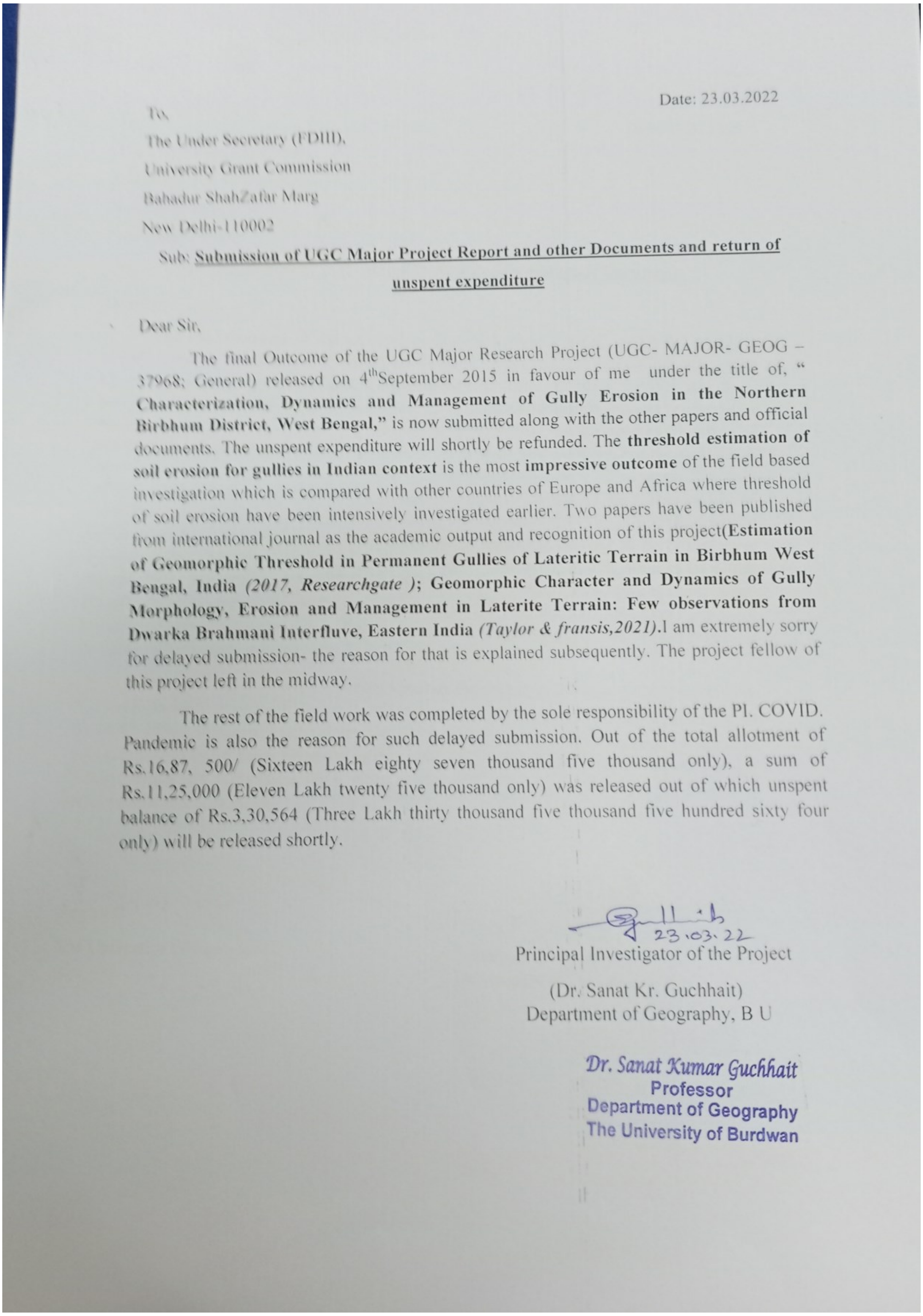
UGC Major Project Final Report

[MRP – MAJOR – GEOG – 37968]

Project Title – Characterization, Dynamics and Management of Gully Erosion in the Lateritic Badlands of Northern Birbhum District, West Bengal

Principal Investigator – Dr Sanat Kumar Guchhait, Professor,

Department of Geography,
The University of Burdwan



Date: 23.03.2022

To,
The Under Secretary (FDIII),
University Grant Commission
Bahadur ShahZafar Marg
New Delhi-110002

Sub: **Submission of UGC Major Project Report and other Documents and return of unspent expenditure**

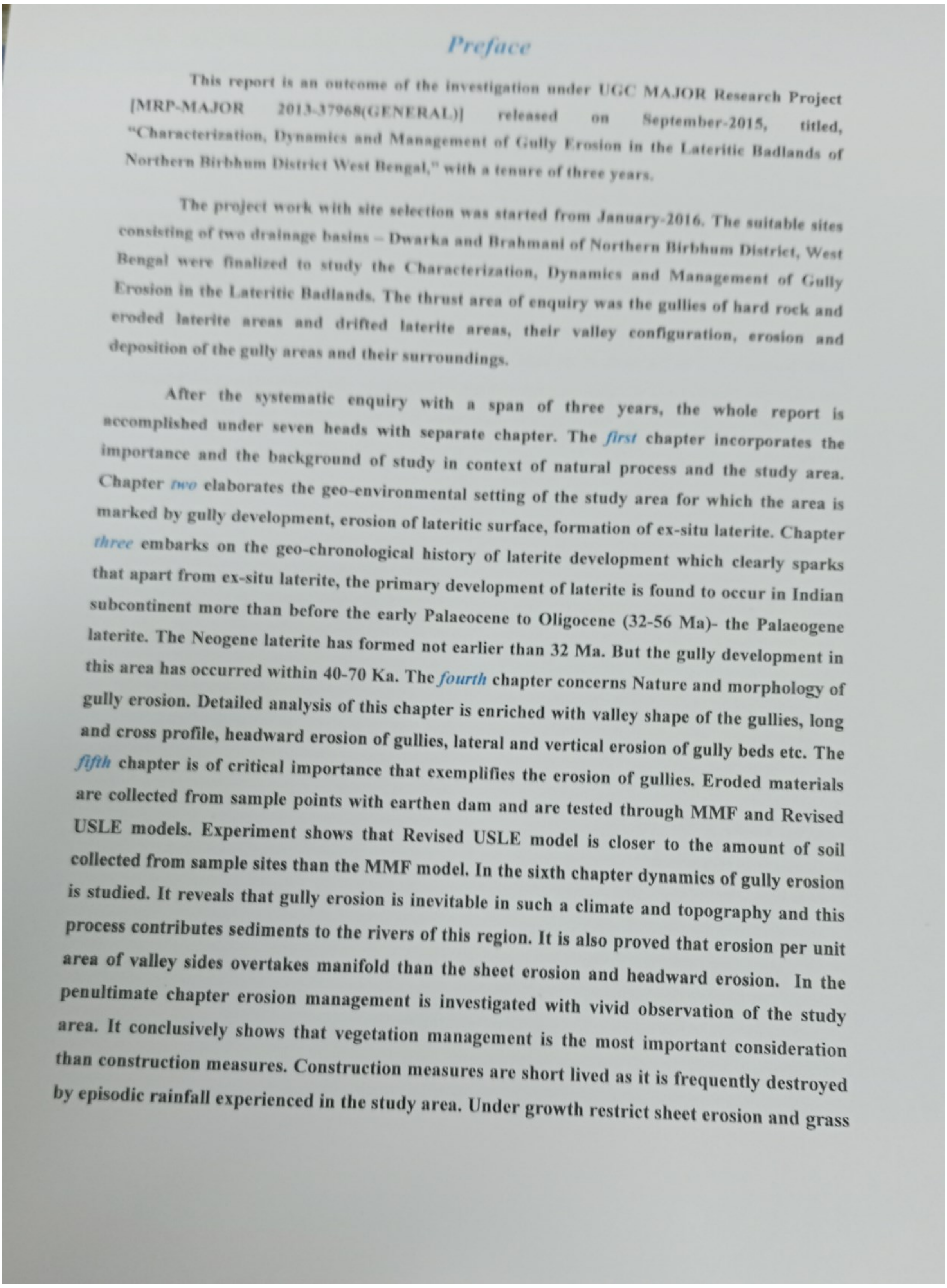
Dear Sir,

The final Outcome of the UGC Major Research Project (UGC- MAJOR- GEOG – 37968; General) released on 4th September 2015 in favour of me under the title of, " **Characterization, Dynamics and Management of Gully Erosion in the Northern Birbhum District, West Bengal,"** is now submitted along with the other papers and official documents. The unspent expenditure will shortly be refunded. The **threshold estimation of soil erosion for gullies in Indian context** is the most **impressive outcome** of the field based investigation which is compared with other countries of Europe and Africa where threshold of soil erosion have been intensively investigated earlier. Two papers have been published from international journal as the academic output and recognition of this project(**Estimation of Geomorphic Threshold in Permanent Gullies of Lateritic Terrain in Birbhum West Bengal, India** ***(2017, Researchgate)***; **Geomorphic Character and Dynamics of Gully Morphology, Erosion and Management in Laterite Terrain: Few observations from Dwarka Brahmani Interfluve, Eastern India** *(Taylor & fransis,2021)*.I am extremely sorry for delayed submission- the reason for that is explained subsequently. The project fellow of this project left in the midway.

The rest of the field work was completed by the sole responsibility of the PI. COVID. Pandemic is also the reason for such delayed submission. Out of the total allotment of Rs.16,87, 500/ (Sixteen Lakh eighty seven thousand five thousand only), a sum of Rs.11,25,000 (Eleven Lakh twenty five thousand only) was released out of which unspent balance of Rs.3,30,564 (Three Lakh thirty thousand five thousand five hundred sixty four only) will be released shortly.

23.03.22
Principal Investigator of the Project
(Dr. Sanat Kr. Guchhait)
Department of Geography, B U

Dr. Sanat Kumar Guchhait
Professor
Department of Geography
The University of Burdwan

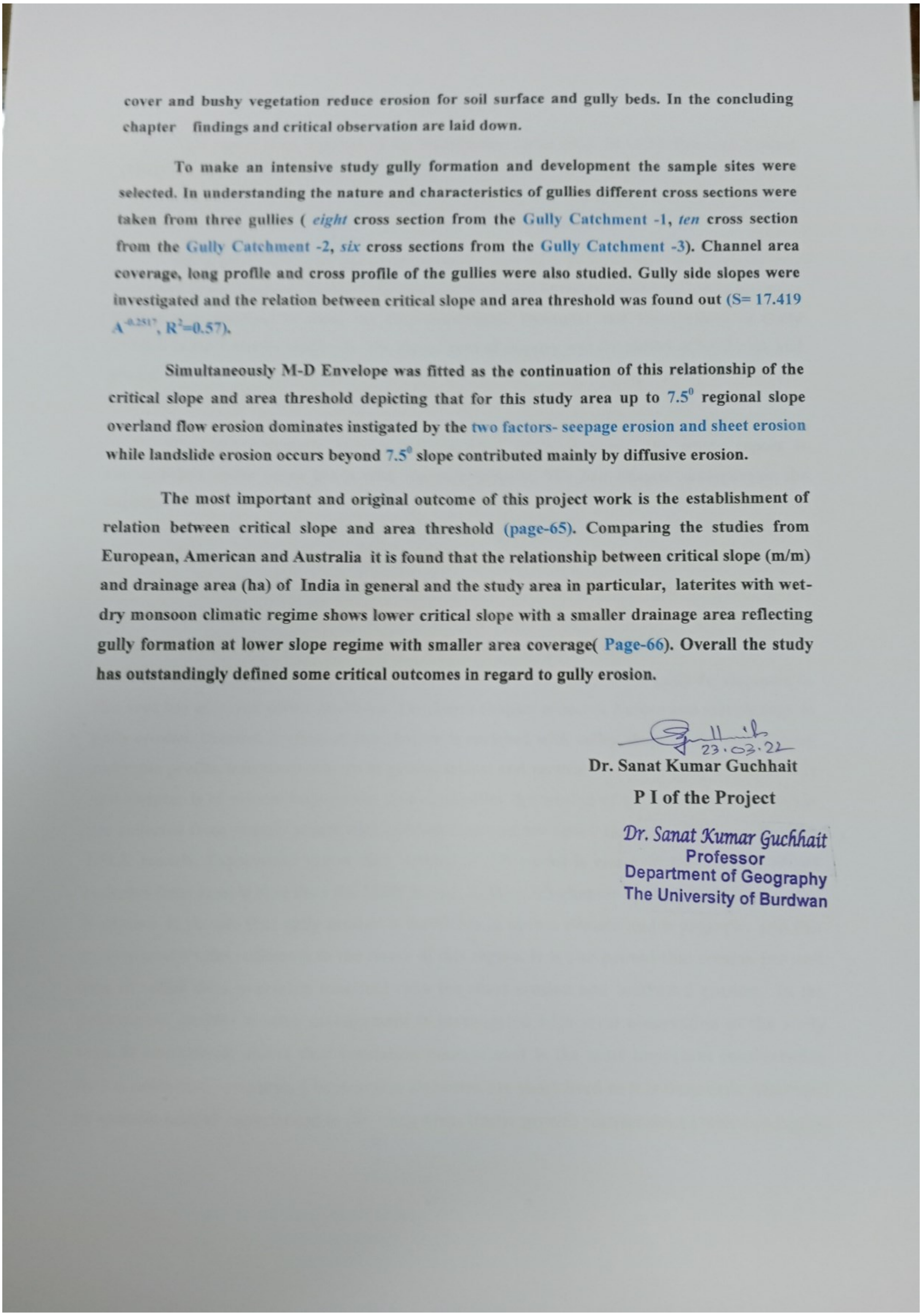


Preface

This report is an outcome of the investigation under UGC MAJOR Research Project [MRP-MAJOR 2013-37968(GENERAL)] released on September-2015, titled, "Characterization, Dynamics and Management of Gully Erosion in the Lateritic Badlands of Northern Birbhum District West Bengal," with a tenure of three years.

The project work with site selection was started from January-2016. The suitable sites consisting of two drainage basins – Dwarka and Brahmani of Northern Birbhum District, West Bengal were finalized to study the Characterization, Dynamics and Management of Gully Erosion in the Lateritic Badlands. The thrust area of enquiry was the gullies of hard rock and eroded laterite areas and drifted laterite areas, their valley configuration, erosion and deposition of the gully areas and their surroundings.

After the systematic enquiry with a span of three years, the whole report is accomplished under seven heads with separate chapter. The *first* chapter incorporates the importance and the background of study in context of natural process and the study area. Chapter *two* elaborates the geo-environmental setting of the study area for which the area is marked by gully development, erosion of lateritic surface, formation of ex-situ laterite. Chapter *three* embarks on the geo-chronological history of laterite development which clearly sparks that apart from ex-situ laterite, the primary development of laterite is found to occur in Indian subcontinent more than before the early Palaeocene to Oligocene (32-56 Ma)- the Palaeogene laterite. The Neogene laterite has formed not earlier than 32 Ma. But the gully development in this area has occurred within 40-70 Ka. The *fourth* chapter concerns Nature and morphology of gully erosion. Detailed analysis of this chapter is enriched with valley shape of the gullies, long and cross profile, headward erosion of gullies, lateral and vertical erosion of gully beds etc. The *fifth* chapter is of critical importance that exemplifies the erosion of gullies. Eroded materials are collected from sample points with earthen dam and are tested through MMF and Revised USLE models. Experiment shows that Revised USLE model is closer to the amount of soil collected from sample sites than the MMF model. In the sixth chapter dynamics of gully erosion is studied. It reveals that gully erosion is inevitable in such a climate and topography and this process contributes sediments to the rivers of this region. It is also proved that erosion per unit area of valley sides overtakes manifold than the sheet erosion and headward erosion. In the penultimate chapter erosion management is investigated with vivid observation of the study area. It conclusively shows that vegetation management is the most important consideration than construction measures. Construction measures are short lived as it is frequently destroyed by episodic rainfall experienced in the study area. Under growth restrict sheet erosion and grass



cover and bushy vegetation reduce erosion for soil surface and gully beds. In the concluding chapter findings and critical observation are laid down.

To make an intensive study gully formation and development the sample sites were selected. In understanding the nature and characteristics of gullies different cross sections were taken from three gullies (*eight* cross section from the Gully Catchment -1, *ten* cross section from the Gully Catchment -2, *six* cross sections from the Gully Catchment -3). Channel area coverage, long profile and cross profile of the gullies were also studied. Gully side slopes were investigated and the relation between critical slope and area threshold was found out ($S= 17.419 A^{-0.2517}$, $R^2=0.57$).

Simultaneously M-D Envelope was fitted as the continuation of this relationship of the critical slope and area threshold depicting that for this study area up to 7.5^0 regional slope overland flow erosion dominates instigated by the two factors- seepage erosion and sheet erosion while landslide erosion occurs beyond 7.5^0 slope contributed mainly by diffusive erosion.

The most important and original outcome of this project work is the establishment of relation between critical slope and area threshold (page-65). Comparing the studies from European, American and Australia it is found that the relationship between critical slope (m/m) and drainage area (ha) of India in general and the study area in particular, laterites with wet-dry monsoon climatic regime shows lower critical slope with a smaller drainage area reflecting gully formation at lower slope regime with smaller area coverage(Page-66). Overall the study has outstandingly defined some critical outcomes in regard to gully erosion.

23.03.22

Dr. Sanat Kumar Guchhait

P I of the Project

Dr. Sanat Kumar Guchhait
Professor
Department of Geography
The University of Burdwan

CONTENT

Chapter 1.0

1.1 Introduction

The detachment, entrainment, transportation and deposition of soils or earth materials are categorized as erosion and sedimentation and these processes have operated on the land since the first rains millions of years ago. The most important fact that these processes are capable of stripping the fertile topsoil from the land, topsoil that was tens, hundreds or even thousands of years in making (Toy et al., 2013). They are capable of destroying the productivity of land (also permanent loss of land and sterilization of land) in just a few years or even months, affecting the economy, livelihood and ecological balance of a region. Due to its temporal and spatial ubiquity, together with numerous impacts, soil erosion is an essential research topic for physical and social scientist alike. Soil erosion is an issue where the adage "think globally, act locally", is clearly applicable. Think globally, because soil erosion is a common problem that has, does, and will continue to impact the global community. Act locally, because effective erosion control requires action at the hillslope, field, stream channel and upland watershed scales.

In different parts of the world, the most intensified soil erosion is the gully erosion which is an extreme form of soil erosion and land degradation, affecting multiple soil and land functions through inter-connected networks of narrow channels over the slope (Ahmad, 1970; Singh and Dubey, 2002). Soils have critical relevance to current global issues such as food and water security, climate regulation, land degradation and desertification and nowadays intensive gully erosion has raised question on the environmental sustainability and the actions of land users. If we continuously loss soil, then we shall immediately face hurdle to achieve food security in the developing countries like India where agriculture till now is the socio-economic base. It is learned that soil resource is being lost from the land area 10 to 40 times faster than the rate of soil renewal imperilling future human food security and environmental quality (Pimentel, 2006; Pimental and Burgess, 2013). Rill and gully erosion is endlessly triggering land degradation and expansion of wasteland in many parts of the world, as well as in India.

Table 1.1 Land degraded area by water erosion in few selected states of India

State	Total Area (km^2)	Degraded and Wastelands Classes ('000 ha)			Area (%)
		1	2	(1+2)	
Uttar Pradesh	238,566	12,370	514	12,884	54
Madhya Pradesh	308,641	11,881	1,584	13,465	44
Karnataka	191,791	7,450	349	7,779	41
Jharkhand	79,714	2,825	356	3,181	40
Meghalaya	22,429	127	579	706	31
Rajasthan	342,239	7,436	1,196	8,632	25
Himachal Pradesh	55,673	941	43	984	18
Bihar	94,163	820	229	1,049	11
Andhra Pradesh	275,045	8,050	814	8,864	32
West Bengal	88,752	1,167	97	1,264	14

Source: ICAR (2010); **Notes:** Class 1 – Exclusively water erosion (> 10 tonnes ha^{-1} yr^{-1}); Class 2 – Water erosion under open forest

Many governmental organizations have estimated the extent of land degradation in India and the value varies from 53.28 to 173.64 M ha. Land degradation due to soil erosion is a momentous hazard in India and gully erosion already engulfs about 3.975 million ha of land in India (Yadav and Bhusan, 2002; Pathak et al., 2006; Singh et al., 2015). It is estimated that soil erosion takes place at the rate of 1.35 tonne ha^{-1} $year^{-1}$ in India, and about 29% of total eroded soil is slot permanently to sea and 10% is deposited in the reservoirs (Narayana et al., 1983; Sharda et al., 2010; Sharda and Dogra 2013). Singh et al. (1992) estimated that soil erosion took place at a rate of exceeding 40 t ha^{-1} yr^{-1} in the ravines and badlands of India. According to Indian Council of Agricultural Research (ICAR) about 83,310,000 ha of land is classified as degraded and wasteland and Uttar Pradesh has ranked highest in that case where 54 percent of total area is now degraded (table 1). About 23.62 M ha of land is affected by water erosion which includes loss of top-soil (13.25 M ha), gully formation (8.31 M ha) and ravines (2.06 M ha) (ICAR, 2010). In the humid sub-tropical region of India soil erosion (about 15 million tonnes per year) leads to low crop productivity and an annual loss of 13.4 million tonnes in the production of crops due to water erosion equivalent to about $2.51 billion (Bhattacharyya et al., 2007; Sharda et al., 2010 and 2013).

Some soils are very much susceptible to water erosion and this type of erosion makes the landscape into dissected badlands and ravine topography in India. Pleistocene alluvium of Yamuna and Chambal Basin are dissected by deep gullies and it makes spectacular and famous ravines of India (Sharma, 1980). One of the erosion prone soils of India is lateritic and red soil group which is ubiquitous in the plateau fringe of West Bengal and the region is specially termed as the *Rarh* Plain (Biswas, 1987). In West Bengal surprisingly the laterite and other ferruginous materials are very much vulnerable to water erosion and this *Rarh* Plain is continually dissected by dense network of rills and gullies. The Birbhum district of West Bengal and the adjoining Dumka district of Jharkhand are the northern part of *Rarh* Plain. This region is intensively dissected by the rills and gullies, developing a badland typed landform named *Khoai* (the name was given by Kabiguru Rabindrantath Tagore). The present study encompasses a lateritic region which is situated in the Dwarka – Brahmani Interfluve of eastern India (i.e. south-eastern fringe of Rajmahal Basalt Traps) and it covers northern part of Birbhum district (West Bengal).

In this terrain taking steps to prevent or control gully erosion should require no justification, but before taking any action or plan for soil conservation it is utmost necessary to understand the individuality of rill and gully erosion in the lateritic region and to examine the erosion risk as observed now. Based on the above facts and important issues it can be said that our fundamental and greatest priority is to assess the gully erosion dynamics and soil loss rate in the particular terrain, then to control the erosion and to restore the degraded land. Therefore, in a nutshell through subsequent sections this field-based pedo-geomorphic research is trying to encompass the geo-environmental settings of study area, morphology and hydro-geomorphic processes of gully erosion, modelling of soil erosion and suggestive measures of erosion management in the *Rarh* Plain.

1.2 Important Concepts and Terms

Having distinct approaches of research in geomorphology and pedology, the landforms and soils should be treated in the perspective of mutual interaction in a geomorphic system where both geomorphic and pedogenic processes are dominated. Also, this research includes the various concepts and methods of regolith geomorphology, geology, sedimentology and hydrology to understand the each minute aspect of soil erosion in a particular geomorphic unit (i.e. river basin). So, before going into main sections it is necessary to know and clarify the important terms and concepts used in the geomorphic study of gully and soil erosion modelling in the laterite.

