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Review

Gully infested terrain deformed lands: extent, formation, issues and management

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ABSTRACT

Gully erosion and the associated soil loss have caused major environmental disasters worldwide. Gully erosion causes numerous environmental and socio-economic consequences, and most of them are negative. Land degradation caused by ravines and gullies is a serious problem in many areas around the world. Ravine formation due to combined effect of climate, geological and human interference gets activated by other processes such as gully head cutting, scouring, selective erosion transport of sediment etc. Gully induced ravine are densely dissected areas which are severely degraded subjected to water erosion and soil disappeared or lost most of its fertility. The major factors causing gully erosion are high intensity rainfall, soft and deep alluvium soil, height difference between table land and stream, uncontrolled biotic interference etc which converts into ravine or badlands. Many technologies have proved to be effective in gully management including conservation structures like chute, gabions, vegetative barrier, checkdams etc. However, most of the techniques are adopted by the farmers as they directly not provide any rapid benefits.

Keywords: Gully erosion, ravine, factors, management, sediment, structures

INTRODUCTION

Sheet erosion, is the first step of soil erosion which consists of washing away fertile top soil layer, is the most extensive form of erosion, occurring even on moderately sloping lands. Gully erosion, which generally starts after sheet erosion has remained unchecked for some time, has already rendered large areas useless, and is steadily increasing. It causes enormous losses to agriculture every year by reducing the productive capacity of lands. Human and animal population, physical infrastructure, agricultural lands and socio economic system of the land/areas are adversely exposed to multifaceted hazards. The term gully and ravine are often used as synonyms. Literary meaning of ravine is ‘a small narrow steep-sided valley that is larger than a gully and smaller than a canyon and that is usually worn by running water’. Ravine or gully erosion infested landscapes are also known as *lavaba* (French), *vossoroca* or *bocoroea* (Brazilian) and *arroyo* (Central Russia and South West America). In Indian context, the word ravine refers to a network of gullies which are generally spread along any river system.

Gully eroded areas of the world

Gullies not only occur in badlands and mountainous or hilly regions but also more globally in soils subjected to soil crusting such as loess (European belt, Chinese Loess Plateau, North America), sandy textured soils (Sahelian zone, north-east Thailand) or in soils prone to piping and tunnelling such as dispersive soils and also near rivers like those in India (Chambal, Yamuna and Mahi). The gully formation processes are triggered by inappropriate cultivation and irrigation systems, overgrazing, log haulage tracks, road building and urbanization. Iacob and Laura, (2011) highlighted the extent of gully eroded areas in different countries based on various computational models. In Europe, an area of about 115 million hectares (about 12% of the Europe’s surface) is affected by water erosion. The most affected areas are the Mediterranean region and large areas in the central and eastern parts of the continent due to natural contributing factors (relief, climate, soil, etc.) and to anthropogenic factors (massive deforestation, improper practice of agriculture, overgrazing on the same area). Through water erosion, approximately 400 thousand gully erosion formations were formed, covering over 500 thousand hectares (Gardner, 1996). Greece has about 40% of the total area of cultivated land affected by erosion, and over 800 active torrents transport over 30 million m^3 of solid material. China is affected by erosion - approximately 3.7 million km^2 (about one third of the country (Mircea, 1999). In Lesotho, a country with an area of only 30,000 km^2, about 20-30 large thousand ravines occupy 4% of the arable area of the country (Mircea, 1999).

The problem of soil erosion is prevalent over 53 per cent of the total land area of India (Dhruvanarayana and Ram Babu, 1983). India looses about 16.4 t of soil ha^{-1} yr^{-1}, of which 29 per cent is lost permanently into the sea, 10 per cent gets deposited in the reservoirs reducing their capacity by 1–2 per cent every year and the remaining 61 per cent gets displaced from one place to another (Mandal and Sarda, 2011). The regions of high erosion include the severely eroded gullied land along the banks of the rivers Yamuna, Chambal and Mahi river systems. Lesschen *et al.* (2007) reported that the potentially vulnerable lands in southeast Spain for gully erosion increased for the different scenarios, ranging from 18 to 176 ha.

