activity of uplifting. It means that neotectonics has played an important role in crafting the ravine landscape.

Competing interest

The authors declare that they have no conflict of interest.

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