1.2.1 Soil Erosion

The word erosion is of Latin origin derived from the verb ‘erodere – to eat away’ (rodere – to gnaw) or to excavate (Zachar, 1982). The term soil erosion, first coined in English, was introduced by McGee in 1911 (Zachar, 1982). Soil erosion is a two phase process consisting of the detachment of individual soil particles from the soil mass and their transport by erosive agents such as running water and wind (Morgan, 2005). When sufficient energy is no longer available to transport the particles, a third phase, deposition occurs (Morgan, 2005).

1.2.2 Erodibility and Erosivity

Soil erosion can be considered as a function of erosivity and erodibility (figure 1.1) (Hudson, 1984). Erosivity is a measure of the capacity of an eroding agent, such as rainfall and overland flow, to erode that soil surface and erodibility refers to the susceptibility of the soil surface to erosion (Hudson, 1984). Raindrop erosivity factors are drop size, velocity, distribution, angle and direction, rain intensity, frequency and duration and runoff erosivity factors are runoff supply rate, flow depth, velocity, frequency, magnitude, duration and sediment content (Charlton, 2008). Erodibility factors are soil properties (e.g. particle size, clod-forming properties, cohesiveness, infiltration capacity), vegetation (e.g. ground cover, vegetation type), topography (e.g. slope inclination, surface roughness, flow convergence or divergence) and land use practices (e.g. contour ploughing, gully stabilisation, terracing, organic content) (Charlton, 2008).

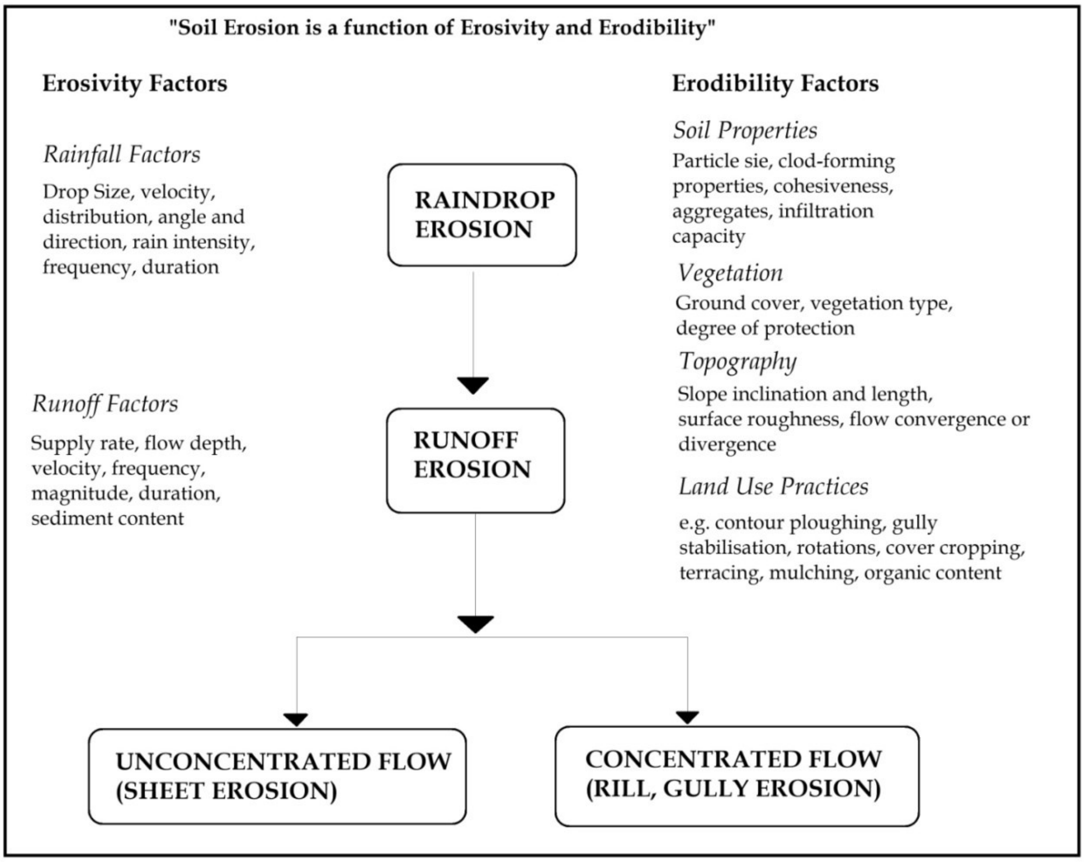


Figure 1.1 Principal Factors of Water Erosion on Hillslopes (Charlton, 2008)

1.2.3 Overland Flow

Overland flow (figure 1.2) occurs on hillsides during a rainstorm when surface depression storage is exceeded and either, in the case of prolonged rain, soil moisture storage or, with intense rain, the infiltration capacity of the soil are exceeded (Morgan, 2005). Flow is rarely in the form of a sheet of water of uniform depth and more commonly is amass of anastomosing or braided water courses with no pronounced channels.

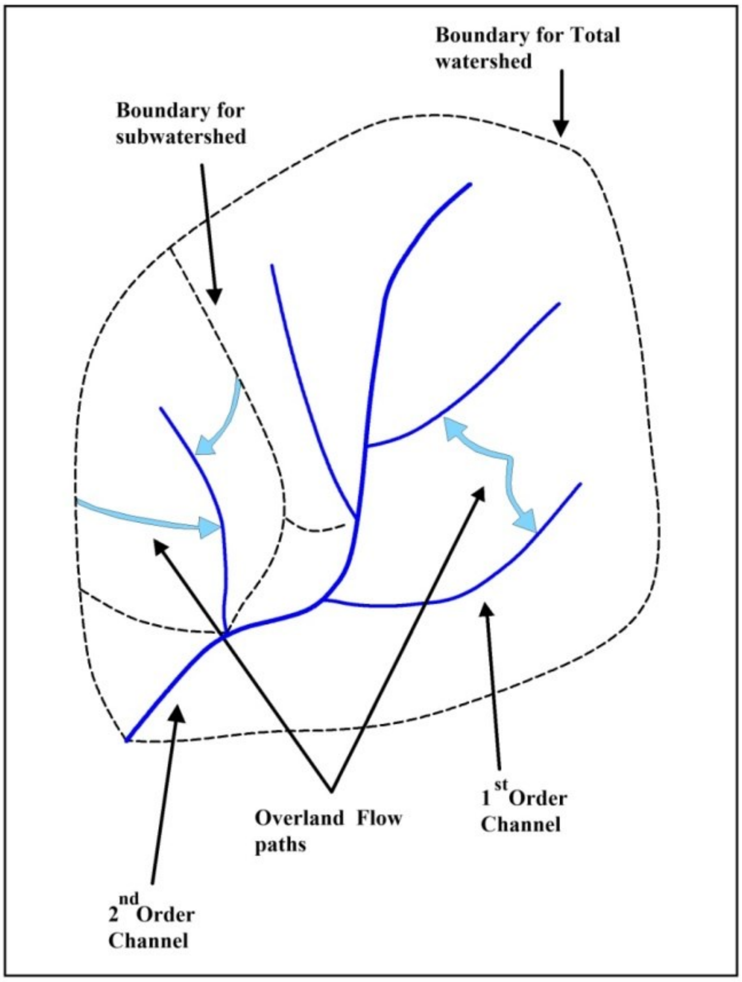


Figure 1.2 Hierarchy of watershed and overland flow paths

1.2.4 Rainsplash Erosion

Rainsplash erosion is caused by the bombardment of soil surface by impacting raindrops (falling raindrops possess kinetic energy to detach soil particles) (Charlton, 2008). At the start of a rain event, falling raindrops beat the soil aggregates, break them, and detach soil particles. These particles clog the large soil pores and thus, reduce the infiltration capacity of the soil (Osman, 2014). Further, raindrops beat the water and splash the suspended soil particles away. Processes of splash erosion involve raindrop impact, splash of soil particles and formation of craters.

1.2.5 Sheet Erosion

Sheet erosion is more or less uniform erosion of the soil over the whole surface of the land over a particular part of slope and it is caused by combined action of raindrops and overland flow (Zacahr, 1982). When a thin layer of soil is removed by raindrop impact and shallow surface flow from the whole slope, it is called sheet erosion (Osman, 2014). It removes the finest fertile topsoil with plenty of nutrients and organic matter. Sheet erosion can expose tree roots and sub-soil over a large area.

1.2.6 Rill Erosion

When rainfall exceeds the rate of infiltration, water accumulates on the surface and if the land is sloping, it moves along the slope. Detachment and transportation ability increase substantially when flow is concentrated into rills, micro-channels with typical dimensions of 50 – 300 mm wide and up to 300 mm deep (Knighton, 1988). It is widely accepted that rills are initiated at a critical distance in downslope where overland flow becomes channelled (Morgan, 2005). As soon as rainfall starts, runoff promptly develops diminute rills and that portion of runoff that flows between rills is called 'inter-rill erosion'. The inter-rill and rill areas together make up the overland flow areas of landscape and it is the total water erosion that occurs on the overland flow areas (Toy et al., 2013).

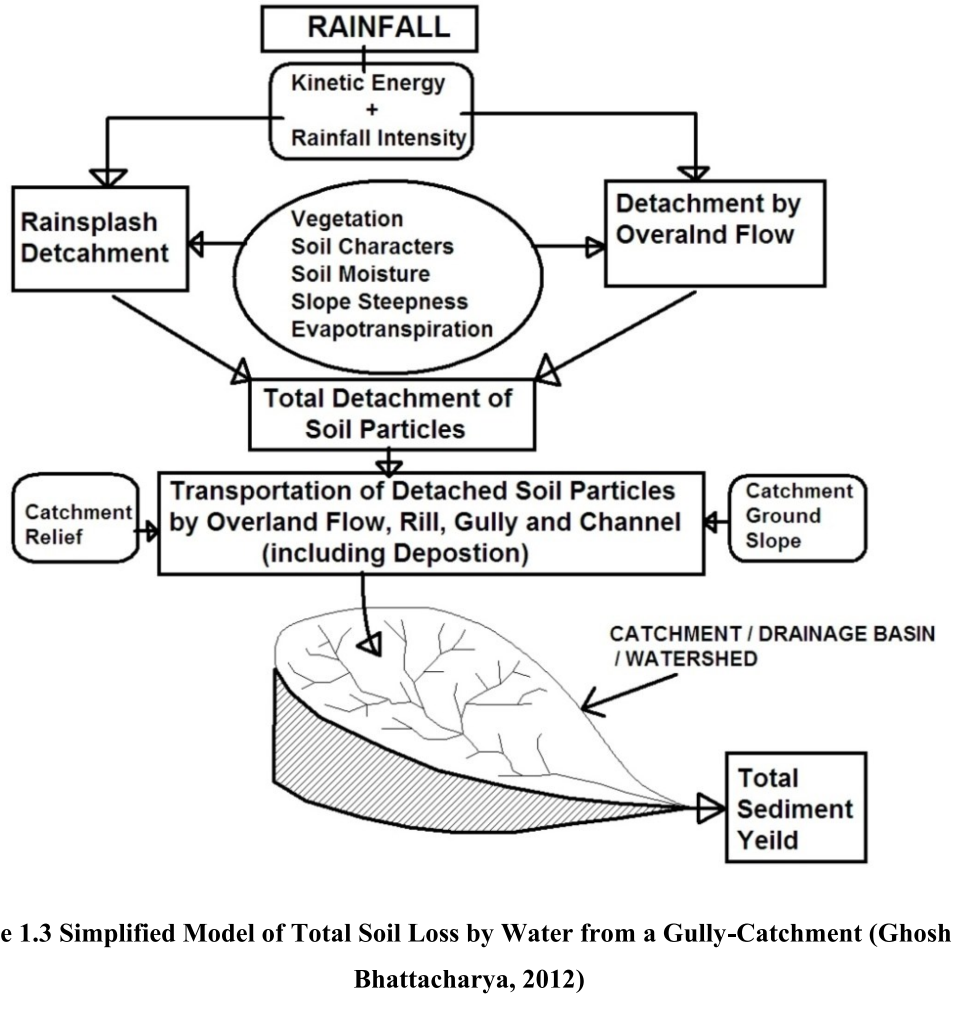


Figure 1.3 Simplified Model of Total Soil Loss by Water from a Gully-Catchment (Ghosh and Bhattacharya, 2012)

1.2.7 Gully Erosion

Gully erosion (figure 1.3) is an advanced stage of rill erosion as the water continues to concentrate and acquires additional energy for scouring, the grooves become deeper and broader and eventually some of them are developed into gullies (Pathak et al., 2005). A gully is defined as an ephemeral or permanent incised channel with minimum cross-section of 930 cm^2 (Vandekerckhove et al., 2000). It is mentioned that a gully is relatively deep (>0.6 m), recently formed eroding channel floors where no well-defined channel previously existed and it has steep sides, low width-depth ratio and steeped profile (presence of knick points), characteristically with a headcut (with plunge pool) at the upslope end, dominated by the processes of concentrated surface flow, piping and mass movement (Brice, 1966; Schumm et al., 1984; Bull, 1997; Knighton, 1998; Erskine, 2005).

1.2.8 Ravine and Badlands

The word ‘ravine’ denotes gullied lands containing systems of gullies running more or less parallel to each other (Sharma, 1986). In American south-west, the term ‘arroyo’ is generally used, which is synonymous to ravine (Charlton, 2008). A ravine is a channel of ephemeral flow denuded and guided essentially by the process of rejuvenated stream, as steep side and head scarps, width and depth always grater than a gully (Sharma, 1986). On other side, according to Singh and Dubey (2002) the term ‘ravination’ used in Indian papers comprises the linear fluvial erosion of loose and unconsolidated materials by rills and gullies, which ultimately, results in the development of badland topography. The phrase ‘badland erosion’ derives from the French *mauvaiseterre*. The French used this expression to describe unmanageable terrain furrowed by erosion in the prairies of Dakota and Nebraska to the south of the Black Hills (Zachar, 1982). Zachar (1982) suggests should include all soils which are not used for intensive production because of their bad properties. The term badland refers mainly to eroded land above, but descriptions of badlands is available to date show that these include both primary or barren land, and secondary wasteland.

1.3 Literature Review

A number of significant studies have been carried out by various scientists of the country and abroad to study laterites, measuring soil loss using models and different aspects of rill and gull erosion. The research area of gully and ravine erosion includes the consideration of identification and mapping of ravine lands, understanding the character of soil, gully morphology, extent and magnitude of soil erosion, genesis of rills and gullies and contribution factors of soil erosion. Gully erosion on laterites has attracted many geologists, geomorphologists, soil scientists, agricultural scientists, engineers, planners and specifically geographers. So we have reviewed the literatures on three main aspects or themes of research – (1) laterites, (2) different aspects of gully erosion and genesis of gullies, and (3) measurement of soil erosion using models.

1.3.1 Review on Laterites

The term laterite has been applied to such a diverse array of geomorphic features that it no longer has value as a precise descriptive term (Patton and Williams, 1972). The term ‘laterite’ was originally suggested by F. Buchanan (1807) as a name for highly ferruginous deposits first observed in Malabar in India (Raychaudhuri, 1980). Maignien (1966) wrote a book, named ‘Review of Research on Laterites’, mentioning different definition of laterites, scope of the problem regarding laterites, global distribution of laterites, and classification of laterites. Paton and Williams (1972) successfully pointed out that the persistence of error in modern studies of laterite stemmed from early confusion over what laterite was and how it formed. McFarlane (1976) had devoted eleven unique chapters (book entitled ‘Laterites and Landscape’) regarding historical reviews of theories of laterite genesis, different views to define laterites, constituents of laterites, the environment of laterite with reference to geology, topography, climate, vegetation, profile of laterite, laterite structures, genesis of high level and low level laterites, lateritic landforms and denudation chronology in Uganda.

In India most of the in depth studies regarding Indian laterites are done by eminent geologists. Roy Chowdhury et al. (1965) have revealed the origin of laterites in India, including classification and process of formation. Raychaudhuri (1970 and 1980) has provided the concise account of Indian laterites and lateritic soils, including classification, description on laterites of West Bengal and management of soils. The best preliminary study on laterites and lateritic soils of West Bengal was done by Niyogi et al. (1970) and Biswas (1987). Jha and

Kapat (2003, 2009 and 2011) have given notable contribution on the study of erosion prone laterites of Birbhum, West Bengal having spatial scale of C.D. block and mouza level. Similarly Das and Bandyopadhyay (1995) and Sen et al. (2004) have studied the laterites of Garhbeta, Paschim Medinipur.

1.3.1 Reviews on Gully Geomorphology

Mechanism of gully and ravine erosion, phases of gully development, gully reclamation and management have been widely studied by geomorphologist, soil scientists, agricultural scientists etc. at national and international level. Gilbert (1917 & 1970), Horton (1945 & 1970), Strahler (1956), Leopold et al. (1969), Young (1972) and Knighton (1998) have provided important ideas and works about water erosion, stages of development of rill and gully erosion, hillslope processes, channel initiation and different aspects of gullies. Hudson (1984) points out the different forms of water erosion, providing a sole chapter about nature, causes and management of gully erosion. Zachar (1982), Lal (2001), Posen et al. (2003), Valentin et al. (2005), Carey (2006), Blanco and Lal (2008) have attempted to cover all aspects of water erosion, factors of gully erosion and quantitative analysis of tunnel erosion, rill and gully erosion. Morgan (1986 and 2005) gives much more focus on the genesis of gullies, newly developed quantitative measurements of gully erosion and management of gullies.

In India Ahmad (1970), Sharma (1970, 1976, 1982, 1986 and 2009) and Singh (1987, 1991, 1993, and 1996) have given notable contribution in the research of ravine and gully erosion. Sharma (1970, 1980, 1982 and 2009) reviews the progress of researches in ravine and gully geomorphology in India and he points out five prime theories of origin of ravines and gullies in Indian context. Singh and Agnihotri (1987), Singh and Dubey (2002) have done extensive research on the genesis and management of gullies with an environmental geomorphic approach. Rill mechanism, Gully initiation, slope modification, badlands development and gully erosion processes in the laterite terrain were scientifically discussed by Kar and Bandyopadhyay (1974), Bandyopadhyay (1987 and 1988), Das and Bandyopadhyay (1996) and Sen et al. (2004). Jha and Kapat (2003, 2009 and 2011) have extensively studied the degraded lateritic land of Paschim Medinipur and Birbhum districts of West Bengal and Dumka block of Jharkhand.

1.3.3 Reviews on Soil Erosion Modelling

At international level numerous predictive empirical models and physical based models are developed to assess soil erosion precisely in the hillslopes and catchments. With more comprehensive soil and land use database, Wischmeier and Smith (1972 and 1978) had been developed the Universal Soil Loss Equation (USLE), applying in Alps Mountain. Morgan (1986 and 2005) has mentioned several methods and models of soil erosion estimation, focusing more on USLE and Morgan, Morgan and Finney method. Morgan and Duzant (2008) have applied modified MMF method for the estimation of soil loss on crops and vegetation cover. They have described important field methods of evaluation soil erosion by water using USLE method mainly.

At national level Singh and Dubey (2002) have measured soil erosion by direct field measurement and USLE in a catchment. Similar study is done by Jha and Paudel (2010) and Pandey et al. (2009) in the mountainous watersheds of Himalayas. At regional level Jha and Kapat (2003, 2009 and 2011) predict the erosion rate of lateritic soils of Birbhum using USLE model.

1.4 Development of Project Plan

The aforesaid research and experimental works have mostly been carried out in entirely different climatic, pedogenic and agro-economic environment of the concerned regions and hence the investigators have obtained various environmental responses from different geo-environmental systems. Reviewing the former research works and preliminary survey we have identified following important issues or key areas to frame the project work regarding the geomorphic analysis of gully erosion in the lateritic region:

- Loose secondary laterites are overlain on the hard primary laterites. These exposures of secondary laterites are very much susceptible to rill and gully erosion. Under certain topographic conditions and internal character of laterites the extreme overland flow gets enough potentiality to erode the surface of laterites in the time of rainstorm events.
- Gullies and ravines are developed on various types of soils but evolution of gullies on laterites is a very complex phenomenon which is still unexplained. Therefore, the stages of rills and gullies development over lateritic terrain should be given prime importance to draw new direction of soil erosion research.
- To estimate annual rate of soil erosion several models or methods can be applied but the selection, application and validity of models or methods are very crucial aspect of

soil erosion research. MMF and USLE methods are very widely used in soil erosion study but there is difference between actual field data and calculated data. There is no argument about the applicability of MMF or USLE in lateritic soils.

- There are several internal and external variables in the models of soil erosion estimation. But importance and dominance of those variables are not judged. The question is raised why the lateritic profile of West Bengal is more prone to water erosion and what are the internal factors of lateritic soils which enhances soil erodibility.

Therefore, this experimental project work is developed to give importance to the above mentioned issues. It principally aims to find out morphometric attributes and erosion dynamics of gullies in relation to erosion risk assessment and to estimate annual soil erosion rate in connection with erosion control strategies.

1.5 Methodological Outlook

To carry on the proposed project operations we need a full well-equipped research design (figure 1.4) which is enough flexible, appropriate, efficient, economical and scientific. Research design of soil erosion study stands for advance planning of the methods to be adopted for collecting the relevant data and the techniques to be used in their analysis, keeping in view the objectives of the research. Soil erosion study has an interdisciplinary outlook which incorporates geology, geomorphology, pedology and hydrology under the shade of one umbrella - pedogeomorphology. So the framework of project design should be strong enough to make it viable for long term, adopting sound methodology of aforesaid disciplines.

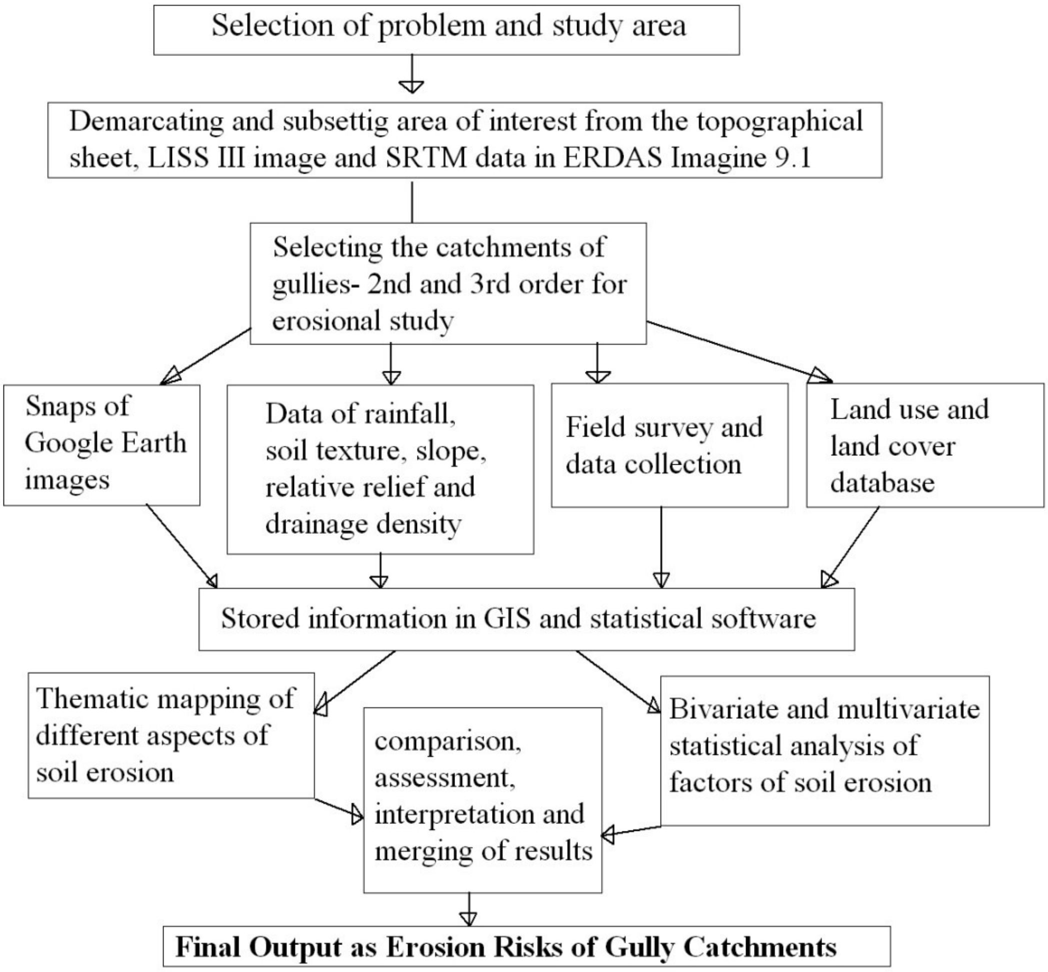


Figure 1.4 Flowchart of methodology used in the project work

1.5.1 Study Area Selection

The selected study area has approximately 176 km^2 of areal coverage, encompassing eastern plateau fringe of Rajmahal Basalt Traps which consists of western Rampurhat I block of Birbhum district, West Bengal and eastern Shikaripara block of Dumka district, Jharkhand. It is the lateritic elevated interfluve portion (mean relief of 50 - 60 metre) of Brahmani (north) and Dwarka (south) Rivers. The laterites and lateritic soils of Cainozoic Era are found here over the Rajmahal Trap-Basalt of Jurassic to Cretaceous Period.