Advanced stage of gully erosion- Ravines and its formation and characterisation

Human civilization developed due to the river. Rivers are considered as the lifeline for human evolution. It is the river which provides the worlds most fertile soil on which human depends for cultivation of food. However the same river can become the major source of devastation of human life, if not managed properly. Human activities like those of deforestation, overgrazing, mismanagement of land and soil resource lead to degrade these rich resources. The same might have caused ravine formation, when such fertile lands were mismanaged by human. Possible theories according to Haigh, 1984 are:

(a) According to *Indian soil conservationist* ravine are formed due to mismanagement of land. The surface runoff mismanagement due to deforestation, overgrazing and improper tillage operation in an environment which is particularly susceptible to erosion. The erodibility of soil is also due to the amount and intensity of rainfall in the region. Sometimes the erodibility of deep alluvial soils often lead to ravine formation. In India ravine formation cannot be correlated with climate change. In Gujrat and Rajasthan the rainfall is from 500-750mm annually and that of Yamuna region of Agra its 750-1000mm annually.

(b) However *Indian geoscientist* quotes it differently. According to them ravine are formed on the Gangetic basin due to the peripheral shift of the Peninsular shield by the pressure against Himalayan and suggests the discontinuous incision pattern id due to differential rate of disturbance.

In many developing countries, several villages and communities have been displaced and virtually disappeared as a result of the scourages of gully erosion. Ravines are a result of these gullies within unconsolidated, relatively loosely bound material such as soft sediments. Although ravines and gullies occur all over India, the largest incidence is found in Madhya Pradesh, Uttar Pradesh and parts of Rajasthan. The most significant areas of erosion in the world are termed as badlands and gullies (Nadal-Romero *et al.*, 2011; Poesen *et al.*, 2003). The substratum of these landforms is usually characterized by unconsolidated or poorly cemented materials. Most of them occur in fine material (e.g., marls, shales, silts and clays) although they may also occur in poorly consolidated sands. They develop predominantly in horizontally bedded, relatively impermeable rocks. The origin and progression of gullies has often been related to piping or tunnel erosion where high hydraulic gradients occur in dispersive materials (Vandekerckhove, 2000).

A ravine is generally a fluvial slope landform of relatively steep (cross-sectional) sides, on the order of twenty to seventy percent slope. Ravines may or may not have active streams flowing along the downslope channel which originally formed them; moreover, often they are characterized by intermittent streams, since their geographic scale may not be sufficiently large to support a perennial watercourse.Ravines are landforms narrower than a canyon and is often the product of stream cutting erosion. Ravines are typically classified as larger in scale than gullies, although smaller than valleys. Ravines are formed due to cumulative effects of factors like overgrazing, indiscriminate destruction of vegetation or forest, unplanned cultivation practices, severe water erosion. Ravines are by not a recent problem but a process where thousands of hectares of fertile land along the banks of rivers like Yamuna, Chambal, Mahi and their tributaries have been ruined by ravine formation in Uttar Pradesh, Madhya Pradesh, Rajasthan and Gujarat. But the rapid spread of ravines is a recent phenomenon is reported more in Chambal (Mugdal, 2005). The major factors responsible for formation and development of ravines are severe misuse and management of rainwater and faulty agricultural practices in the upper river catchments resulting in heavy siltation rates and meandering of rivers and backflow of water from adjoining porous strata into the river system leaving behind a network of gullies.

MAJOR ISSUES ASSOCIATED WITH GULLY INFESTED AREAS

Damage caused by gully erosion is found to be most severe in the alluvial plains of the semi-arid and arid zones in the developing world, where it threatens precarious subsistence-oriented agricultural systems.