For in-depth research first of all we should pay focus on spatial scale or spatial unit of study. As the drainage basin is universally considered as fundamental unit of geomorphic study, then it is thought to select different orders of gully-catchments where the distinctiveness of land use – land cover, different profiles of laterites and soil erosion processes are easily analysed. Alongside to get a picture of topographical variations, slope categories, aspects of drainage etc. it is very useful to select one square km grid on the basis of topographical sheets of Survey of India. Importantly to measure gross erosion slope facets, *viz.* valley side slopes of catchments, are selected. Dividing the catchment into several slope facets (perpendicular to contours, from water divide to the base of gully) erosion rate can be measured. So it is planned to subdivide the study area into different orders of gully-catchments because it can provide actual spatial distribution of soil erosion rate and can identify erosion prone catchments.

Measurement of erosion demands an ideal spatial and temporal scale which would represent the whole soil denudation system under a wide range of variables. Five relevant spatial scales are chosen for this study:

(1) the point (1 m^2) scale for inter-rill erosion (splash erosion),
(2) the plot (<100 m^2) for rill erosion,
(3) the hillslope (<500m) for soil erosion modelling and sediment deposition,
(4) the field (<1 ha) for channels and
(5) the small watershed (<50 ha) for spatial interaction effects and prioritization of erosion risk watershed.

1.5.2. Data Collection

Considering the objectives and methods of research outlook the required database is borrowed from both secondary and primary sources. It is expected to include the hydrological, geomorphological and pedological dataset under one shade of umbrella. The expected sources of main secondary data are regional soil report, geology report and other physical environmental report published by NBSS and LUP, Census of India, district gazetteer, official websites of IMD Pune and Kolkata, Irrigation and Waterways Dept. of Govt. of West Bengal, Geological Survey of India (GSI), related e-books and e-journals. The topographical sheets of Survey of India (72 P/12/NE, R.F. 1:25,000 and 72 P/12, R.F. 1:50,000), District Resource Map of Geological Survey of India, District Planning Map of NATMO (National Atlas Thematic Mapping Organization) and Block map of Census of India are most important sources of spatial information. Landsat TM and ETM+ (30 m resolution) images are downloaded from the website of Global Land Cove Facility (GLCF) and SRTM (Shuttle Radar Topography Mission, 90 m resolution) and ASTER (*Advanced Spaceborne Thermal Emission and Reflection Radiometer*, 30m resolution) elevation data are downloaded from the websites of GLCF and Consortium for Spatial Information (CGIAR-CSI). The spatial information is stored in Geographic Information System (GIS) and the thematic maps are prepared using GIS software (ArcGIS 9.2, Erdas Image 9.1 and MapInfo Professional 11.5). The different statistical analysis (e.g. linear and curvilinear regression, correlation, principal component analysis, cluster analysis and multiple regressions) is done in Microsoft Excel 2007 and SPSS 14.0 software.

In this case we have gathered the daily, monthly and annual rainfall data from three IWD are collected (Irrigation and Waterways Department, Government of Wes Bengal) raingauge stations at Nalhati (24°17′25′′N, 87°49′44′′E), Rampurhat (24°10′13′′N, 87°46′50′′E) and Mollarpur (24°04′35′′N, 87°42′36′′E) which are situated at eastern part of study area, having areal distance of 18 to 25 km. The calculated mean annual rainfall for this region is 1510 mm in 2016 (maximum intensity of erosive rain is 25.21 mm hr^{-1}) and the per day rainfall amount is 17.48 mm, considering total rainfall and rainy days in a year.

In spite of importance of secondary database, this research demands rigorous field investigation, direct measurement and survey to gather primary data regarding erosion. With the help of instruments and manpower we have to collect soil samples along each slope facets with certain interval. In many cases several vertical laterite profiles were studied to understand the genesis of lithofacies and the lateritsation processes. Detailed field investigations for weathering archives are conducted in the sample sites (covering *Rarh Bengal*, figure 3.1*)* of Nalhati (24° 17′ 47′′ N, 82° 49′ 28′′ E), Pinargaria (24°12′13′′ N, 87°40′13′′ E), Ghurnee Pahar (24°15′43′′ N, 87°39′11′′E), Adda (23°52′11′′ N, 87°32′47′′ E), Dubrajpur (23°47′12′′ N and 87°25′19′′ E), Sriniketan (23°41′31′′ N and 87°40′31′′ E), Hetodoba (23°26′45′′N and 87°32′07′′E), Bishnupur (23°05′28′′ N and 87°16′15′′ E), Garhbeta (23°05′28′′ N and 87°16′15′′ E) and Rangamati (22°24′42′′N, 87°17′55′′E), covering the span of study area.

Data regarding land use, land cover, slope, sediment load, sediment deposition, rainfall, runoff and other geomorphic data of gullies can be collected from filed plots. As the study deals with physical processes so our focus is placed much more on pedogeomorphic database but it can’t ignore the influences of human activities to enhance or reduce soil erosion rate. So with proper structured questionnaire it is expected to get primary information about the observable factors of soil erosion and human perception on erosion. To analyse the gully morphology several long and cross profiles were performed in the selected catchments. Google Earth Imagery and GPS-based mapping were performed to portray the spatial extent of gullies. Apart from the quantitative data, the research emphasizes on direct empirical observation and field perception of researcher. Therefore, agglomerating significant primary, secondary, qualitative and quantitative dataset the research objectives can be finally achieved in a fruitful way.

1.5.3 Geomorphic Field Survey

The spatial scale to study erosion processes is here plot-scale (10 to 100 m^2) and field scale (100 to 10,000 m^2). In terms of identifying the geomorphic thresholds in gully initiation, the present experimental work includes the 118 gully heads (both valley-floor and valley-side gullies). To depict the role of ground slope and to identify critical slopes (i.e. potential for gully incision) we have selected 146 valley-side slopes randomly in this lateritic terrain, including gullied and un-gullied slope segments. Sprinter 150 m of Leica Geosystem was used to measure the angle of slope facets. Alongside in few cases (due to obstacles) from ASTER DEM (Digital Elevation Model) the slope length and angle (usually from gully headcut to water divide) is measured to judge the length of surface flow (responsible for gully erosion).Drainage area is calculated from the flow direction and flow accumulation algorithm of ArcGIS 9.3 using drainage lines (digitized from toposheets) and DEM.

For the purpose of the study we have selected few catchments of gullies having distinct network, land use – land cover and hydrogeomorphic identity. Using Garmin GPS (Global Positioning System) receiver 76csX (horizontal accuracy of ±3 m) we can locate exact locations of slope facets, rills, gull heads and eroded features including up-to-date spatial information. To judge the calculated and observed erosion rate we have selected few catchments, with natural vegetation-bushes, covered with grass and bare soil, and covered with crops. Erosion, deposition and sediment load are thought to be measured during heavy rain-storm. Runoff of each catchment is expected to calculate using modified SCS (Soil Conservation Curve) Curve Number method and land use – land cover classification of satellite images.

Figure 1.5 Spatial extent of gullies and sample locations of gully heads in the areas of (a) Maluti (24°09´45´´N, 87°41´14´´E) and (b) Bhatina (24°10´25´´N, 87°42´33´´E) (Google Earth imagery date: 13/01/2014), and filed photographs showing (c) collection of sediment at the base of gully head at Maluti, Jharkhand, (d) barren lateritic upstream landscape of gully-head catchment at Bhatina, West Bengal, and (c) downstream dissection of laterites by deeply incised gully and expansion of gully heads at Bhatina, West Bengal.

Soil erosion is thought to be measured using erosion pins at the inert-gully crests, middle and bottom portions of the valley-sides of gully. To calculate the channel erosion and volume of sediment yield we have expected to conduct cross-sectional survey of selected transect along the valley (from gully head to gully mouth) using Sprinter Leica Auto Level instrument (height accuracy ± 1.5 mm, distance accuracy ± 1 mm) and Leica DistoS910 Laser Distance Meter (height accuracy ± 0.05 mm, distance accuracy ± 1.0 mm). The main task is to calculate the eroded area between two transect profiles and then to estimate volume, multiplying the area with length between two transect (figure 4.14). The area of profile is measured using the trapezoidal equation or cone. To estimate loss of earth materials between two transects can be estimated using the following equation.

Loss of Earth materials (kg) = Bulk density of earth materials / volume of each segment

The bulk density of laterite profile (up to 2 m) is estimated in the laboratory taking different samples from different depths. The calculated average bulk density is 2.205 gm cm^{-3}. After summation of transect value in a gully the total loss of earth materials is measured. This loss of land is permanent lost due to gully erosion in the catchment.

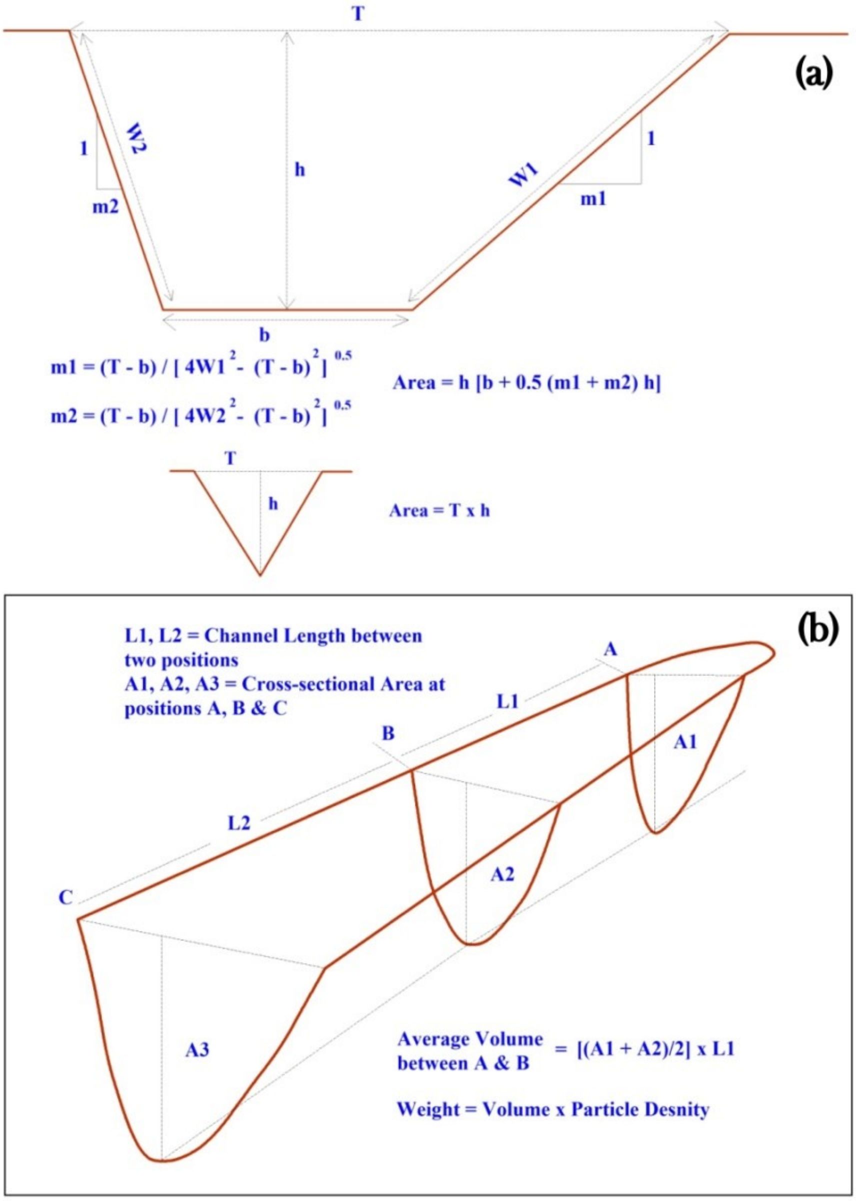


Figure 1.6 (a) Geometric representation to estimate gully cross-sections, and (b) a model of estimating gully erosion through volume measurement and particle density

The observed mass movement or loss of land during the rainstorm is bank failure in the sidewall of gully and also headcut. Formation cracks and undercutting by erosive flow enhances the chances of bank failure or erosion. To estimate the potential sites of bank failure a survey was performed using Leica DistoS910 Laser Distance Meter (height accuracy ± 0.05 mm, distance accuracy ± 1.0 mm).At first the vulnerable banks were indentified, then depth of bank and width of cracked mass were estimated to calculate the volume of mass. The area of irregular shaped bank was measured by the instrument using the 3D area measurement tool (figure 4.15). The gully bank retreat rate was measured at selected way points using Garmin GPS receiver 76csXand Google Earth History images. The difference (length in m) of present and former positions was calculated by the GIS ruler in the Google Earth and the rate of retreat (m yr^{-1}) was calculated on the basis of year difference. Using same principle the gully head migration rate was measured in the 116 sample gully head locations.

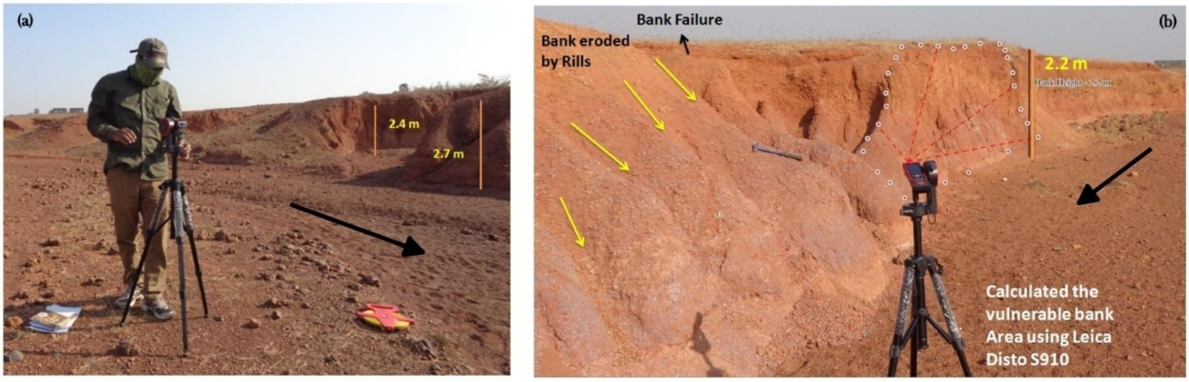
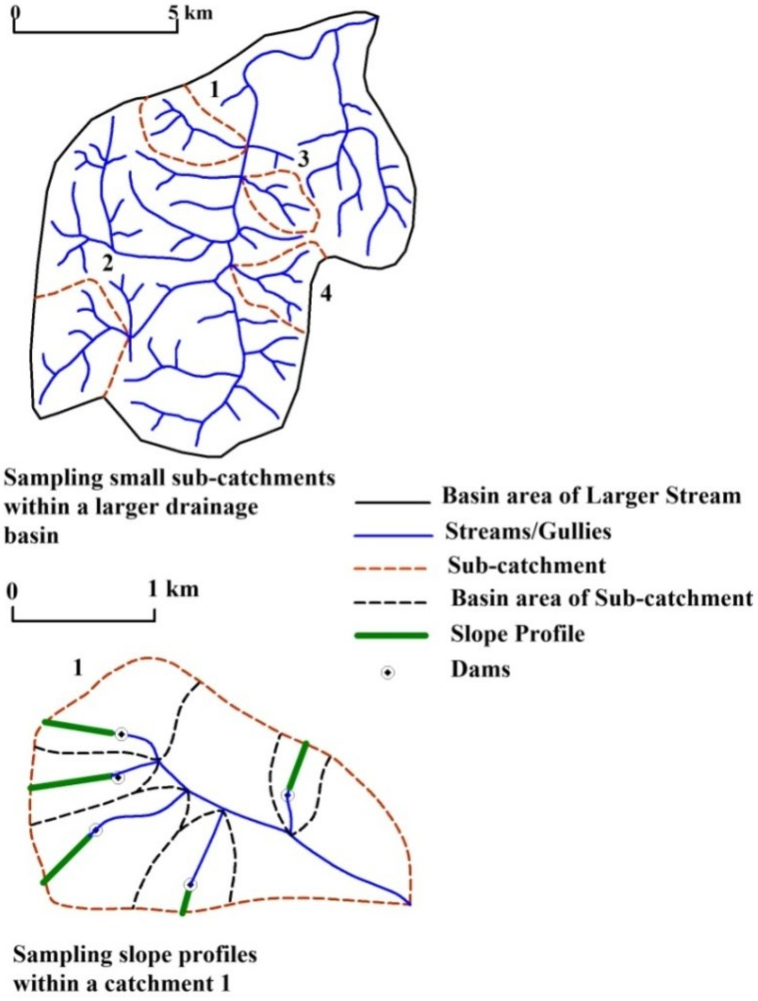


Figure 1.7 Estimating vulnerable gully sidewall or bank using Leica Disto S910 at (a) gully catchment 1 and (b) gully catchment 3

1.5.4 Experimental Site Preparation

The selection of measurement sites to establish the pattern of sediment movement poses a problem of sampling. Since it is only possible to take measurements at specific points in the landscape, it is important that these area representative of the catchment as high erosion prone zone (where maximum erosion is observed). From the field survey it is observed that except channel erosion gully head slope is the key pathways of sediment transport to the main gully channel. The main mission is that if a full picture of soil erosion by water over a landscape is to be established, it is necessary to examine the various sources of sediment, the pathways along which it is moved to the catchment outlet and the opportunities for deposition on the ways.

Here the catchment of gully is considered where minimum interference of human are noticed, because it is the purpose to study slope erosion processes and variable interaction of soil – land use factors in the normal and natural condition. Therefore, in this lateritic terrain a high erosion risk catchment of gully is selected, i.e. Gully Catchment 1 which has well defined basin area (about 1,09,250m^2) and dense network of gullies (8.33 km km^{-2}). Firstly, six gully heads are identified and then six gully head slope elements (considering 2 m width of slope strip to incorporate soil – land use parameters) are selected, denoting S1 to S6 respectively. The slope is measured using Leica Sprinter 150 m and other parameters of models are estimated in field survey (2016 – 2017). The total slope length is the overland flow part between the gully head and water divide. The steepness of slope elements varies from 5°58′to 11°06′, whereas slope length varies from 20.1 m to 74.6 m. Maintaining a certain distance from active gully head, six check dams have been developed (denoting Dam 1 to Dam 6) at the base (i.e. gully floor) of representative slope elements to trap eroded sediments coming from upslope in a year (2016 – 2017).



Sampling small sub-catchments within a larger drainage basin

Sampling slope profiles within a catchment 1

Figure 1.8 Experimental designs for erosion modelling at hillslope scale in a catchment

The basic structure of check dams has V-shaped design and the dams have height range of 40 – 55 cm and width range of 92 – 190 cm. The basic materials of sand, cement and laterite boulders are used to prepare these check dams as the sediment trap tanks in January, 2016. During monsoon season (June to October) of 2016 the eroded materials of these slope elements are trapped behind the dams. Then, after one year the sedimentation depth behind the dams in January, 2017 is measured. Now sedimentation volume is calculated as multiplying sedimentation area and depth and sedimentation at six dam sites. After that, multiplying the volume with bulk density of eroded materials (1.71 gm cm^{-3}), estimated weight of sedimentation materials is measured and divide it with strip area of slope element to calculate rate of erosion per area between 2016 and 2017.

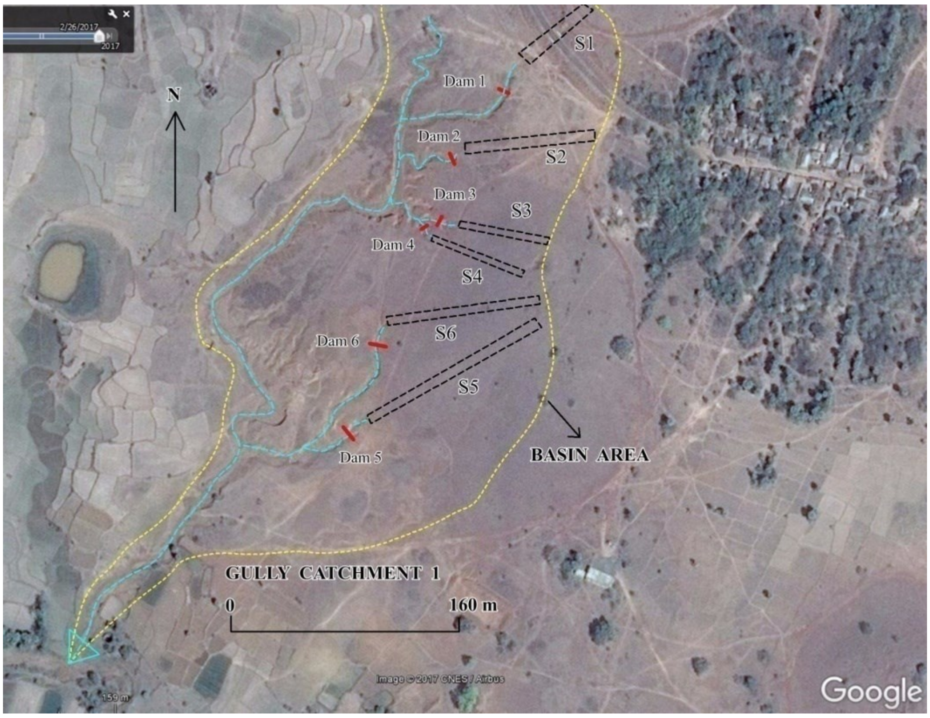


Figure 1.9 Sample slope profiles and dam sites in the gully catchment 1 (Google Earth Imagery, 26/02/2017)

1.5.5 Research Design and Modelling Techniques

The mass data set pertaining to climatic, hydrologic, geomorphic, pedological etc. generated through instrumentations, field measurements and post-field calculation are stored, tabulated and scientifically analysed with the help of software. In this case we have used Erdas Imagine 9.1, ArcGis 9.2 and MapInfo Professional 11.5 for thematic mapping and satellite image interpretation. SPSS 14.0 and Microsoft Excel 20037 are used for rigorous statistical analysis. The study area is well demarcated using topographical sheets and boundary of study area, basin areas, slope facets and point features are transformed into vector layers in GIS software and GPS. Getting all sorts of vector data we have subset the study area from SRTM data and satellite images (Landsat and IRS) of different time period. Using image processing software and applying supervised classification system (having proper training sites and ground truth verifications) and different types of indices (i.e. NDVI, NDWI, soil index and iron index) we have classified the images of different time period to identify spatial changes in relation to degradation or erosion. We have tentatively used different measures of central tendency, measures of dispersion, confidence limit, correlation, regressions, significance tests, principal component analysis, dendrograph, cluster analysis etc. to get significant results.

Table 1.2 Stages of erosion model development, selection and application in study area (modified from Morgan, 2011)

Sl. No.	Stages	Requirements	Remarks
1	Objectives	Definition of problem; required temporal and spatial scales; required output; required level of accuracy of prediction	Annual rate of soil loss at hillslope scale
2	Conceptualization	Understanding of system being modelled; required level of simplicity / complexity; definition of system variables; definition of key processes; construction of flow diagram etc.	RUSLE has included rill and inter-rill erosion; RMMF has water phase and sediment phase in soil erosion system
3	Process Description	Decisions of best available mathematical descriptions of processes; parameterization of system variables; availability of input data	All equation of RUSLE and RMMF have defined with descriptions; estimating values of models' parameters
4	Boundary Conditions	Selection of appropriate time and space boundaries	Yearly rate of soil loss and hillslope above gully head
5	Sensitivity Analysis	Rationality of model; determination of most sensitive input parameters; required level of accuracy of input data	Average Linear Sensitivity analysis (Nearing et al., 1989)
6	Calibration	Feasibility of calibration; selection of key parameters for calibration; calibration procedures	Selection of dominant parameter and weight scores of parametric values in models
7	Validation	Criteria for goodness-of-fit; selection of dataset for validation; validation procedure; required level of accuracy for acceptance of model	Model Efficiency Coefficient of model (Nash and Sutclifee, 1970; Morgan, 2005)
8	Application	Decision of whether model is appropriate; data requirements, setting up and running of the model; analysis of results	Interpretation of results and comparison of models with observed data

Models are of necessary simplifications of reality (Morgan, 2005). Researchers seek models that describe how the system functions in order to enlighten understanding of the system and how it responds to change. It is not possible to take measurements at every point in the landscape and it also takes time to build up a sufficient database and long-term measurements. In order to overcome these deficiencies, models can be used to predict erosion under a wide-range of conditions. Reminding other critical issues (table 1.2), the first step in choosing a model is to identify how the model will be used, the information that is needed from the model and the information that is available for input into the model (Morgan, 2011; Toy et al., 2013). The second step is to determine the resources available for implementing and using the model comparison to the resources required to implement alternative model (Toy et al., 2013). The third step is to review the available models and select one (Boradman and Favis-Mortlock, 1998). Most of the models used in soil erosion studies are of the empirical grey-box type (Morgan, 2005). They are based on defining the most important factors through the use of observation, measurement, experiment and statistical techniques, relating them to soil loss. In the present study RUSLE (Renard et al., 1997) and RMMF (Morgan, 2001) models are chosen to estimate annual rate of soil loss in hillslope scale.

To predict soil loss by water action we have employed two popular and widely used models – (i) Revised Universal Soil Loss Equation (RUSLE) and (ii) Revised Morgan, Morgan and Finney method (RMMF). These simplified models encompass numerous factors and associated parameters, related to climate, soil, land cover, topography and time. Then the required input parameters to models are collected from each slope facets of gully-catchment, viz. soil texture, soil moisture, bulk density, soil depth, soil cohesion, runoff depth, rainfall intensity, effective rainfall, slope steepness, slope length, canopy cover etc. Inputting these parameters to operating functions of the models we can estimate annual soil erosion rate per slope section and can make inference of total erosion form a catchment. The prime objective is to estimate annual mean potential soil erosion rate above gully heads in a catchment and to validate the models in comparison to soil loss tolerance limit and observed results in a year.

It is carried out on RUSLE and RMMF models to show that the models behave rationally. Rational behaviour is generally judged on whether the level of sensitivity of the factors in the model matches what is expected in reality and whether the relationships between output and the controlling factors accord with what is observed in field (Morgan, 2005 and 2011). Validation is the process of ensuring that the model serves its intended purpose as described in the user requirements (Morgan, 2005; Toy et al., 2013). Although an important part of validation is to determine how well the model fits with measured data. Erosion models typically fit measured average annual soil loss with an uncertainty of about ± 25 % for moderate erosion rates of about 6 to 60 metric tons per hectare per year (Toy et al., 2013).

Chapter 2.0

2.1 Geo-environmental Setting of Study Area

The geomorphic unit of study area is recognized as an interfluve in between Brahmani (north) and Dwarka (south) rivers (confined by 24° 20′ N to 23° 40′ N, and 87° 26′ E to 88° 21′ E) which are flowing in the northern part of Birbhum district, West Bengal (figure 2.1). Dwarka River Basin (2,978 km^2) is a sub-basin of Mayurakshi River Basin and Brahmani River (1,139 km^2) is a sub-basin of Dwarka River. Both the river have originated from the Rajmahal Hills of Dumka District, Jharkhand and Dwarka flows through Birbhum and Murshidabad districts of West Bengal where it joins with Mayurakshi to form Babla River that finally outfalls into the Bhagirathi River. Brahmani River meets with Dwarka near Nabagram, Murshidabad. Geomorphologically, the interfluve of Dwarka – Brahmani is associated with plateau proper and plateau fringe of Chotanagpur, having laterite exposures and basaltic hills, and also the northern part of the *Rarh* Plain (Biswas, 1987). Most of the Peninsular Rivers flow from west to east direction, guided by the general basement slope towards the Ganga-Brahmaputra Delta. Geologically, the present research work deals with the contiguous unit between Rajmahal Basalt Traps (RBT) (Early Cretaceous origin) and the Bengal Basin which exhibits shallow Quaternary alluvium deposits and palaeogenesis of the deep weathering profiles under intense tropical wet – dry palaeoclimate on the basaltic surface to form hard ferruginous crust, i.e. ferricrete.

2.2 Characteristics of Study Area

The selected study area of Dwarka – Brahmani interfluve (about 176 km^2, confined by 24°08′N to 24°14′ N and 87°38′ E to 87°44′ E latitude and longitude respectively), covering Shikaripara block (Dumka, Jharkhand), Rampurhat I and Nalhati I blocks (Birbhum, West Bengal) (figure 2.2). This area is located at 5 to 6 km west of Rampurhat railway station on the highway of NH 114A (around Rampurhat to Dumka road). The region belongs to southern fringe of RBT (50 – 448 m from msl) which was chemically weathered due to lateritization processes from Palaeogene to Late Pleistocene. Field study reveals successive occurrences of fresh quartz-normative tholeiite Rajmahal basalt, weathered coarse saprolite, kaolinite pallid zone, mottle zone and pisolitic ferricrete in the sample sections, analogous to ideal tropical profile of laterite (discuss in details in chapter 3). Each laterite section reflects both primary *in-situ* type palaeogenesis of high-level plateau laterites and secondary *ex-situ* evolution of piedmont slope laterites which are prone of water erosion, forming patches of badlands in the *Rarh* Plain. These badlands of Himalayan Foreland Basin and Chotanagpur Plateau Fringe are believed to have developed due to neo-tectonic activities, strengthen by south-west monsoon and intensive fluvial erosion in Late Pleistocene – Holocene (Ranga et al., 2015 and 2016). In the *Rarh* Plain of West Bengal (i.e. typical tropical morpho-genetic region, lying west of the Bengal Basin), the badlands of lateritic terrain is popularized as *'khoai'* in Bengali language (Ghosh and Guchhait, 2015). The specific geo-environmental settings of study area are discussed in the following sub-heads.

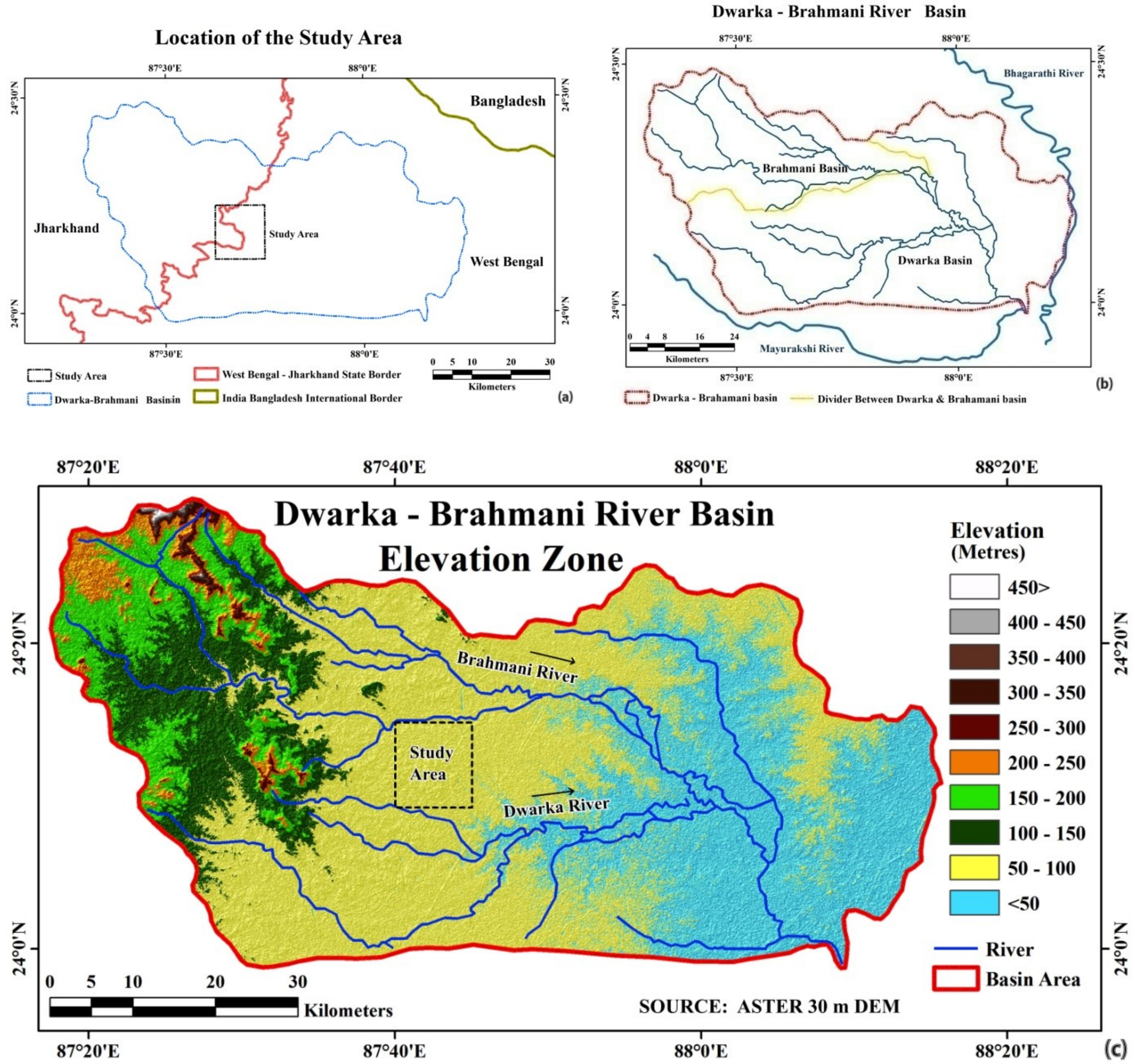


Figure 2.1 Location map and Elevation Zonation of Dwarka-Brahmani River Basin

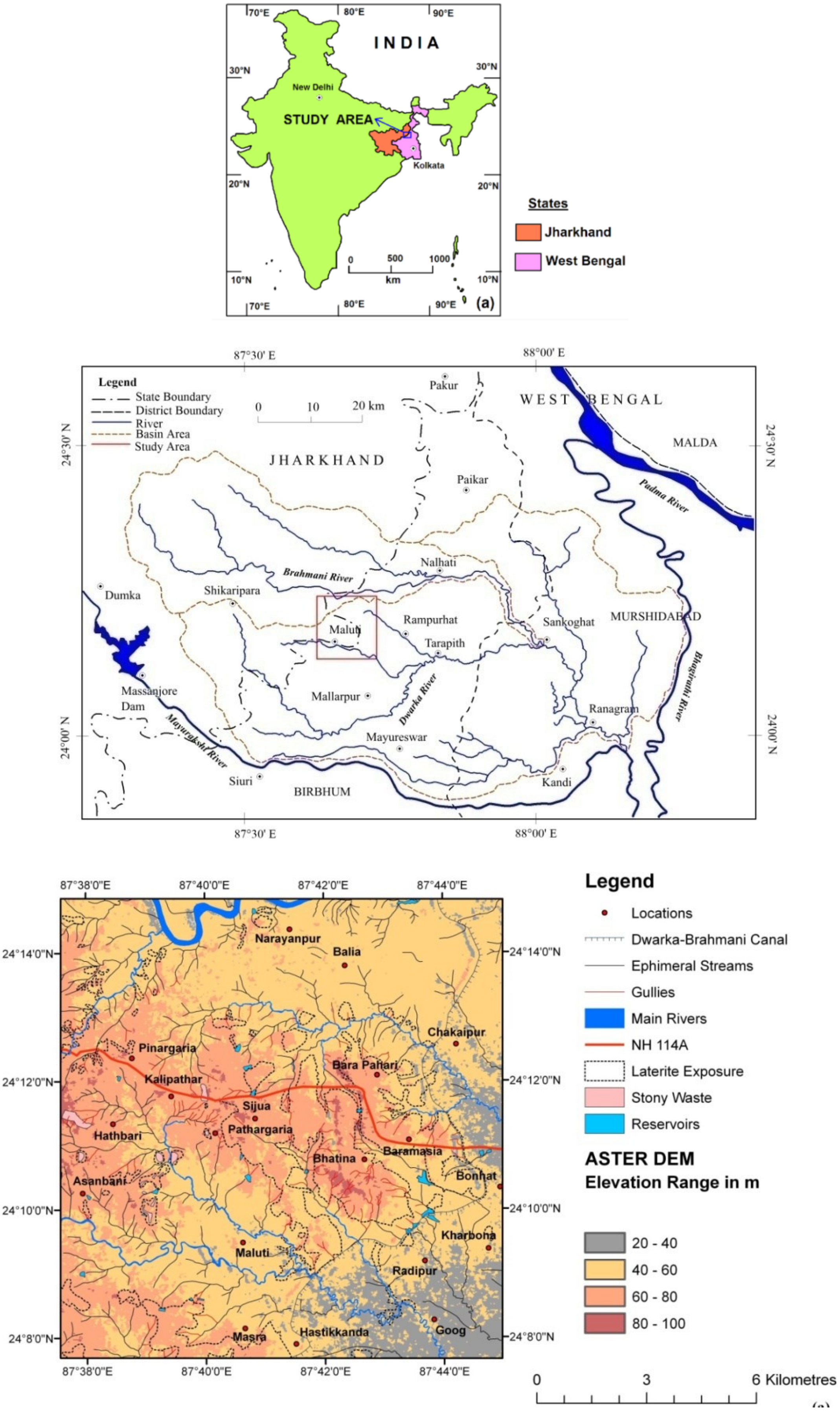


Figure 2.2 Location map and geomorphic representation of study area

2.3 Geology

The base of Quaternary to Palaeogene alluvium is the Rajmahal Basalt Traps which is older than Deccan Basalt Traps. The Rajmahal effusions are linked to India's passage over the Kerguelen and Crozet Hot Spots (Sengupta, 1972; Baksi, 1995; Kent et al., 1996; Mahadevan, 2002; Das Gupta and Mukherjee, 2006; Mehrotra et al., 2014). Kent et al. (1996) suggest that eruption of the Rajmahal lavas and formation of Southern Kerguelen Plateau are best explained by the presence of the Kerguelen hotspot close to the eastern margin of India just after ~ 113 – 116 Ma; followed by this event, the Deccan volcanism (63 – 69 Ma) found far into west, the Netarhat Plateau of Jharkhand state.

Though up to 28 flows, aggregating to a thickness of over 331 m have been reported from a borehole drilled in the western shelf of Bengal Basin by the Geological Survey of India (GSI), only 15 flows are demarcated amidst the outcrops of Rajmahal hills (Mahadevan, 2002). According to Ball (1877) the site of an volcanic vent is suspected in the Gandeshwari Hills, close to Simra, some 35 km SSE of Colong. On the basis of palaeomagnetism, the RBT was located near southern latitude of 46°S at time of volcanism (Radakrishnamurty and Sahasradudhe, 1958). The ^{40} Ar / ^{39} Ar and K-Ar age of basalts, calculated from the samples of the central and southwest RBT, yield an age of ~ 88 to ~ 118 Ma (Bakshi et al., 1987; Bakshi, 1995; Kent et al., 1997; Mahadevan, 2002). The radiometric ages recorded from some of these areas are 117±3 Ma at Galsi, 118±2 Ma at Barddhaman and 118±7 Ma at Debagram respectively (Das Gupta and Mukherjee. 2006). ^{40} Ar / ^{39} Ar geochronology data reveals that the lava pile of RBT of Jharkhand and alkali basalts of the Bengal Basin were emplaced at ~118 Ma (Kent et al., 1997).

The gravity modelling confirms that the RBT is well characterized by an elongated nature of relative high Bouguer anomaly (0 to 25 mGal) along 87°E in contrast to predominantly low Bouguer anomaly (0 to - 40 mGal) in its surroundings of Bengal Basin (Singh et al., 2004). This gravity modelling confirms that the Gondwanas (including coals) are preserved in a down-faulted shield edge of the Bengal Basin over an irregular basin floors. The N-S trending basin margin fault system (i.e. Chotanagpur Foothill Fault, Garhmayna – Khandaghosh Fault and Pingla Fault etc.) deepened the depth of basement from 1 – 4 km (north) to 5 to 10 km (South) (Nath et al., 2010; Ghosh and Guchhait, 2015).

The Rajmahal volcanic together with the intertrappean beds have a maximum exposed thickness of ~ 230 m (Ball, 1877; Kent et al., 1996). Presences of profuse remains of flora in the intertrappean beds (mainly cherts) signify the thick vegetative growth (Ptilophyllum flora, Palynomorphs, Dinoflagellates and plant mega fossils of Early Cretaceous) between successive eruptions (Kent et al., 1996; Tripathi et al., 2013). Over the RBT successively laterites, hard clay and caliches bearing Rampurhat Formation and alternating sand, silt and clay bearing Kandi Formation were developed (table 2.1).

Table 2.1 Geological succession since Archaean in Birbhum District

Lithology	Geological Unit	Age
Alternating layers of sand, slit and clay	Kandi Formation	Middle to Late Holocene
Hard clays impregnated with caliche nodules	Rampurhat Formation	Late Pleistocene to Early Holocene
Laterite	-	Cainozoic
Rajmahal Basalt Traps	-	Jurassic to Cretaceous
Sandstone and Shale	Dubrajpur Formation	Triassic to Jurassic
Sandstone and Shale with coal seam	Raniganj Formation	Upper Permian
Black and Grey Shale with Ironstone, Sandstone	Barren Measure Formation	Middle Permian
Siltstone, Sandstone and Shale with coal seam	Barakar Formation	Lower Permian
Pegmatite (unclassified)		Proterozoic
Granite Gneiss	Chotanagpur Gneissic Complex	Archaean to Proterozoic
Gabbro	Unclassified Metamorphics	Archaean to Proterozoic
Quartzite	Unclassified Metamorphics	Archaean to Proterozoic
Amphibolite, Hornblende, Schist	Unclassified Metamorphics	Archaean to Proterozoic

Source: Baksi et al. (1987)

2.4 Topography and Slope

In the RBT the high elevation zone (200 – 250 m) in the RBT is observed in the western part where the basalts are overlain on the Gondwana rock beds. The alluvium zone and the laterites are mostly found in the elevation zone of 0 – 50 m and 50 – 100 m respectively (figure

2.3). The cross-profiles of the region reflects the west to eastward slope and the elevation peaks of western part are the different basalt traps of different periods (figure 2.3).

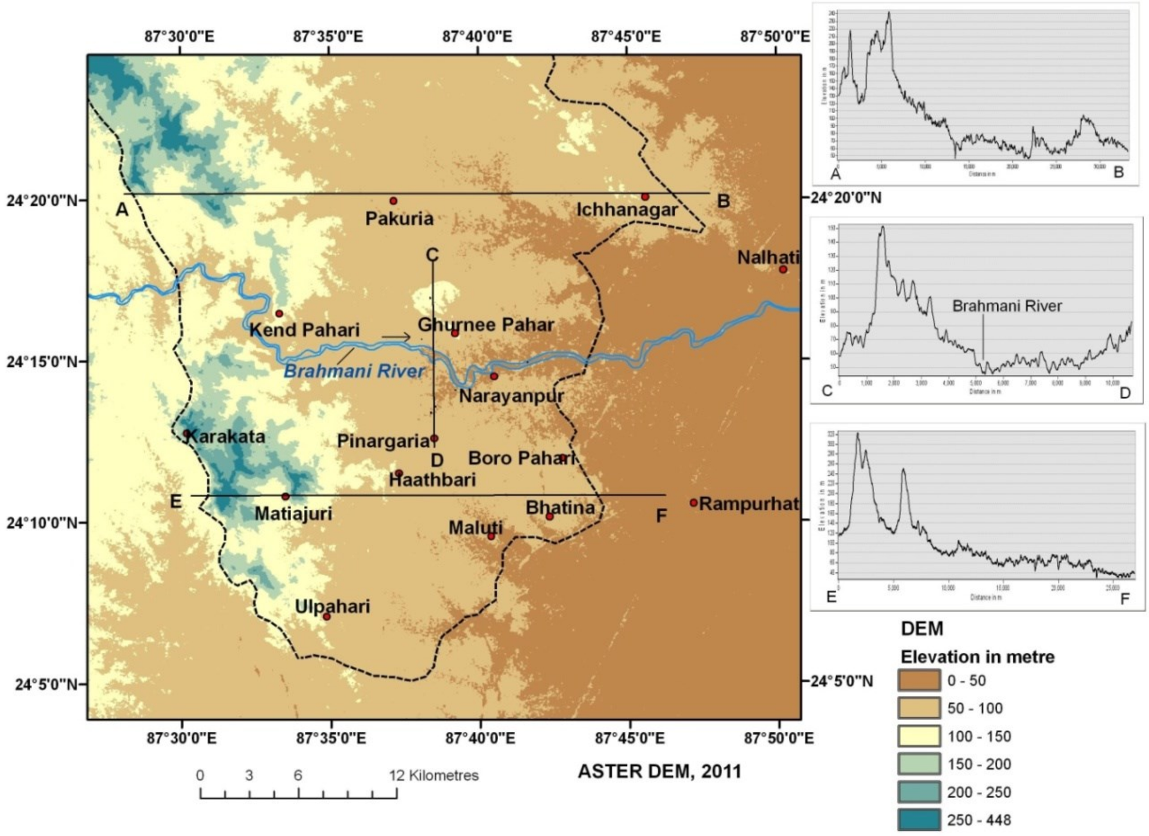


Figure 2.3 Elevation map (ASTER 30 m DEM) and different elevation cross-profiles of study area (note: dotted black colour polygon represents region of RBT outcrop)

Tectonic forces and resultant erosion contour the slope and its steepness are related to geological structure, but the successive erosion modifies the convex slope towards high steepness and deposition of concave slope can reduce the steepness. Observing the slope morphology of gully-catchments it is found that the slope steepness above gully head (i.e. convex part) varies from 5° to 13° in the study area and high degree of slope favours flow convergence and rill / gully initiation. High degree and long length of slope provide maximum kinetic energy to overland flow during the rainstorm and the accumulated flow gets enough force to overcome the surface resistance to erode. The convex slope with bare laterite surface is much prone to rainsplash erosion than concave slope (Hudson, 1984).