1. ***Low soil fertility status of agriculture table land***

Agricultural land decreases with development of gully area, can decrease farm productivity by incision into land and/or depleting soil resources and can thus decrease crop yields (Zgłobicki 2015; Ionita *et al.,* 2015). Negative economic effects of gully erosion have been reported in numerous case studies (e.g. Yitbarek *et al.,* 2012; Frankl *et al.,* 2013). In agriculture lands ephemeral gullies are commonly found which is bigger than rill erosion but smaller then classical erosion. The results of one-time desurfacing experiments highlighted by Govers et al. (2007), to mimic inter-rill erosion, noted that gradual erosion has a much weaker effect on crop productivity than the sudden removal of a significant proportion of the topsoil. The impact of gully erosion are usually unpredictable and often more serious and flashy. To combat gully erosion, most upland rice farmers fill gullies with wood and trash (i.e. weeds removed from cropland). This helps in limiting the growth of existing gullies. Comparatively few studies have investigated the susceptibility of soils to gully erosion. Soil type and, in particular, the vertical distribution of the erosion resistance of the various soil horizons largely controls the size and, more specifically, the depth and cross-sectional morphology of gullies. Ireland et al. (1939) were the first to point to the important role of the resistant Bt-horizons in controlling gully depth and gully head shape in the southeastern USA. Poesen (1993) found that soil shear strength at saturation of the various loess-derived soil horizons is a good indicator of their resistance against concentrated flow erosion. For loess-derived soils, Nachtergaele and Poesen (2002) showed that erosion of Bt-horizons caused by various processes like water erosion, tillage erosion, removal of soil during root and tuber crop harvesting, land levelling, therefore, largely increases the risk for deep gully development. Other reported soil horizons resistant to gully erosion are plough pans, fragipans, petrocalcic horizons or unweathered bedrock. On the other hand, less permeable soil horizons can induce positive pore water pressures in the overlying soil layers which in turn lowers the erosion resistance of these soil horizons, particularly when seepage conditions (return flow) occur (Huang and Laflen, 1996).

2. ***Accelerated runoff***

In gullies accelerated runoff on steep slopes, enhanced drainage and aridification processes (Daba, 2003) are the common observation. Such sites are found in arid region of the Negev highlands of southern Israel, where gully incision erodes alluvial sediments and loess deposited along the valleys. The agricultural fields and the main biomass are limited to narrow valleys. The gullies concentrate the runoff into narrow channels, preventing the floodwater from irrigating the whole width of the valley. In the Ethiopian highlands, the development of gullies has led to an enlarged drainage of the intergully areas, resulting in soil moisture decrease and a corresponding crop yield reduction on plots located near the gully walls (Nyssen *et al.,* 2004). Furthermore, gully channel development increases runoff and sediment connectivity in the landscape, hence increasing the risk for flooding and reservoir sedimentation significantly. In severely crusted environments, gully bottoms are the main runoff water transmission sources to recharge ground water, which may be a crucial issue in semiarid environment as exemplified in southern Niger (Esteves and Lapetite, 2003).

3. ***Soil and sediment deposits***

Sedimentation and soil loss are the other major impacts of gully erosion. Wasson et al. (2002) reported that about 96% of the sediment in the Lake Argyle reservoir of tropical north western Australia, has come from less than 10% of the catchment, in the area of highly erodible soils formed on sedimentary rocks of which about 80% of the sediment in the reservoir has come from gully and channel erosion. Similarly, in a 1.2 km^2 gullied catchment in south eastern New South Wales, multi-parameter fingerprinting of sediment deposited in successive downstream pools has identified gully walls responsible for between 90 and 98% of the pool sediment when the grazed pasture surface was the only other potential source (Krause *et al.,* 2003). Sediment tracers were also used to quantify erosion from cultivated fields and identify major source areas of channel bottom sediment in an intensively cropped tributary of the Umatilla River in north eastern Oregon, USA (Nagle and Ritchie, 2004). Rill and gully erosion contribute between 60% and 70% of all sediments (Zhu and Cai, 2004) in Chinese Loess Plateau. According to Poesen et al. (2003), gully erosion represents a major sediment-producing process, generating between 10 and 95% of total sediment mass at catchment scale whereas gully channels often occupy less then 5% of the total catchment area. Survey within the catchments of 22 Spanish reservoirs clearly indicated that specific sediment yield increases when the frequency of gullies increases in the catchment (Poesen *et al.,* 2002)

Soil loss by gully erosion also depends upon the time period. For example, data presented by Poesen et al. (2002) indicate that soil losses caused by ephemeral gully erosion for a relatively wet winter on the Iberian Peninsula represent 47–51% of total soil loss by water erosion, whereas at the medium time scale (i.e. 3–20 years) this figure rises to 80–83%. Other factors like gully type, soil type, land use, climate and topography are considered as the major factors determining soil loss from gully areas. Where soils were mostly silty, coarse loamy or sandy, rill erosion on the hillslopes became more important, reducing the relative contribution of ephemeral gully erosion in valley bottoms to overall sediment production. In central Belgium, ephemeral gully volumes that eroded in truncated soil profiles (i.e. with no Bt-horizon) can be four to five times larger than volumes eroded by ephemeral gullies developing into intact soil profiles (Poesen, 1993).