Average slope map is prepared using Wentworth method on the basis of contour data (5 m interval). There zones are recognized – (1) < 1° (very low slope), (2) 1° – 2° (low slope) and (3) > 2° (moderate slope) (figure 2.4). The high closeness of contour in the central region generates moderate slope and most of the region have low slope category. Moderate slope zone is associated with maximum drainage density (including numerous gullies) and numbers of gullies. The moderate slope zone has an areal coverage of only 6.09 km^2, whereas moderate slope zone covers an area of 94.17 km^2.

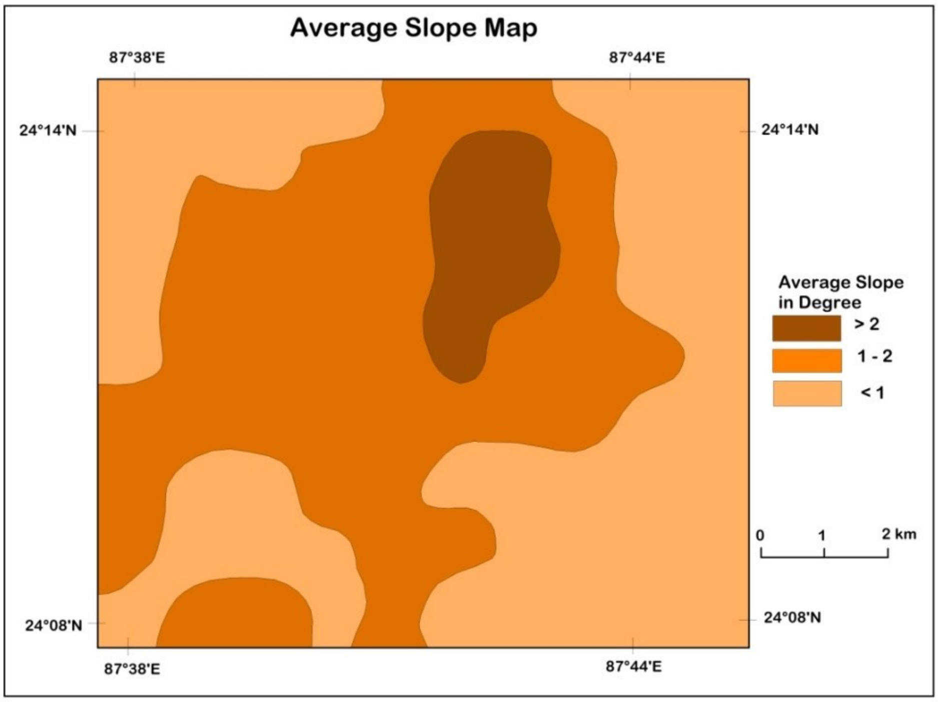


Figure 2.4 Average slope categorization in the study area (derived from Toposheet 72 P/12/NE, R.F. 1:25,000)

2.6 Climate

The climate of this region has been identified as sub-humid and sub-tropical monsoon type, receiving mean annual rainfall of 1300 to 1437 mm. The amount of rainfall is decreasing from western to eastern part. On the basis of 2010 – 16 rainfall data, the mean annual rainfall of Paikor, Md. Bazar, Rampurhat and Mallarpur is 720.0 mm, 1176.0 mm, 1293.5 mm and 1372.8 mm respectively. The peak monsoon and cyclonic rainfall intensity of 21.51 mm hr^{-1} (minimum) to 25.51 mm hr^{-1} (maximum) is the most powerful climate factor to develop this lateritic badlands. The recorded maximum and minim temperature is 45° C (April – May) and 9° C (December – January) respectively, with seasonal variation of 15° to 19° C. The period between mid-June and September is the active erosion phase due to heavy downpours, removing ferruginous sediments from the gully catchments.

The region is experiencing intense thunderstorms during hot summer and prolonged rainfall during the tropical depression and cyclone. The present climate of this region reflects a unique morpho-genetic region – Tropical Wet-Dry Zone (Koppen A_w Climate) of Planation Surface Formation (Chorely et al., 1984) where chemical weathering, sheet floods and hillslope erosion are dominant with the development of red loam kaolin rich ferruginous materials, tors and badlands are mostly developed.

2.7 Drainage and Geo-hydrology

The region is dissected by the numerous ephemeral and perennial streams of Dwarka and Brahmani River system. Specifically Chila Nadi and Kandor Nala are the two important streams which flow from west to east direction. As it is a lateritic highland, many other ephemeral gullies are bifurcated from the central highland, except the south to north directed Dwarka-Brahmani Irrigation Canal. Drainage density (Horton, 1945) is an important indicator of linear scale of landform elements in the stream-eroded topography. A thematic map of drainage density per km^2 (figure 2.5) is prepared on a spatial scale of 176 km^2 on the basis of topographical sheet (72 P/12/NE, R.F. 1:25,000). Most of the region is covered by low (1 – 2 km km^{-2}) and moderate (2 – 3 km km^{-2}) drainage density category (figure 2.8). Low and moderate drainage density region is estimated as 92.63 km^2 and 63.80 km^2 respectively (table 2.5). Very high drainage density (4 – 5 km km^{-2}) is observed in the elevated bare surface (relative relief of 15 – 25 m) where numerous gullies are dissecting the secondary laterites.

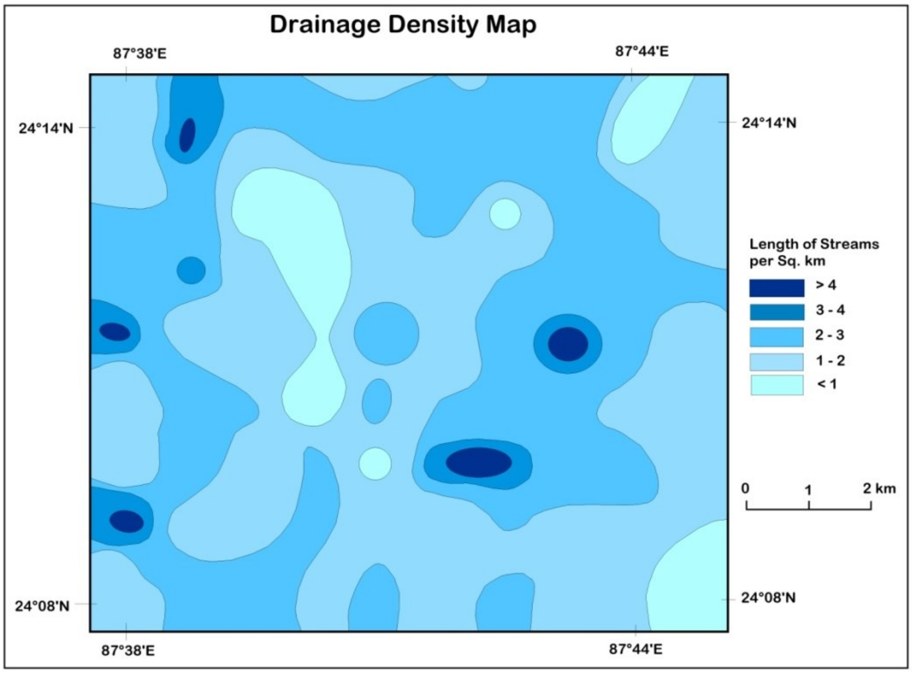


Figure 2.5 Zonation of drainage density in the study area (derived from Toposheet 72 P/12/NE, R.F. 1:25,000)

The laterites are underlain over the kaolinite clay which acts as perched aquifer and it forms many ephemeral springs at the base of high-level laterites. Many springs are located in

Harinathpur, Dhirnagar, Belbani, Haldasa, Phulpahari, Sunrichua, Tildanga and Kanchpahari. Many springes are observed along the gully floors. Basalts are found at a depth range from 15 to 28 m from the surface. On an average of ten years (2006 – 2015) in the pre-monsoon period the average groundwater level is above 10 metre and in the post-monsoon period the level can reach about 3 metre depth. At Nalhati block of Birbhum the water level fluctuation (2006) of pre-monsoon season is 3.06 – 9.72 mbgl (metre below ground level) and in post-monsoon it is 0.30 – 5.83 mbgl.

2.8 Soil and Vegetation

In and around the study area the soil series of Bhatina, Raspur and Jhinjharpur (Sarkar et al., 2017) has been developed in the present geo-climatic setting. Generally, the thin solum is loamy-skeletal and hypothermic in nature developing on the barren lateritic wastelands with sparse bushy vegetation and grass. The dark reddish to brown coloured sandy clay loam of 0 – 16 cm (A horizon, maximum grass root zone) is developed over the fragmented secondary laterites. These soil series has weak fine crumb and granular structure (slightly hard, friable and slightly sticky), 2 – 5 mm size of manganese nodules, > 2 mm size of ferruginous nodules with goethite cortex, 30 to 40 percent gravels and pebbles, excessive drained surface and pH of 5.4 – 5.7 (table 2.2).

The natural vegetation of the study area belongs to the tropical moist and dry deciduous type with few evergreen types. The observed natural vegetation species are: Babul (*Acacia nilotica*), Bel (*Aegle marmelos*), Behara (*Terminalia belerica*), Sal (*Shorea robusta*), Mahua (*Madhuca indica*), Khair (*Acacia catechu*), Khajur (*Phoenix sylvestris*) and Jamun (*Syzygium cumini*) etc. Though once upon a time the most of the region was covered under thick forest, mainly Sal; due to encroachment of stone crushers, mining and agriculture the forests are fragmented and vanished from some places. Still six scattered Reserve Forests (RF) are still alive, viz., Loripahari RF, Tumbani RF, Chandpur RF, Radipur RF, Bhatina RF, and Bonhat RF, and two protected forests are found, viz., Chhora P and Chakaipur RF.

Table 2.2 Description of soil series found in the study area

1. Soil Series – Bhatina

Layers	**Depth (cm)**	**Pedological Descriptions**
A	0 – 16	Dark reddish brown sandy clay loam; weak fine crumb and granular stricture; slightly hard, friable, slightly sticky and slightly plastic, 30 – 40 % gravels; medium and fine pores; $_p$H 5.4, abrupt wavy boundary
C_r	16 – 34	Weathered rocks with ferruginous concretions

2. Soil Series – Raspur

A_1	0 – 12	Strong brown and brown to dark brown loamy sand; weak medium crumb structure; slightly hard, friable pores and insect channels; very few hard Fe-Mn concretions; $_p$H 6.0; clear wavy boundary
B_w	12 – 31	Strong brown and brown to dark brown gravely sandy loam; weak, medium sub angular blocky structure; slightly hard, friable and slightly sticky; many fine and coarse roots; many fine and coarse gravels, $_p$H 6.2; gradual wavy boundary
C_r	31 – 52	Yellowish red to dark reddish brown; laterite mass with quartz fragments

3. Soil Series – Jhinjharpur

A_1	0 – 9	Strong brown sandy clay loam; weak medium sub angular blocky structure; slightly hard, friable, slightly sticky and slightly plastic; many fine and medium roots; appreciable amount of gravels; $_p$H 6.0; clear smooth boundary
B_{w1}	9 – 35	Strong brown sandy clay loam; weak, fine sub angular blocky structure; slightly hard and plastic; few fine roots;, appreciable gravels; $_p$H 6.2; clear smooth boundary
B_{w2}	35 – 42	Yellowish red sandy clay loam; weak, fine sub angular blocky structure; slightly hard, friable and sticky; few fine roots; appreciable gravels; Fe-Mn and Fe-AL mottles; pH 5.8; clear smooth boundary
C_r	42 – 56	Weathered granite-gneiss and quartz fragments

Source: Sarkar et al. (2007)

2.9 Land Use and Land Cover

The agricultural productivity is very low and most of the arable land remains fallow in dry season. The main crops are paddy, maize, corn and oilseed. Another distinctive land use of this region is stone mining and *morrum* mining which have modified the slope and morphology of the basaltic hills and the lateritc lands. Gradually it engulfs the afforested region (Acacia Plantation) also (figure 2.9). In the central part of the region an aerodrome is developed and it is used by Indian Air Force. In this area slope and topography has been modified and natural forest cover is also destroyed, but now acacia plantation covers the region. In the grassland parts, livestock grazing is observed and most of the land is infertile barren lateritic cover which has surface crusting of ferruginous materials.

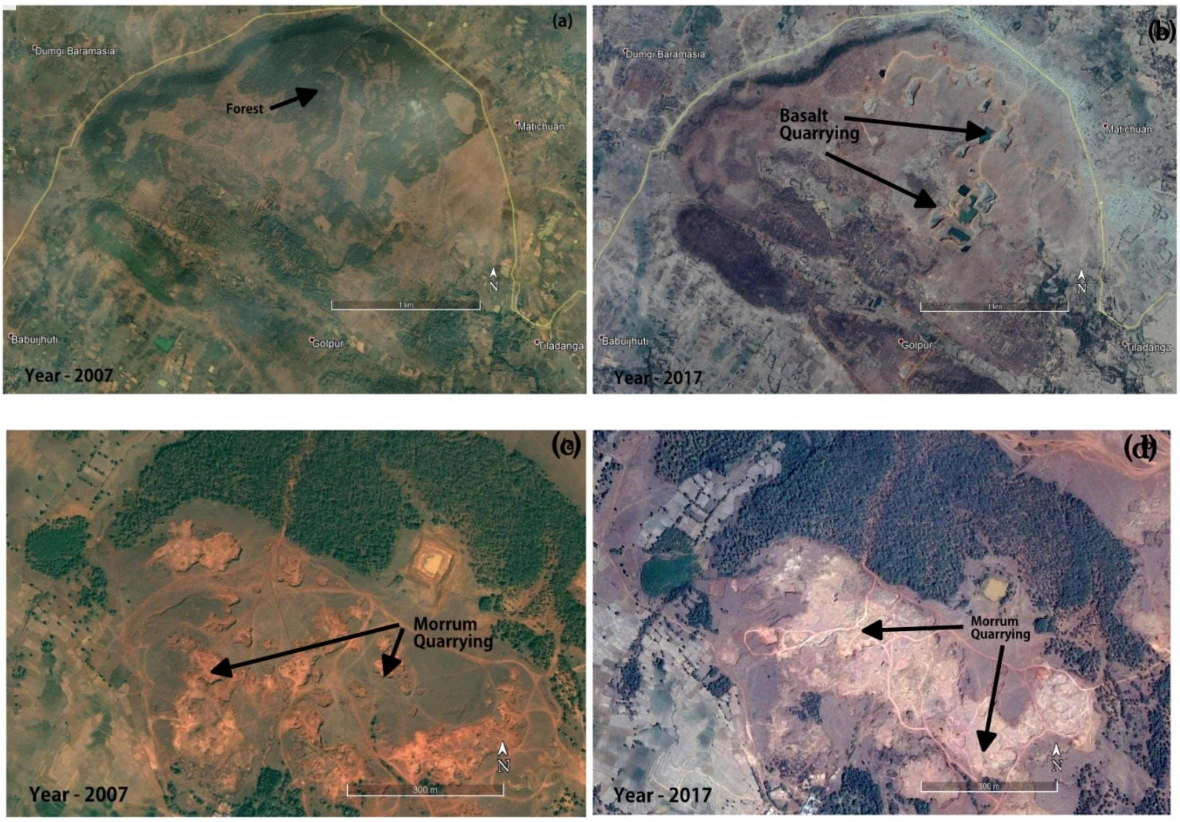


Figure 2.6 Identifying the Changes in land use through Google Earth Imagery - (a) and (b) the forest land are vanished due to development basalt quarrying in between 2007 and 2017 at Nalhati, Birbhum, (c) and (d) the lateritic land is engulfed by the morum quarrying in between 2007 and 2017 at Rampurhat, Birbhum

Using IRS LISS IV 5-m resolution (Dec, 2016) satellite image and Erdas Imagine 9.0 software a supervised classification has been performed to derive and analyse the broad categories of land use and land cover. The resultant image classification shows that green covers are identified as the natural green vegetation and grassland which covers an area of 58.83 km^2. The pediment surface of laterite is mainly covered with grass and the upland parts of hard laterites are covered under thick forest. Stone quarries, roads, built-up area and barren fallow land (including basalt exposure and non-arable land) cover an area of 79.56 km^2 which acts as main source region of surface runoff in the peak monsoon. Bare lateritic surface and *morrum* quarries cover an area of 16.78 km^2. At the time of satellite image (taken during winter, 2016) the existing area of arable land accounts for 28.92 km^2.

Chapter 3.0

3.1 History of Development of Lateritic Surface and Gully

It is quite impossible to travel far in India without observing the remarkable ferruginous crust to which Buchanan in 1807 gave the name of laterite. The geomorphic unit of laterites is recognized as *'Rarh* Bengal*'*, i.e. land of red soil, in the south-western part of West Bengal (Bagchi and Mukherjee, 1983; Sarkar, 2004). These patches of laterites hold the remnant forest of tropical deciduous plant species and the surface is intensively eroded by rills and gullies, developing badlands. One of the thrust areas of this research is to investigate soil erosion particularly in the lateritic terrain which is nothing but the erosion. So, it is utmost necessary to analyze first the erosion surface in light of geomorphic evolution and then to analyze the erosion processes operated on it.

The term 'Laterite' was first published in scientific literature in nearly 210 years ago. There are now very extensive scientific literatures to understand the variable aspects of laterite and lateritization processes. The laterite literature is heavily encumbered by problems of terminology and often different materials are described by a single term to avoid overloading the large laterite vocabulary. Now, the earth scientists prefer to use the term 'laterite profile' instead of only 'laterite' to study all the ferruginous weathered profiles and horizons, because laterite profile includes the sections of weathered rocks, pallid zone, mottle zone and ferricrete (i.e. duricrust).

3.2 Occurrence of Laterites in Study Area

The zones of laterites with Neogene gravel deposits is the spatial unit of morpho-stratigraphic study, bounded by the latitude of 21°30′ to 24°40′ N and longitude of 86°45′ to 87°50′ E (figure 3.1). Geomorphologically this part of West Bengal is recognized as western fringe of Ganga-Brahmaputra Delta and geologically this part was formerly developed as the stable shelf province of Bengal Basin which experienced severally marine regression and transgression since Miocene, related to climate change and neo-tectonic activity (Alam et al., 2003; Ghosh and Guchhait, 2015). The distribution of laterites and ferruginous soils of *Rarh* is limited to eastern part of Chotongapur Plateau fringe, covering an approximate area of 7,700 km^2 (comprising the districts of Murshidabad, Birbhum, Barddhaman, Bankura, Purulia and West Medinipur). A parallel west – east flowing (due to general west to east trending slope of underlying structure) peninsular drainage system (*viz.,* Brahmani, Dwarka, Mayurakshi, Ajay, Damodar, Dwarkeswar, Silai, Kangsabati and Subarnarekha rivers) dissect the lateritic *Rarh* region into patches of badlands and tropical deciduous forests of West Bengal (an area of 7,700 km^2).

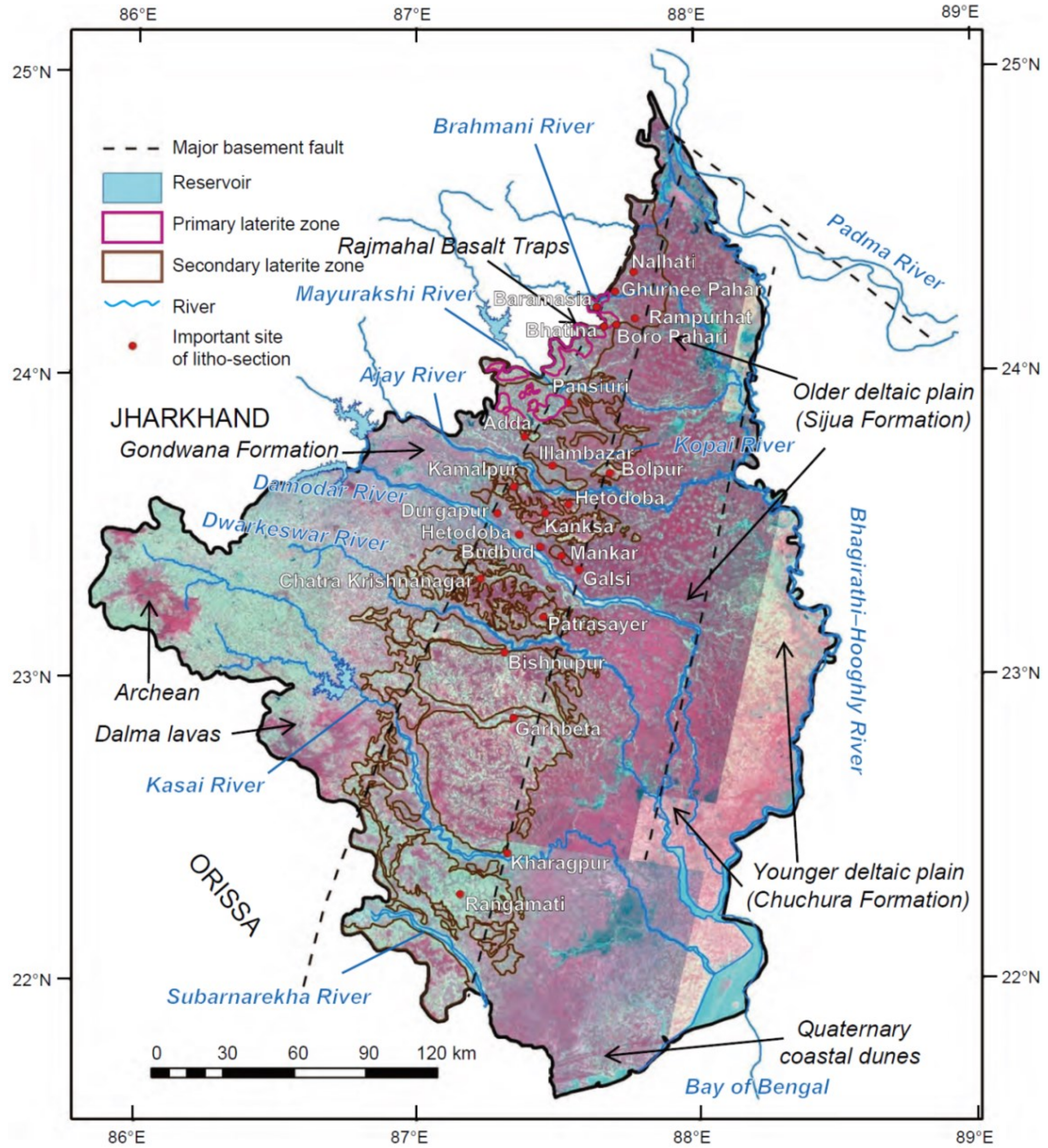


Figure 3.1: Spatial distribution of *Rarh* laterites in relation to basement faults of north-western Bengal Basin (Ghosh and Guchhait, 2015) (source: LANDSAT ETM+ mosaic SFCC image, 2000-2001)

In the terrain of laterite the tropical plant species include *Shorea robusta*, *Madhuca indica*, *Terminalia chebula*, *Eucalyptus globules*, *Tectona grandis* and *Acacia auriculaeformis* (Ghosh and Guchhait, 2015). This region bears the characteristics of a tropical hot and sub-humid type of monsoon climate (mean annual rainfall of 1200 to 1600 mm), controlled mainly by proximity to the Bay of Bengal in the south and the alignment of the Himalayas in the north (Singh et al., 1998). This part of Bengal Basin is indentified as Tropical Wet-Dry Morphogenetic Region (A_W climate) with dominance of basal chemical weathering, surface crusting of Al and Fe minerals, highly seasonal sheetfloods and badlands (Chorely et al., 1984). It is found that approximately 387.91 km^2 of lateritic land has been suffered from the intensive soil erosion which exceeds the tolerance limit of 11.2 t ha^{-1} $year^{-1}$ (Ghosh and Guchhait, 2015).

3.3 Laterites: Composition and Categorization

The term 'Laterite' was coined by the British East India Company's surgeon Francis Buchanan in 1807 during a reconnaissance trip in Angadipuram of Kerala. In the areas of Kerala, where laterite was first described, it consists of mottled saprolite, that is weathered rocks in place (Ollier and Rajaguru, 1989). This material is widespread in southern India and is still actively quarried for the use of buildings, roads and embankments. The common Indian laterite is different from the concretionary ferricrete, often called laterite, which appears to be formed in soil or transported material above the saprolite (Ollier and Rajaguru, 1989; Ghosh and Guchhait, 2015).

Laterite is the reddish-brown coloured product of intense tropical weathering made up of mineral assemblages that may include Fe or Al oxides, oxyhdroxides or hydroxides, kaolinite and quartz, characterized by a ratio $SiO_2 : R_2O_3$ (where $R_2O_3 = Al_2O_3 + Fe_2O_3$) and subject to hardening up on exposure to alternate wetting and drying (Alexander and Cady, 1962; Maignien, 1966; McFarlane, 1976; Tardy, 1992; Bland and Rolls, 1998). According to Ollier and Sheth (2008) the ferricrete of India is categorized as massive, pisolitic (isolated concretions), vesicular and vermicular or vermiform (having worm like holes). The maximum thickness of massive laterite profile varies from 11.17 m in Archean rocks and 15.80 m in basalts to 5.15 m in Paleogene – Neogene sediments and 6.12 m in Older Alluvium zone (Chatterjee, 2008; Ghosh and Guchhait, 2015). Mineralogically the *in situ* laterite of study area is essentially a mixture of varying proportions of goethite [$FeO(OH)$], haematite (Fe_2O_3), gibbsite (Al_2O_3, $3H_2O$), boehmite [$AlO(OH)$], limonite [γ-$FeO(OH)$] and kaolinite [$Al_2Si_2O_5(OH)_4$]. It has been observed that the vermicular laterites of study area have important ferruginous materials, e.g. gibbsite, haematite, goethite and limonite, having high percentage of Al_2O_3 and Fe_2O_3 and high percentage of kaolinite as the base of profile.

Laterites of India are variously classified by Vaidyanadhan (1962), Roy Chowdhury et al. (1965), Raychaudhuri (1980), Wadia (1999) and Ollier and Sheth (2008) – (1) *in situ* and *ex situ* laterites, (2) topographically high-level and low-level laterites, (3) plateau and valley laterites, and (4) primary and secondary laterites. Reviewing the earlier works (Morgan and McIntire, 1959; Niyogi et al. 1970; Sengupta, 1972; Goswami, 1981, Biswas, 1987; Vaidyanadhan and Ghosh, 1993; Das and Bandyopadhyay, 1995; Singh et al., 1998; Chaterjee, 2008) the laterites of West Bengal and study area (i.e. eastern plateau fringe of Rajmahal Basalt Traps) are categorized as primary laterites (i.e. *in situ* weathering of parent rocks) and secondary laterites (i.e. *ex situ* re-lateritization of re-deposited ferruginous materials) to compare these with ideal weathered profile of tropical climate (figure 3.2).

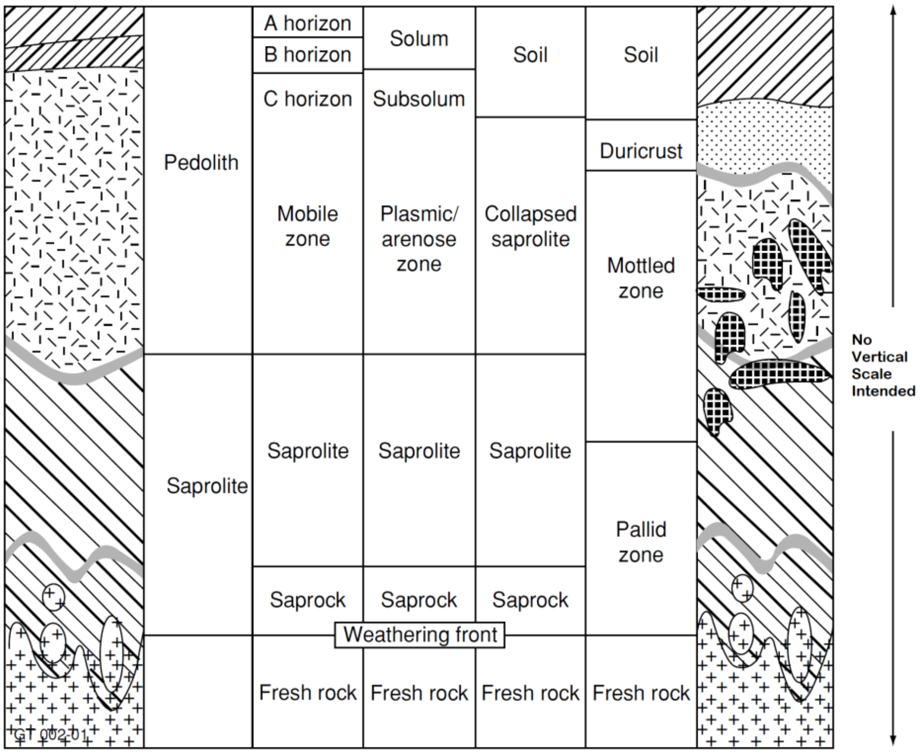


Figure 3.2: A schematic diagram showing the variety of terms used to refer to parts of a tropical regolith profile, i.e. similar to laterite profile (modified from Taylor and Eggleton, 2001; Taylor, 2011)

3.3.1 Primary Laterites

A well developed and well preserved laterite profile of about 11 m thick, will all its attributes of primary laterites is exposed at Nalhati hillock (24° 17′ 47′′ N, 82° 49′ 28′′ E) near Nalhati, Birbhum district (figure 3.3). Pisolitic hardcrust with residual ferruginous latosol varies in thickness from 2.55 to 2.75 m. The broken pisoliths show core to rim colour banding of limonitic to goethite composition (*i.e.* gritty layer). At about 2.75 to 4.0 m depth we have found ferricrete pisolite zone is formed which is characterized by relict columnar structure of basalts. It corresponds to a progressive accumulation of iron and as a consequence, to a progressive development of hematitic iron nodules.

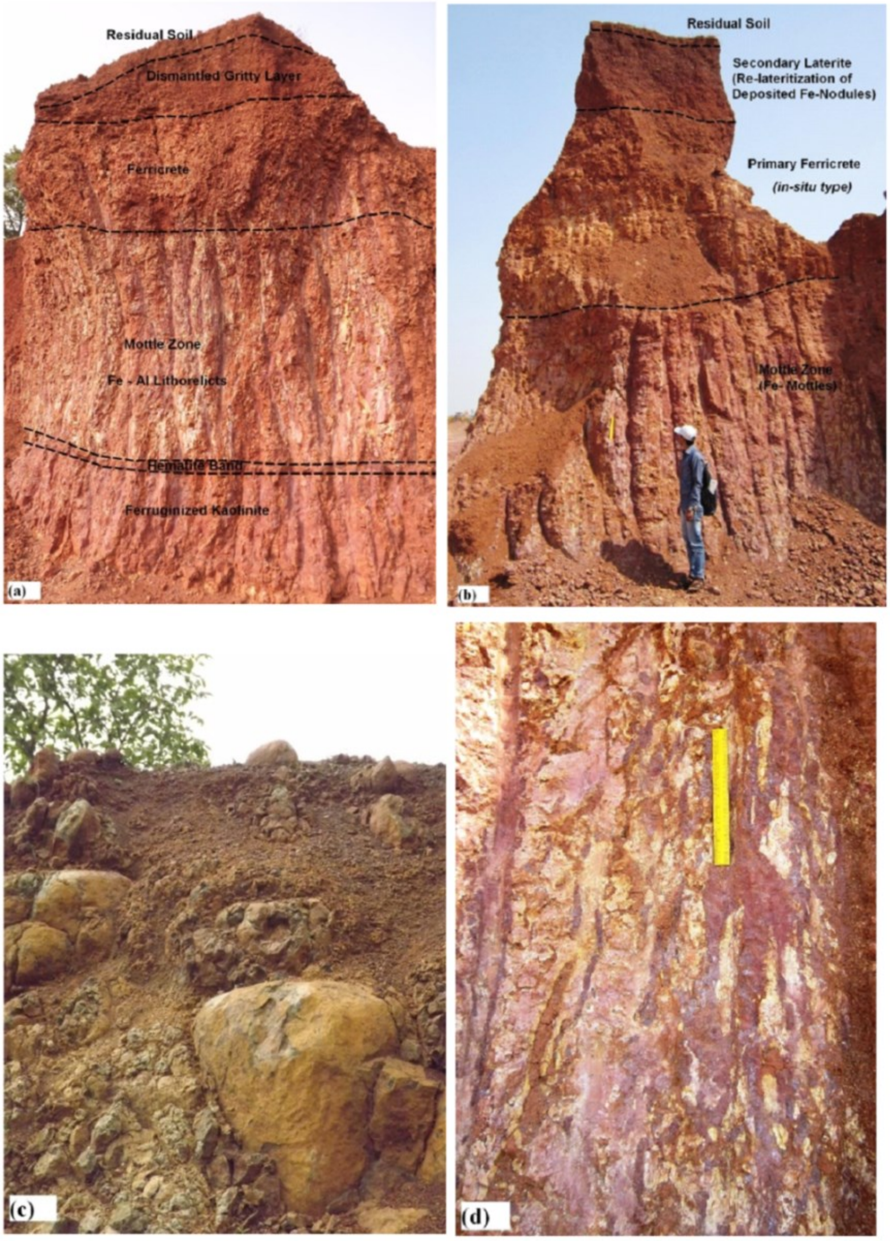


Figure 3.3: (a) Lithosections of dismantled ferruginous layer, vermicular ferricrete and Fe-Al litho-relict mottles at Boro Pahari (24°11´49´´ N, 87°42´39´´ E), Birbhum, (b) development of secondary lateritic hard crust upon massive primary laterite profile at Bhatina (24°10´02´´ N, 87°42´25´´ E), Birbhum, (c) weathering rinds and core stones (saprolite) of Rajamahal basalts in weathered medium at Nalhati, Birbhum, and (d) channels of Fe-mottles (litho-relicts of weathered basalts) in Kaolinite matrix at Bhatina, Birbhum (note: length of scale is 30 cm)

The bleached zone is reduced in size, so that the yellow–white coloured domain decrease in size while the purple–red indurated domain enlarges and develops. A goethite cortex (concentric yellow brown) develops at the periphery of purple–red hematitic nodules. Below the ferricrete the thick mottle clay horizon with relict columnar structure (4.00 to 6.75 m) and laminated white kaolinite clay horizon with yellow ochre with small channels of Fe-Al oxides (6.75 to 9.00 m) are developed. Fe-mottles, mostly of a brown red colour, are diffuse glaebules and result in a concentration of iron which precipitates mainly as goethite and as hematite together with kaolinte matrix. The dominant minerals are secondary kaolinite [$Al_2Si_2O_5(OH)_4$)] and ferruginous hydroxides in amorphous phase. This is followed by saprolite zone of weathered Rajmahal basalts having liesegang banding and weathering rinds. These trap basalts are spheroidally weathered at base. It is constituted of plagioclase, pyroxene, opaque and glass with intergranular to intersertal texture. The similar profiles are found at Baramasia, Birbhum (24°12′12′′ N, 87°40′29′′ E) and Pinargaria, Shikaripara, Jharkhand (24°12′13′′ N, 87°40′13′′ E), and at an altitude of 227 m near Ghurnee Pahar, Birbhum (24°15′43′′ N, 87°39′11′′E)

3.3.2 Secondary Laterites

The *ex-situ* or secondary laterite profile of Sriniketan, Birbhum (23°41′31′′ N and 87°40′31′′ E) is characterized by (1) pebble horizon (2.6 to 3.0 m depth), (2) ferruginized coarse sand (0.55 to 2.6 m depth) and (3) duricrust (up to 0.55 m depth) (figure 3.4). Pebble horizon is characterized by a lag deposits, constituting of pisoids, quartz pebbles and petrified woods of varying sizes set in a ferruginized matrix of sands. The thick layer of coarse sands constitutes gravels and pebbles of varying sizes and ferricrete pisolites which may be derived from distant locations of primary laterites. The duricrust (30 to 5o cm thick) is nothing but a highly ferruginized or iron – cemented gravel and pebble horizon, constituting of quartz, ferricrete pisolite, petrified wood fragment and altered as well as fresh feldspar clasts. Basically it appears as a conglomerate ferricrete and *Gmg* (i.e. inverse to normal grading matrix-supported gravels) fluvial facies. The similar profiles of *ex-situ* laterite are observed at Illambazar (Ajay River section), Birbhum and at Hetodoba village (23°26′45′′N and 87°32′07′′E), Durgapur, Barddhaman. The occurrences of large scale petrified dicotyledonous fossil woods (probably Miocene to Eocene age) with ferricrete nodules and channel lag deposits in the *ex-situ* profiles bear the evidence of secondary lateritization up to Late Pleistocene.

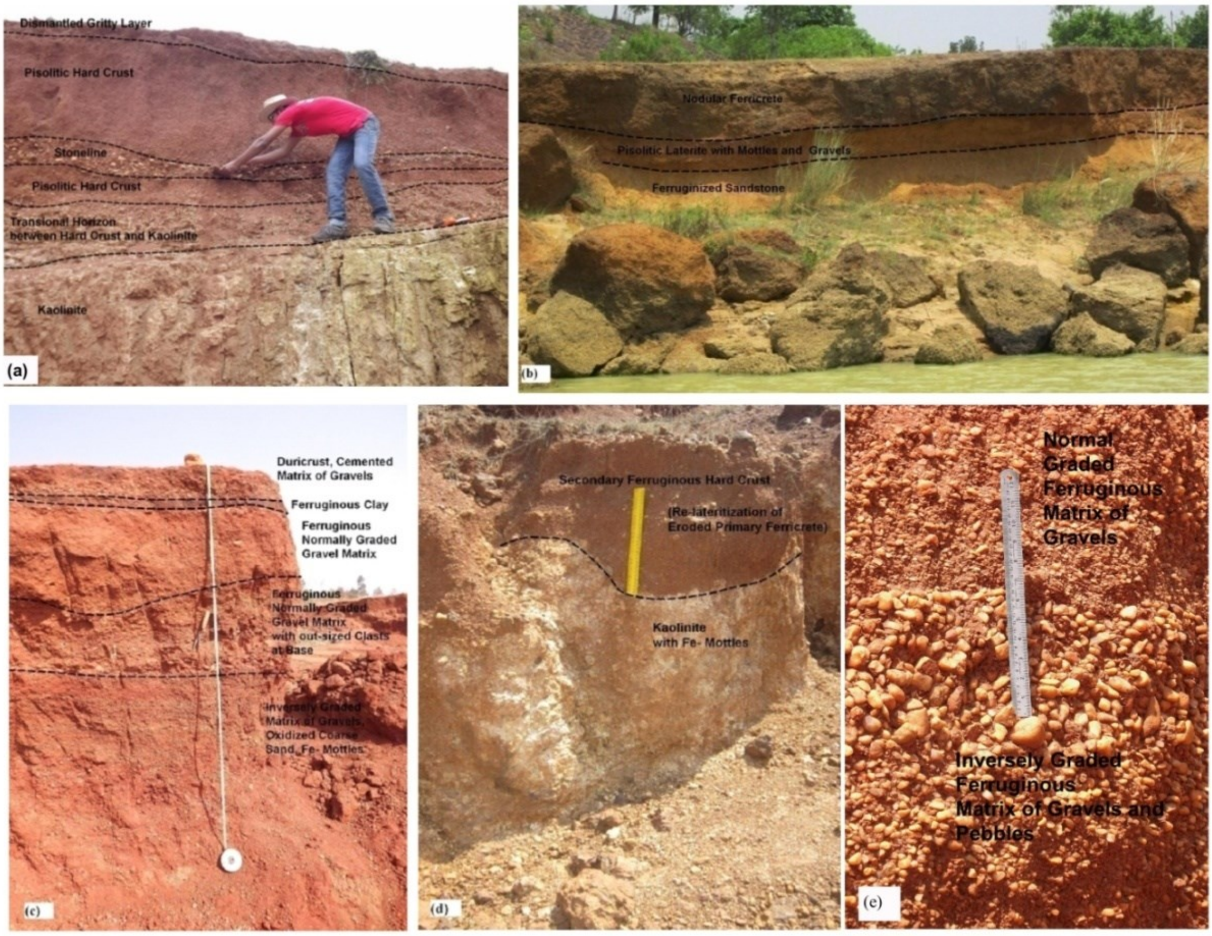


Figure 3.4: (a) Development of pisolitic hard crust with stone lines of gravels and pebbles on kaolinite at Rampurhat, Birbhum, (b) nodular secondary ferricrete on left bank of Ajay River at Illambazar, Birbhum, (c) lithofacies of gravels and ferruginous hard crust at Hetodoba, Barddhaman, (d) formation of secondary lateritic hard crust on kaolinte at Bhatina, Bibhum, and (e) inversely to normal grading of ferruginized gravels and pebbles signifying palaeo fan-deltaic deposition at Hetodoba, Barddhaman (note: length of scale is 30 cm).

3.4 Age of Laterites

The earliest laterites of India were dated back to Early Palaeocene – Early Oligocene, found in Gujarat and Than desert (Sychanthavong and Patel, 1987; Meshram and Randive, 2011). The peak period of lateritization event was started in Neogene when the Indian plate was well established in tropical latitudes. According to the reconstruction of palaeolatitudes, it is found that southern India spent a longer time in the equatorial zone, *i.e.* between 53 million years and < 32 million years (figure 3.5). The accelerated northward drift into Koppen's 'A' zone between 65 and 53 Ma propelled India quite rapidly into the favourbale zone of laterite formation (Kumar, 1986).

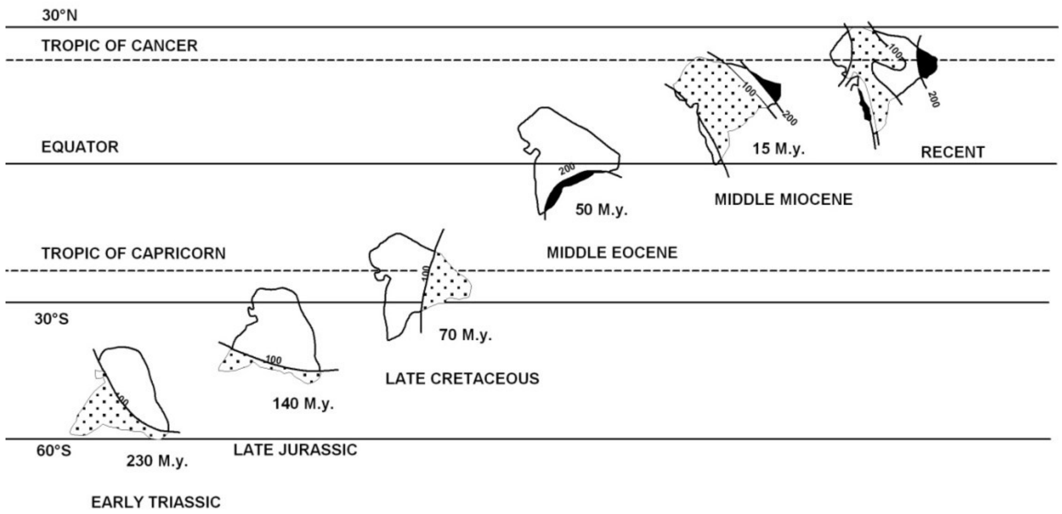


Figure 3.5: Palaeogeographic reconstruction of Indian plate and its entry to the region of tropics since Early Triassic. Onset of lateritization process was started in Middle Eocene. Numbers shows the relative values of precipitation through geological times and no units are implied (Modified from Tardy et al., 1991; Alam et al, 2003; Ghosh, 2014)

The results of ^{40} Ar / ^{39} Ar dating of laterite samples (Bonnet et al., 2014) and other dating information (Schmidt et al., 1983; Kumar, 1986; Sychanthavong and Patel, 1987; Tardy et al., 1991; Bourman, 1993; Widdowson and Cox, 1996; Rajaguru et al., 2004; Mishra et al., 2007; Retallack, 2010) imply that basalts of RBT were weathered intensively to form *in-situ* ferricrete in between ~ 36 and 26 Ma (Late Eocene – Oligocene) and may had been dissected mostly since Neogene under favourbale lateritization climate (becoming source materials of *ex-situ* secondary laterites).

For accurate chrono-stratigraphic age detection, sampling for OSL (Optically Stimulated Luminescence) dating of sample laterite lithofacies in Sriniketan of Birbhum, have been done by Chakraborti, (2011). The possible age as determined by OSL method for the Sriniketan section, shows that the age of sedimentation or time of cut off from the sunlight for the hard crust (0.45 m depth) is 40 +- 2 ka. The age of ferruginized sandstone – pebble horizon (with petrified wood) is about 71 +- 6 ka. The age of laminated siltstone is 79 +- 5 ka. The layer of ferruginous hard crust with gravels was probably developed in Late Pleistocene (well within ~ 125 ka to 10 ka BP).

3.5 Evolution of Laterites

The residual laterite profiles of study area and *Rarh* Bengal are the fossil type formed in past geological ages when climatic conditions were favourbale for lateritization. The lateritization reflects a special type of tropical climatic conditions which is characterized by the contrasted seasons (wet – dry), high temperature throughout the year (28° – 35° C), annual average relative humidity of the air nearer to 60 percent, annual rainfall lower than 1700 mm and long dry seasons during which a relatively low thermodynamic activity of water and atmospheric relative humidity decreases. It is now evidenced that climatic conditions were favourbale for lateritization from Cretaceous to Palaeocene times for during that period, the Indian continent crossed the zone between 30° S and 0° latitude (Schmidt et al., 1983; Kumar, 1986; Tardy et al., 1991). The palaeoclimate of Eocene and Middle Oligocene was more favourable for the *in-situ* type of laterite formation in peninsular India because in Eocene the equator was running across central Gujarat to southern West Bengal (Bardossy, 1981).

The evolution of *Rarh* laterites is directly connected with the Stable Shelf Zone of Bengal Basin, experience maximum marine transgression, sediment depositions, tectonic uplifts and lateritization. The dominance of kaolinite clay with presence of *hystrichospheriods* (in the pores of clay beds) indicates lacustrine to fluvio-lacustrine condition of deposition in Neogene (Mukherjee et al., 1969). The whole of the present day Bengal Basin (including Stable Shelf) was under marine water until Mioene – Pliocene epoch and the strandline grazed the eastern margin of Peninsular Shield, i.e. much inland (towards west of study area) from the present day Orissa – Bengal coastline (Vaidyanadhan and Ghosh, 1993). The Stable Shelf Zone is separated by the Chotangapur Foot-hill Fault (CFF) at west and the Medinipur –Farraka Fault (MFF, or called Pingla Fault) at east. Within this tectonic shelf the *Rarh* laterites of West Bengal (NNE – SSW axis) was developed when the sea finally transgressed from this region since Late Neogene (figure 3.6). At that time, the Indian plate had been crossed the intense weathering zone of equatorial climate which was favourbale for lateritization. Geomorphologically these laterites over Paleogene – Quaternary sequences are represented by degraded badlands which are dissected by the drainage system of west to east flowing rivers of West Bengal. Only the primary laterites of Rajmahal Traps are preserved in butte type structures and under blanket of ferruginous soils. All laterites are topographically restricted within 35 m to 115 m from mean sea level.