Many techniques have proved to be effective for gully prevention and control, including vegetation cover, zero or reduced tillage, stone bunds, exclosures, terracing and check dams. However, these techniques are rarely adopted by farmers in the long run and at a larger spatial scale because their introduction is rarely associated with a rapid benefit for the farmers in terms of an increase in land or labour productivity and is often contingent upon incentives.

TECHNOLOGY RECOMMENDATIONS FOR MANAGING GULLY DEVELOPMENT

Many techniques for gully prevention and control have proved to be effective, including vegetation cover, zero or reduced tillage, stone bunds, terracing and check dams. However, these techniques are rarely adopted by farmers in the long run and at a larger spatial scale because their introduction is rarely associated with a rapid benefit for the farmers in terms of an increase in land or labour productivity and is often contingent upon incentives. Prior to undertaking any repairs or rejuvenation of gullied areas, it is important to carry out a full assessment: causes, options and resources available, including a plan for ongoing monitoring and maintenance. Some examples are cited below

1. Gully management or conservation structures: Some examples explained below were taken from chapter of Gully erosion and its control from Queensland (https://publications.qld.gov.au)

(a) Chute: Gully control chutes are formed by battering gully heads to an acceptable slope depending on the method used to stabilise them. As well as for controlling gullies, chutes are used as by washes in farm dams. They are also used to convey water over steep road batters, to control bed erosion in streams, and for urban developments such as sports fields.

(b) Grass sod chutes: The ability of these chutes to withstand erosion damage depends on an effective cover of a good mat of grass. The grade of such chutes should be kept as low as possible to minimise the flow velocities. Ideally, the grade should be 1:8 (V:H) or flatter, although steeper grades may be effective on stable soil types where a complete sod cover can be assured. If grass seed or runners are used, it may take two years or longer before an effective grass cover is established to stabilise the chute. Sod chutes are generally not recommended for stabilising gully heads greater than 0.5 m in depth unless a good vegetation cover is assured. For the side walls, the side slopes can be constructed at grades of 1:2 (V:H), to minimise excavation. However, where mowing with a tractor is intended, the side slopes should be 1:4 (V:H) or flatter

(c) Geotextile polyester fibres: Grass chutes can be made more stable by incorporating a geotextile, polyester filter material under the topsoil. The geotextile provides strength and stability to the soil profile and plant roots will grow through it. If these products are not UV stabilised they can degrade in sunlight and must be covered by soil or rocks.

(d) Rock chutes and gabions: rock chutes are preferred in areas where soil is likely to move and suitable rocks are handy to the site. For example, in black clay soils that shrink and swell with moisture differences, the rocks are able to marginally relocate without affecting the stability of the structure. Rock chutes work best when they have a vigorous vegetative cover, such as kikuyu, that helps to hold the rocks in place. High rates of runoff from rain falling on the rocks will seep into the soil and the rocks reduce evaporation, thus encouraging grass growth. The grass helps to reinforce the rocks, provides additional roughness and improves its visual appeal. Placing topsoil between the rocks at the completion of the project will encourage grass growth. Gabions are designed to provide erosion protection in a wide range of environments where rock protection is not sufficient. In addition to erosion protection, rock-filled wire baskets are commonly used for geotechnical purposes such as retaining walls.

(e) Sandbag chutes: These chutes are constructed of sandbags filled with a 5:1 mixture of sand and cement. The floor and sides of a chute are lined with sandbags filled with a dry mix of sand and concrete on site. They should be placed on a suitably specified geotextile and laid lengthwise starting from the stilling pond. The bags should be overlapped by one-third of a bag. After the bags have been placed on the chute, a light sprinkling of water is applied to set the concrete. Chute grades of 1:1.5 to1:2 (V:H) are required to give optimum overlap of the placed sandbags.

(f) Drop structures: Drop structures are vertical structures that convey runoff from a higher level to a lower level and are commonly used in road cross-drainage structures. Drop structures are constructed from concrete, concrete blocks, gabion mattresses, steel sheets, concrete in sand bags, or timber. They require some form of energy dissipation at their base to help dissipate the energy gained when runoff flows over the structure. This method is only satisfactory if there is sufficient sediment being carried down the watercourse to silt up the area above the structure within two or three years.

(g)

2. Gully process Modelling

According to Poesen *et al.,* (2003) gully erosion modelling address two major aspects: (a) erosion rates at various temporal and spatial scale and (b) impact of gully erosion on hydrology, sediment and environment. In agricultural lands two major gully types can be often observed: ephemeral and bank gullies. There is a need to model these erosion features, which are complementary to inter rill and rill erosion. Some models like CREAMS, GLEAMS, WEPP, EGEM etc were the common models used for predicting soil loss by ephemeral gully erosion. More particularly, there is a need for more detailed monitoring, experimenting and modelling of the development and infilling of both ephemeral gullies and bank gullies in a variety of agricultural environments. In other words, there is a need to better predict the location, the total length and the cross-section of gullies. The threshold concept could be a useful tool to help locate ephemeral gullies in the landscape. However, threshold conditions for incipient gullying in a variety of climatological, topographic, pedological and land-use conditions first need to be established. Existing erosion models need to be refined to incorporate the effects of the resistance of various soil horizons to concentrated flow erosion and the effects of other soil detaching mechanisms in gullies such as soil fall, slumping and headcutting. Improved gully models are needed to predict more accurately the effects of environmental change on the intensity of this soil degradation process.

3. Vegetative barrier:

Vegetation is the primary, long-term defence in preventing or reducing gully erosion; and, in a favourable climate, it can multiply and thrive and improve over the years. However, gullies are a harsh environment in which to establish vegetation as they dry out rapidly and often have exposed infertile subsoils. The traditional method of rehabilitation/stabilisation of ravines is the use of hard conventional engineering structures such as gabions, rock baskets and sand bags etc, which are very expensive to build and maintain. In addition, these hard structures are also vulnerable to erosion themselves by water seeping behind the structures, undermining their foundations. Here vegetative barriers can be used to favour water infiltration and to protect soil from erosion. Intercepted drops by tall trees without understorey can be larger and can have higher kinetic energy than non-intercepted drops, favouring soil crusting, runoff generation and gully initiation. Effects of plant roots on soil resistance to concentrated flow erosion mainly depend on the characteristics of effective roots (fibrils less than 1 mm in diameter) distributed densely in the depth 0–30 cm. Plant roots reduce gully erosion in improving soil physical properties such as structural stability and infiltrability. In the Chinese loess plateau, an increase in grassland and forestland by 42% and a corresponding decrease in farmland by 46% reduced sediment production mainly due to gully erosion by 31% in the catchment (Li et al., 2003, 2004).

FUTURE THRUST AREAS OF RESEARCH IN GULLY AND RAVINE AREAS

(a) Amount of total soil loss from gully erosion contributing to ravine formation to predict impacts of different land use system and climatic conditions on the risk for gully erosion on temporal and spatial scales.

(b) Very less data are available on the relation between gully and topography, it is clear that topographic attributes such as slope gradient and drainage area affect the density of the drainage network and hence the probability of gully channel development

(c) Although several attempts have been made to develop empirical and process-based models for predicting either gully sub processes or gully erosion rates in a range of environments, there are still no reliable (i.e. validated) models available allowing one to predict effects of environmental change on gully erosion or gully infilling rates at various temporal and spatial scales, and the impacts of gully erosion on sediment yield, hydrological processes and landscape evolution. This is a major research area requiring more efforts (Poesen et al. 2011).

(d) More studies are needed to determine the effectiveness and efficiency of gully erosion control programmes by incorporating the tangible and intangible benefits at field and environment level. Piping-induced gully erosion remains perhaps the biggest challenge in erosion control research.

(e) Methodological framework is needed to be applied to different environments so as to select the most suitable species for gully channels. Developing and promoting location specific agroforestry systems for various agro-climatic zones.

(f) Appropriate measuring techniques for measuring gully erosion rates and controlling factors at various temporal and spatial scales is still lacking.

(g) Studies to measure critical hydraulic conditions for incipient gullying in field conditions is needed to assess critical environmental conditions in terms of rainfall, topography, soils (or lithology) and land use as these factors control either the runoff hydraulics (e.g. rainfall, topography) or the resistance of the soil surface to incision (e.g. soils) or both (e.g. land use).

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