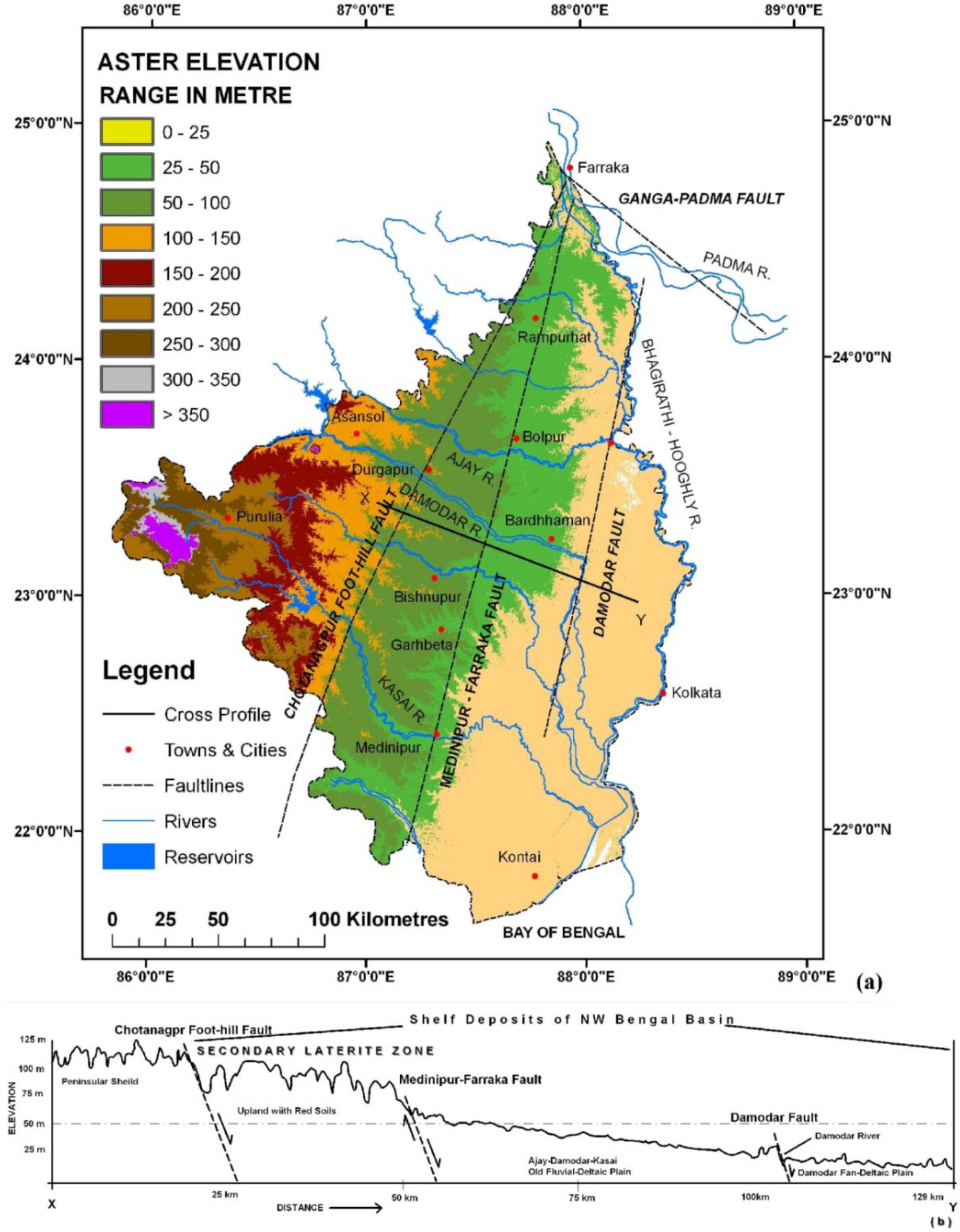


Figure 3.6: (a) Distribution of laterites (see figure 1) in relation to topography and major basement faults of Shelf zone, *viz.,* GPF (Ganga Padma Fault), CFF (Chotanagpur Foothill Fault), MFF (Medinipur Farraka Fault or Pingla Fault) and DF (Damodar Fault) (Ghosh and Guchhait, 2015) in the north-western Bengal Basin (using Landsat ETM+ mosaic SFCC image, 2000 – 2001), and (b) west to east elevation cross profile (X – Y) with emplacement of faults and development of lateritic *Rarh* region (Ghosh and Guchhait, 2015)

3.6 Inversion of Relief and Gully Development

The terrain of *Rarh* laterites are genetically linked with inversion of relief and active tectonics. Inversion of relief refers to an episode in landscape evolution when a former valley bottom becomes a ridge, bounded by newly formed valleys on each side (Pain and Ollier, 1995; Ollier and Sheth, 2008). Inversion of relief occurs when materials on valley floors are, or become, more resistant to erosion than the adjacent valley slopes (Pain and Ollier, 1995). According to the model of Pain and Ollier (1995) the lateral movement of water on hillsides carried weathering products from upper slopes to lower sites, when drainage was often impeded and so chemical precipitation was likely (Ollier and Sheth, 2008). Gradually up to Neogene the valley with filled with ferruginous materials and prolong lateritization formed ferricrete within Late Pleistocene. The surrounding terrain was eroded by streams and gullies to form next valleys and the present summits or interfluves of duricrusted mesas were formed. In the our model (figure 3.7) we reconstructed the event that up to end of Neogene the transported ferruginous materials (due to erosion of primary plateau laterites) re-deposited in the faulted Stable Shelf of Bengal Basin (under marine condition) by the drainage system of peninsular rivers as oldest fan-deltaic to para-deltaic formation in between CFF and MFF. Increased precipitation during the ~ 15 to 5 ka period of peak monsoon recovery probably increased discharge and promote incision and wide spread gully and badland formation (Sinha and Sarkar, 2009). As fluvial erosion proceeds, the valley floor becomes a ridge and interfluves (i.e. laterites of *Rarh Bengal*) bounded by newly formed Late Quaternary valleys on each side.

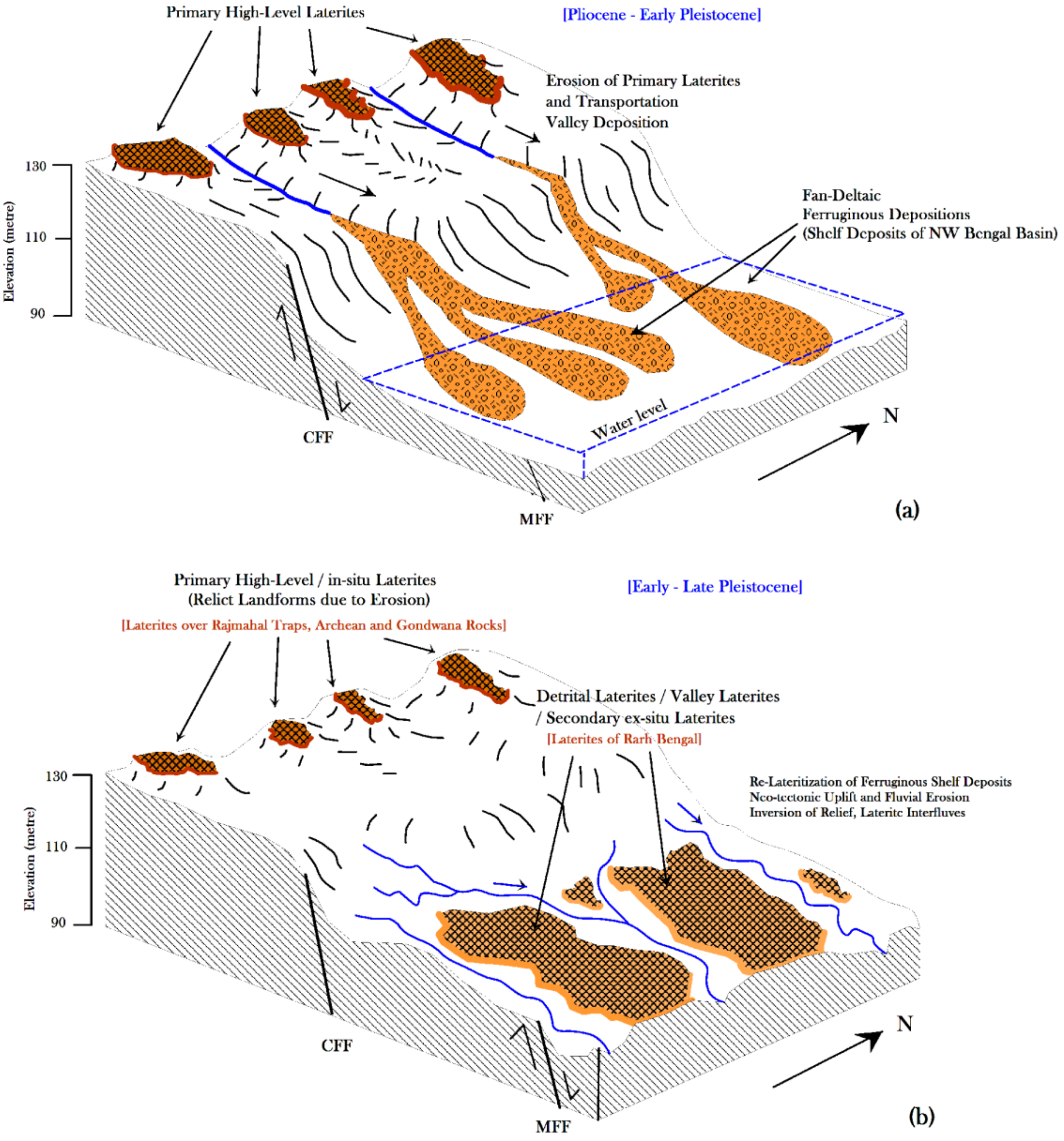


Figure 3.7: A schematic model of *Rarh* laterite evolution, showing (a) erosion of primary laterites and ferruginous fan-deltaic depositions (modified from Mahapatra and Dana, 2009) by rivers and stream in shelf zone of Bengal Basin in between Chotanagpur Foot-hill Fault (CFF) and Medinipur – Farakka Fault (MFF) up to Neogene, and (b) recession of sea, exposure of ferruginous sediments to lateritization climate (Early – Late Pleistocene), re-lateritization to form secondary *Rarh* laterites, neo-tectonic uplift, badland erosion to develop isolated summits of duricrusted mesas and inversion of relief

Chapter 4.0

4.1 Morphology of Gully

In this geo-environmental setting the major geomorphic process is fluvial erosion which has shaped the morphology of total area and formed many patches of lateritic badlands. Water erosion is started from rainsplash erosion and progressive accumulation of runoff aggravates rill and inter-rill erosion, gully erosion, puddle erosion, pedestal erosion, pinnacle erosion, piping and slumping or bank failure (Hudson, 1984). From the recurrent field survey it is clearly observed that the overland flow gets concentrated as thread like channels forming sub-parallel rills in the laterites. Most of the rills are formed at a critical distance downslope from the crest, because at that point the kinetic energy of overland flow overcomes the soil resistance and the flow is channelized. As the water continue to concentrate and acquire additional energy for scouring, these rills become deeper and broader, and eventually some of them coalescence to form deep gullies.

4.2 Nature of Water Erosion in Gullied Area

Apart from the gully erosion few other forms of water erosion are observed as follows in the catchments of gullies (figure 4.1).

- **Puddle Erosion–** Falling raindrops have great capacity to damage loose soils. The sharp impact, as the drops beat the bare surface during violent storms, shatters the clods and soil crumbs and breaks down the soil structure into puddle condition. The soils finely broken into an impervious surface mud.
- **Pedestal Erosion –** When as easily erode soil is protected from rainsplash erosion by a stone or tree root, isolated pedestals capped by the resistant materials are left surrounding soil is shown mainly by splash rather than by surface flow because there is little or no undercutting at the base of the pedestal. The height of pedestal reflect the depth of erode soil.
- **Pinnacle Erosion –** The characteristics erosion pattern which leaves high pinnacles in gully sides and bottoms is usually associated with difficult soils which are highly erodible. This erosion occurs in gullies as the result of deep vertical rills widening until pinnacles are left like islands inn the bed of gully. A more resistant soil layer of gravel or stones or ferruginous crust often caps the pinnacle.

- **Piping –** It is also known as tunnel erosion. It occurs when surface water infiltrates through the soil surface and moves downstream until it comes to a less permeable layer. If there is an outlet so that the water can flow laterally through the soil cover through less permeable layer, the fine particles of the more porous laterite are washed out.
- **Slumping –** It is a type of mass movement, observed during monsoon rainfall. This is shown in cases where the head of the gully has worked back right up to the crest and beyond, where there can be no inflow at the head of the gully. Once the gully has started, erosion is continued by slumping alone in the time of rainfall.

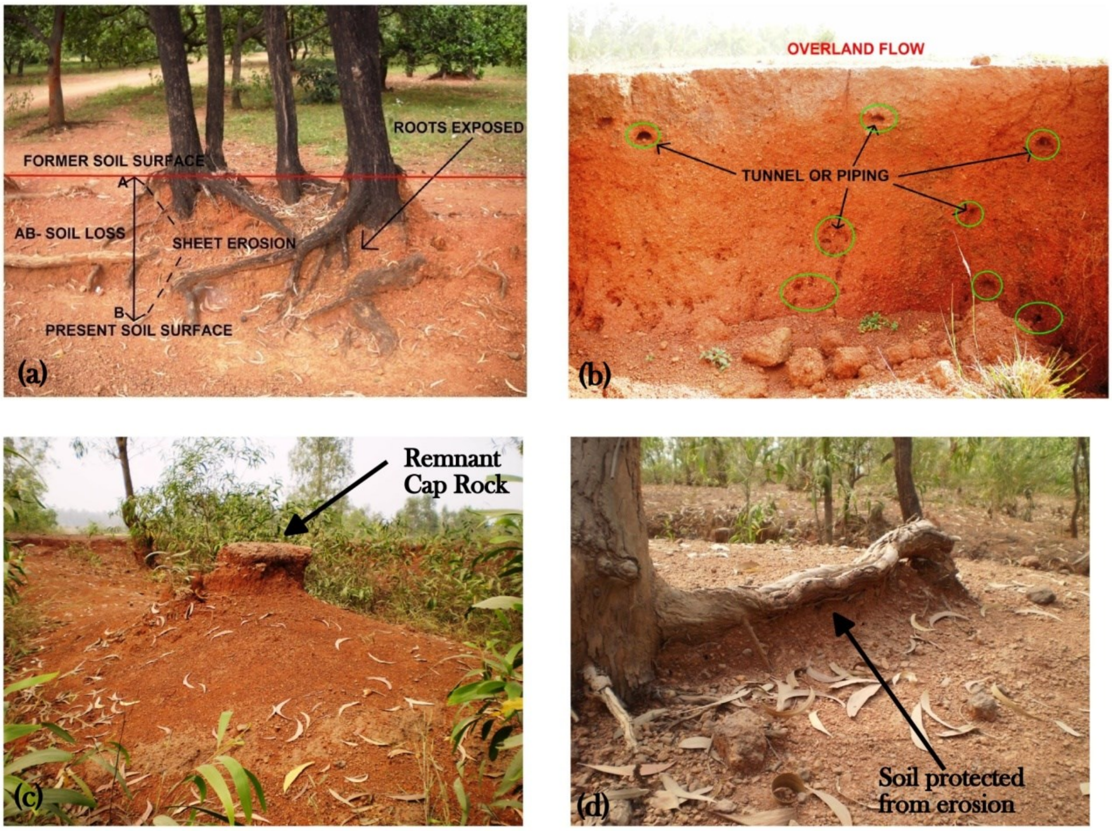


Figure 4.1 (a) Exposed tree roots duet o sheet erosion, (b) tunnel erosion in laterite subsoil, (c) pinnacle erosion through grading of divides, and (d) pedestal erosion

4.3 Characterization of Gully and Its Morphology

Rills and gullies are common and generally are companion geomorphic features on hillslope (figure 4.2), but they are different both morphologically and mechanically. When rainfall exceeds the rate of infiltration, water accumulated on the surface and if the land is sloping, it moves along the slope and moving water concentrates along tiny sub-parallel channels called rills (Osman, 2014). Gullies have been defined as stream channels whose width and depth do not allow normal tillage; in other words, they are channels that cannot be crossed by farm implements (Bocco, 1991). Gullies are developed as enlarged rills, but their genesis may be much more complex and usually involves an inter-relationship between – (1) volume and type of runoff, (2) the susceptibility of the materials to erosion and gully erodibility and (3) land use and conservation practices. Based on the geomorphic observation of study area it is learn that there are much differentiation between rills and gullies which are explained as follows.

Figure 4.2 (a) Initiation of parallel rills and formation of grooves, and (b) a deeply incised gully with vertical sidewall in the laterites

The morphological distinction between rills and gullies is attributed to different processes controlling their formation and development (Bull and Kirkby, 1997; Poesen et al., 2002; Gao, 2013). Rills formed during one rainfall event (i.e. thunderstorm) tend to have higher resistance than their neighbouring areas and hence may subsequently be filled by sediment deposition when new rills are formed during the following event. This means that rills are negative-feedback or self-stabilizing systems (Bull and Kirkby, 1997). By contrast, gullies, once formed, maintain their positions as permanent channels. Gullies have steep sides, low width/depth ratios, and a steeped profile, characteristically having a headcut and various steps or kinckpoints along their courses. These rapid changes are occurred in slope alternate with sections of very gentle gradients, either straight or slightly convex in a gully longitudinal profile. Rills exist only on hillslopes, whereas gullies commonly occur at the valley bottom and in swales. On hillslopes, rills are formed with gentle slopes of 2^0 – 5^0, whereas gullies tend to have steeper slopes ranging from 8^0 – 16^0 or even steeper.

4.3.1 Classification of Gully

The wide variation of gully morphology has led to attempts of gully classification based on physical and land-use factors, planforms, locations and parameters representing gully cross-sectional shapes (figure 4.3).

A simple, physically based classification distinguishes gullies as ephemeral and permanent gullies.

- **Ephemeral Gullies –** These are impermanent channels that are obliterated periodically by cultivation (e.g. deep tillage or land-levelling operation) or natural processes (i.e. deposition). Their infilling generally leaves topographic depressions or swales, which assure the return of new gullies developed subsequently to the same position. Ephemeral gullies are small channels that can be filled by normal tillage and can re-from in the same location by additional runoff events.
- **Permanent Gullies –** These are deeply incised channels that have cross sections permanently recognizable without flowing water and have identifiable banks. Permanent gullies are steep-sided channels that are too deep to easily ameliorate with ordinary farm tillage equipment. Permanent channels range from alluvial channels to incised U or V-shaped ephemeral channels and to shallow complex digitate systems.

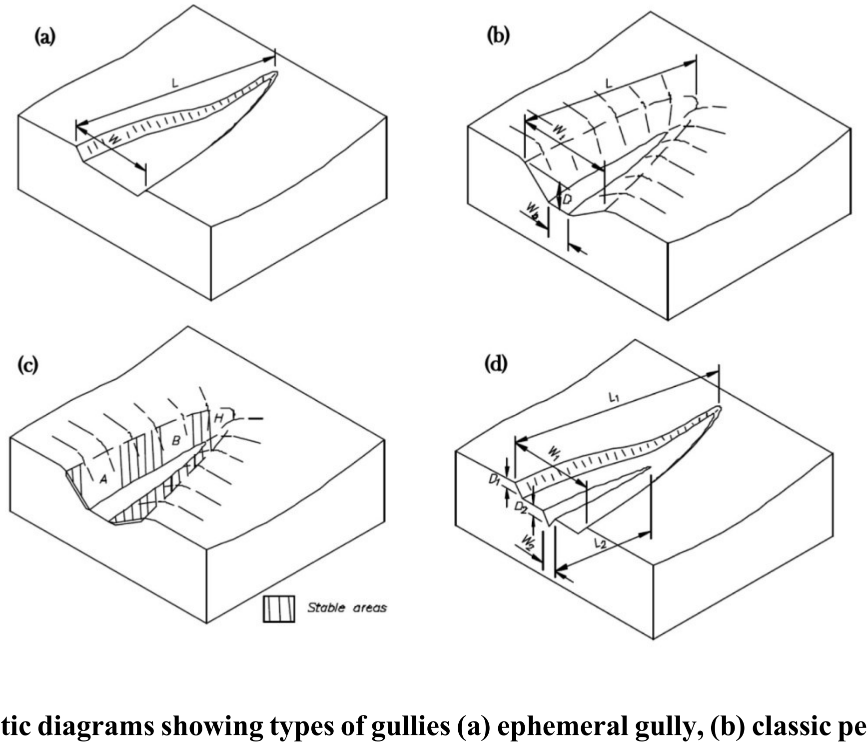


Figure 4.3 Schematic diagrams showing types of gullies (a) ephemeral gully, (b) classic permanent gully, (c) classic gully portions actively eroding and (d) ephemeral and classic gully combination (Toy et al., 2013)

Based on connectivity in the landscape the gullies may be (1) discontinuous or (2) continuous (Leopold et al. 1964, Poesen et al., 2002). If gullies occur on valley floors, a section of a discontinuous gully is characterized by a vertical headcut, a channel immediately below the headcut with depth greater than its width, a bed gradient less than that of the original valley floor, and a decreasing depth of the channel downstream. Continuous gullies discharge into streams at the bottom of the slope and hence form part of a drainage network.

Based on form and pattern, there are six classes of gully forms: (1) linear, (2) bulbous, (3) dendritic, (4) trellis, (5) parallel and (6) compound gullies (Bocco, 1991). Based on morphology three types of gullies are found – (1) V or U-shaped axial gullies, (2) digitate gullies and (3) frontal gullies (Bull and Kirkby, 1997). Gully heads can be classified on the basis of head size and dominant process (Poesen et al., 2002) – (1) Gradual head (initiation of gully with cross-sectional area greater than 929 cm^2), (2) Transitional Head (incision more than rills and formation of inclined head wall), (3) Rilled-abrupt Head (formation of vertical head wall and development of plunge pool, and (4) Abrupt Head (rills are engulfed by gully head retreat and formation deep vertical wall) (figure 4.4).

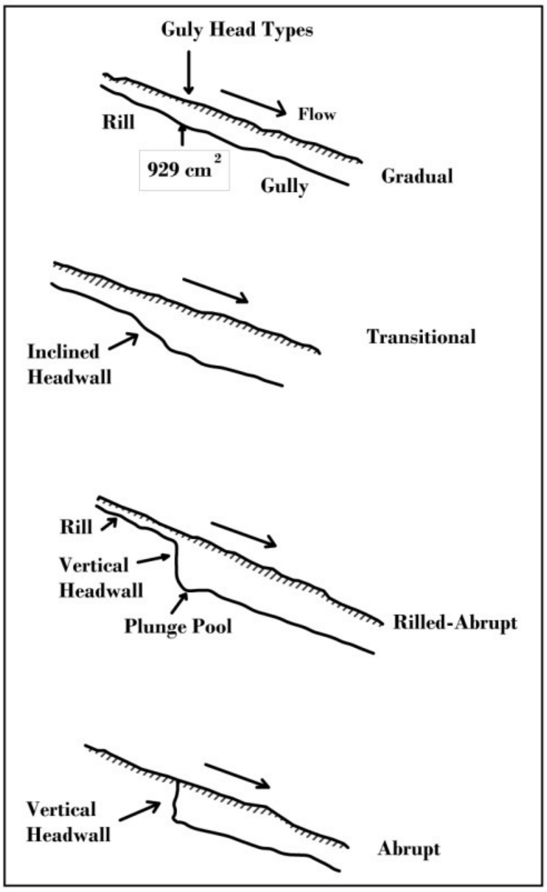


Figure 4.4 Classification of gully head types according to their longitudinal profile (Poesen et al., 2002)

4.3.2 Gully Classification Scheme in Study Area

Apart from above classification schemes, the classification of gullies should be based on field observations and aerial view, and it includes the gully planform, gully side morphology and forms of the longitudinal and transverse profiles. Based on 118 gully head samples in the study area two classification schemes have been formulated – (1) gully classes based hydro-geometry and (2) gully classed based on transverse shape.

(1) **Gully Classes Based Hydro-Geometry**–The size (depth), drainage area and average runoff discharge rate are estimated in the 118 sample gully heads (figure 4.5). The simplest classification system is based on gully depth (signifying the extent of incision and stage of gully development): < 1 – 2 m depth is recognized as small gully, 2 – 5 m depth is recognized as medium gully and > 5 m depth is identified as large gully. Flow rate measurement is an effective way to classify gully because high amount of runoff during rainstorms is associated with large drainage area, high percentage of bare surface, increasing flow convergence and high level of erosion. So, it is identified that < 0.3 m^3s^{-1} discharge rate is associated with small gully, 0.3 – 2.0 m^3s^{-1} is associated with medium gully and > 2.0 m^3s^{-1} is recognized as large gully in the study area. The annual runoff yield of < 100 – 350 mm is associated with small gully, whereas 350 – 600 mm and > 600 mm runoff yield are associated with medium and large gully. From the result (table 4.1) it is found that 38.72 percent gullies are associated with small gullies which have < 2400 m^2 basin area, < 3 – 5 m width and < 1 – 2 m depth. About 48.25 percent of gullies are assonated with medium gullies which have basin area of 2400 – 7200 m^2, 5 – 10 m width and 2 – 5 m depth. Out of 118 samples, 13.03 percent of gullies are recognized as large gully which have basin area of > 7200 m^2, > 10 m width and > 5 m depth (table 4.1).

Table 4.1 Hydro-geometry based gully classification

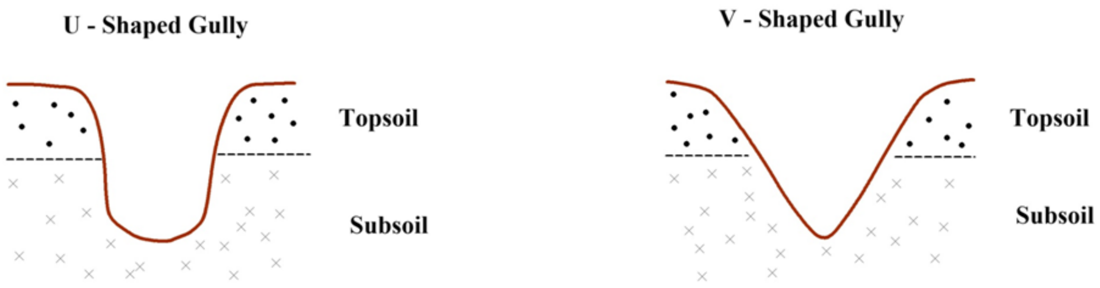
Gully Class	Depth (m)	Width (m)	Basin Area (m^2)	Annual Runoff Yield (mm)	Percentage of Gullies
Small Gully	< 1 – 2	<3 – 5	<2400	<100 – 350	38.72 %
Medium Gully	2 – 5	5 – 10	2400 – 7200	350 – 600	48.25%
Large Gully	>5	> 10	> 7200	> 600	13.03%

Note: Total Sample of Gully Heads – 118

Figure 4.5 Photographic representation of gully classes in the study area, i.e. (a) small gully, (b) medium gully and (c) large gully

(2) **Gully Classes based on Shape** – Three principal transverse gully shapes are identified in the study area and these shapes have deep relation with erosion dominancy, stage of development and erodible soil layers. Gullies are classified according to shape of cross-section (figure 4.6):

- **U-shaped Gullies** – These gullies are formed where both topsoil and subsoil have the same resistance against erosion. Since the subsoil is eroded as easily as the topsoil, nearly vertical walls are developed on each side of the gully.
- **V-shaped Gullies** – These gullies develop where the subsoil has more resistance than topsoil against erosion. This is the most common gully form.
- **Trapezoidal Gullies** – These are formed where the gully bottom is made of more resistant material than the topsoil and subsoil because the erosion rate along the gully bank is greater than along the bottom.



(a)
Subsoil as resistant as topsoil

(b)
Subsoil more resistant than topsoil

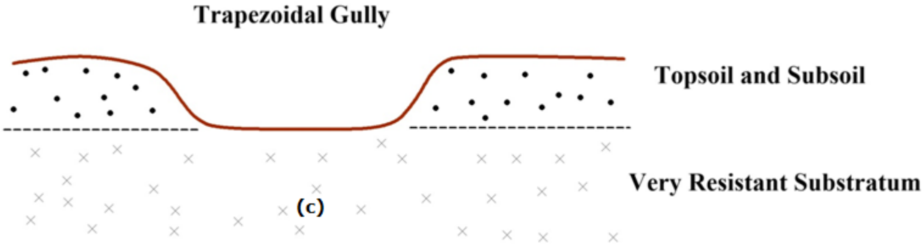


Figure 4.6 Diagrammatic representation of gully classes in the study area, i.e. (a) U-shape gully, (b) V-shape gully, and (c) Trapezoidal gully

In the study area, out of total 118 gullies 49.27 percent of gullies are recognized as U-shaped gullies where vertical and sidewall erosion are both operated, having meandering course of main channel (table 4.2). In these gullies the secondary duricrust and mottle zone are evenly eroded due to similar resistance power. About 39.55 percent of gullies are identified as V-shaped gullies where valley incision is more active than lateral expansion. These active gullies are the initial stage of permanent gully development on the Laterites and these are formed at high angle slope base of hillsides. Only 11.18 percent of gullies are recognized as trapezoidal gullies where the primary hard laterites are exposed due to deeply incised erosion for which valley deepening is stopped and valley widening is increased. In these gullies the bank sides are eroded due to initiation of secondary rills and bank gullies. Alongside many sections of these gullies are stabilized due to vegetation growth. It is found that during evolution of gully development V-shaped gullies are transformed into U-shaped gullies and trapezoidal gullies thereafter in the late stage in this lateritic region.

Table 4.2 Gully classes based on shape

Gully Class	Percentage of Gullies	Morphology	Dominant Processes
U-Shaped Gully	49.27%	Both topsoil and subsoil have the same resistance against erosion.	vertical and sidewall erosion
V-Shaped Gully	39.55%	Subsoil has more resistance than topsoil against erosion	valley incision is more active than lateral expansion
Trapezoidal Gully	11.18%	where the gully bottom is made of more resistant material than the topsoil and subsoil	initiation of secondary rills and bank gullies

Note: Sample of Gullies– 118

4.4 Cross Profiles of Gullies on Laterites

To understand the changing transverse profile of gully along the channel from head to mouth, several cross-sectional surveys were performed using Leica Sprinter 150 m (height accuracy ± 1.5 mm and distance accuracy ± 1 mm) and Garmin GPS (horizontal accuracy±3 m) in three selected gully catchments of lateritic terrain (figure 4.7). Plotting successive cross-profiles along the downstream gully floor it can be learn that shape of gully can reflect the stages of development and dominancy of processes. These gully-catchments (figure 4.8) have distinct properties in terms of gully geomorphology and geo-environmental characteristics, with minimum interference of human.

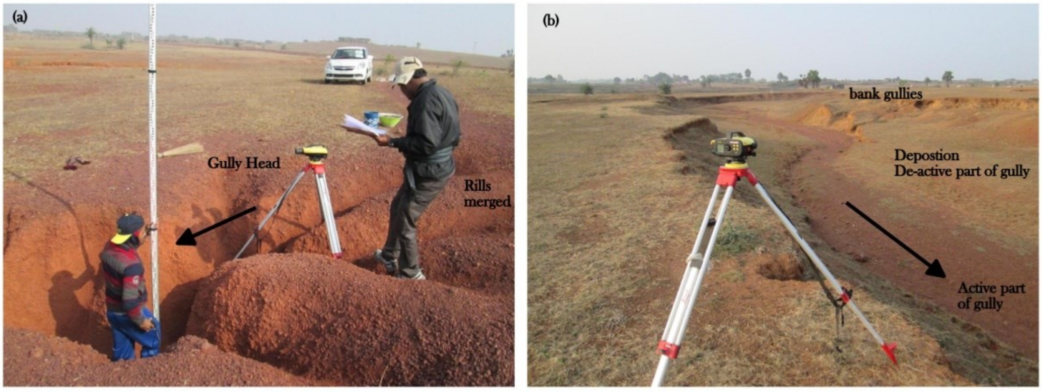


Figure 4.7 Cross-profile survey using Leica Sprinter 150 m at (a) V-shaped gully of catchment 1 and (b) wide U-shaped gully of catchment 3

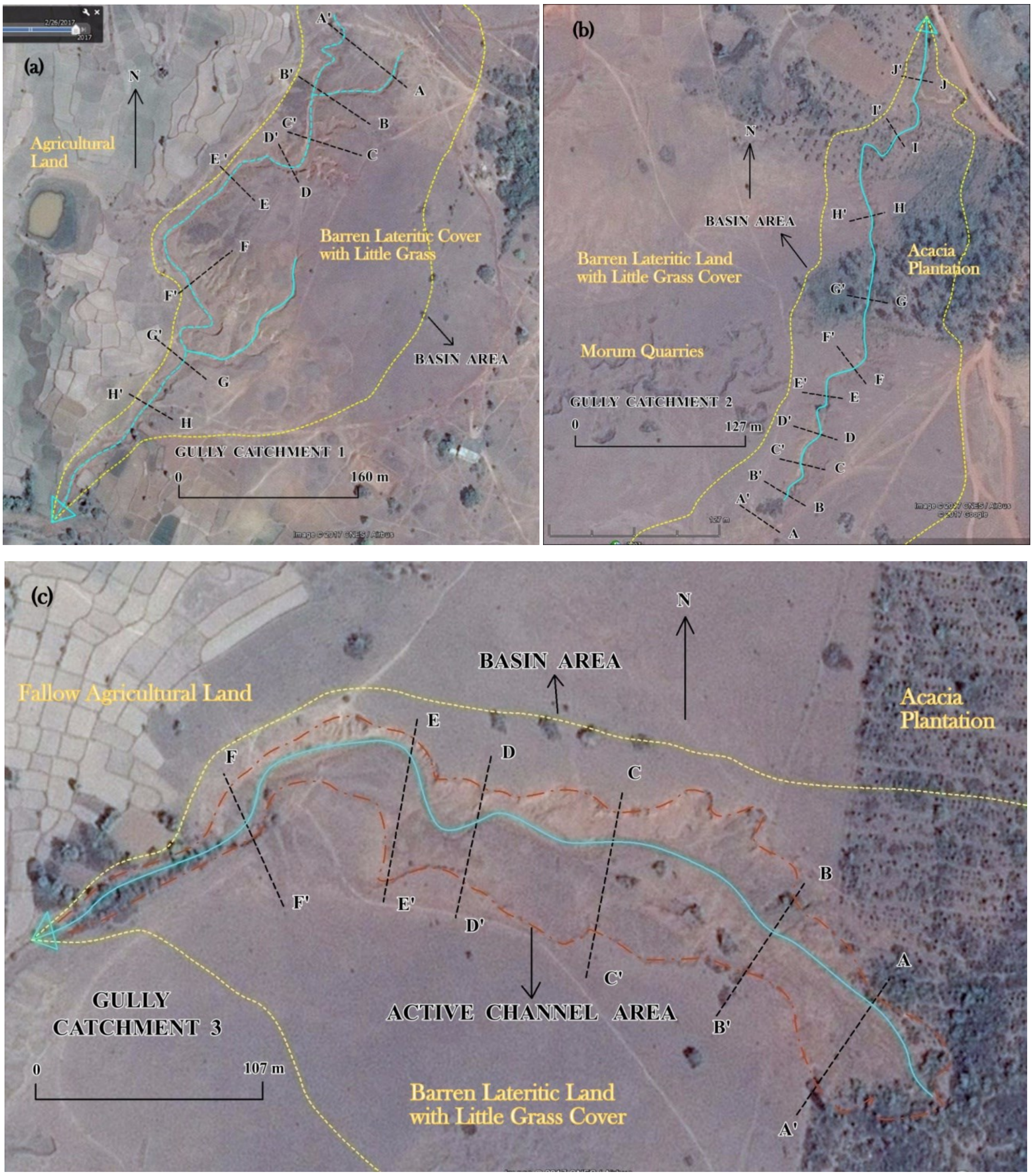


Figure 4.8 GPS-based vector layers of gully channels and transverse profiles placed on Google Earth Imagery (16th Dec, 2016) to portray the ground condition of gully

- Gully catchment 1 has basin area of 1,09,250 m^2, having average drainage density of 1.8 km km^{-2}, 28 m of relative relief and average slope of 6^0 towards south-west. The catchment has primary hard laterite at upper part and loose secondary laterite at lower part. High pediment slope with loose ferruginous materials and soils are observed and most of the land is appeared as barren laterite cover with few patches of grasslands. Observing the successive profiles (starting from gully head) it is found that the shape of gully is characterized by V-shape at initial part, but with distance the shape becomes U-shape and wide (figure 4.9). Initially two v-shape gullies are formed, reflecting active phase of erosion and headwardmigration. At a distance these two gullies are joined to form a single incised channel. The gully becomes wide (dominancy of deposition) with vertical banks due to bank failure and development of bank-side rills and gullies. At the lower part of catchment the sub-surface layers of laterite are very much erodible and weak in structure. This feature helps to develop wide U-shape gully floor.

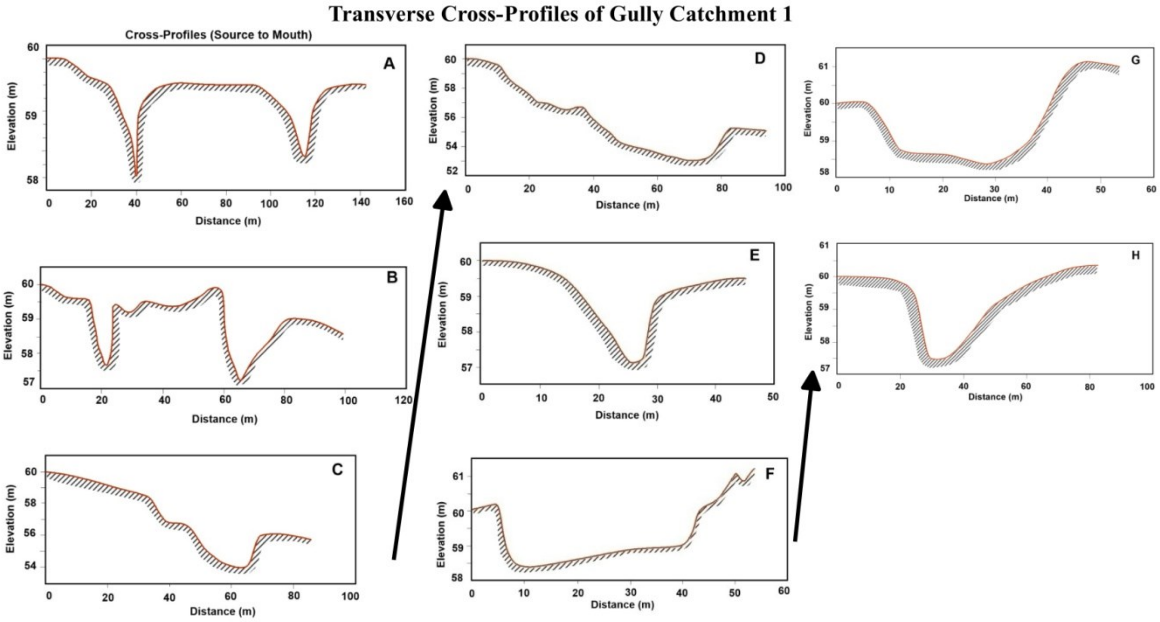


Figure 4.9 Leica Sprinter 150 m transverse cross-sections (A to H) in catchment 1

- Gully catchment 2 has basin area of 1,18,325 m^2, having average drainage density of 1.35 km km^{-2}, 19 m of relative relief and average slope of 4^0 towards north. The catchment has loose secondary laterite cover at the surface but the hard primary laterite is remained at basal part. The pediment slope is very low and soils are very much compact at downstream. In few patches the hard laterites are exposed in banks and gully floors. Upper catchment is mostly covered under barren laterite and grassland and lower part is under thick vegetation cover due to Acacia plantation programme. In the middle part few laterite morum quarries are active. In this land use and land cover many sub-parallel rills are merged to form single gully at upper catchment. The successive profiles reflect that initially two v-shape gullies are formed and at a distance these two gullies are joined to form a single incised channel, having U-shape form. Similarly in this case at initial part vertical erosion is dominated, but with distance the lateral erosion is more dominated. The last three profiles reflect trapezoidal shape of gully which means that valley floor is made of more resistant material (exposure of hard laterite) than the topsoil and subsoil (figure 4.10).

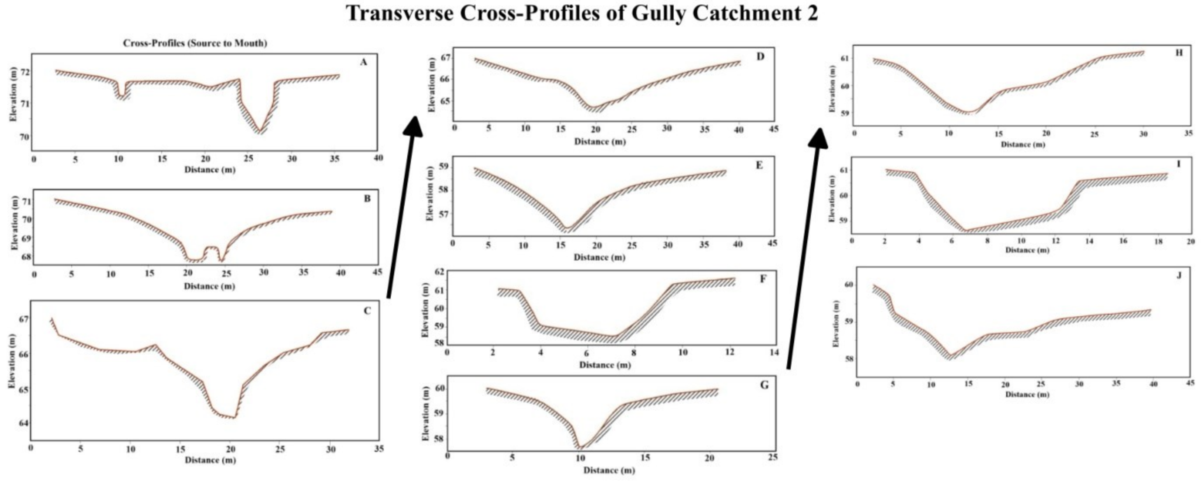


Figure 4.10 Leica Sprinter 150 m transverse cross-sections (A to J) in catchment 2

- Gully catchment 3 has basin area of 2,16,050 m^2, having average drainage density of 1.9 km km^{-2}, 14 m of relative relief and average slope of 3^{0}30$^’$ towards west. In the upper catchment hard primary laterites are observed and in pediment slope the loose secondary laterites occur. Natural vegetation and plantation patches are observed in the upper catchment, but most of land is covered under grassland and lateritic barren cover. The most striking feature of this catchment is that the gully channel is situated in mature stage of development with wide gully floor and shallow depth. Re-vegetation and excessive deposition are observed in the gully floor. Initially a wide v-shape gully is formed with very steep vertical headcut and with increasing the distance the U-shape valley is formed with increasing wideness. Alongside the banks become very steep and these are eroded by sub-parallel rills and bank gullies. At the lower section of catchment due to exposure of hard laterite and kaolinite layer the vertical incision is stopped, but valley widening is quite active during the rainstorms. It forms a trapezoidal shape of gully floor (figure 4.11).

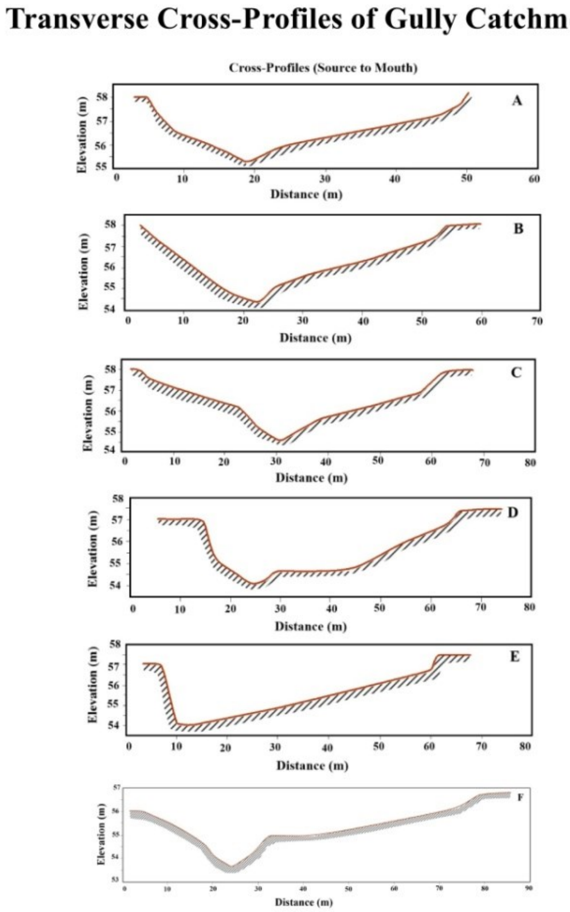


Figure 4.11 Leica Sprinter 150 m transverse cross-sections (A to F) in catchment 3

From the above analysis it can be concluded that in the geo-environmental settings of lateritic terrain three gully catchments show similar genesis and evolution of transverse profiles from gully head to mouth, but each one has unique stage of development in respect of origin and intrinsic factors of catchments. If we consider dynamic meta-stable equilibrium of gully erosion, then it is summarized that when the hard resistant laterites are exposed and the vertical erosion becomes energized to erode more resistant material and it eventually forms V-shape gully (more depth) at earlier stage. Loose laterites are more erodible and it needs low level energy to erode, so the gully becomes wide and U-shape (less depth). From the observation it is found that the catchments having more bareness and v-shaped gullies are recognized as more active stage of development, but the catchments having more vegetation cover and gully stabilization are identified as mature stage of development. Here three successive forms of gully are observed in a single catchment, i.e. V-shape valley become U-shape valley with increasing distance and the U-shape valley becomes trapezoidal valley.

4.5 Geomorphic Threshold of Gully Erosion

After the rainsplash detachment the second erosive factor is overland flow in catchment scale (figure 4.12). Intense rainfall is the primary trigger, but the local conditions such as slope morphometry, land use and soil characteristics control the triggering of gully erosion (Rossi et al., 2015). It is found that after a critical distance from the water divide the gully head is formed because the depth of the overland flow increases with distance and it cumulatively increase shear stress on the surface to allow incision at a certain part of slope (figure 4.12) (Morgan, 2005). The location of gully head reflects the critical hydraulic condition where flow erosivity overcomes the erodibility (Toy et al., 2013). This critical condition can be explained and determined by the concept of threshold in wide range of conditions.

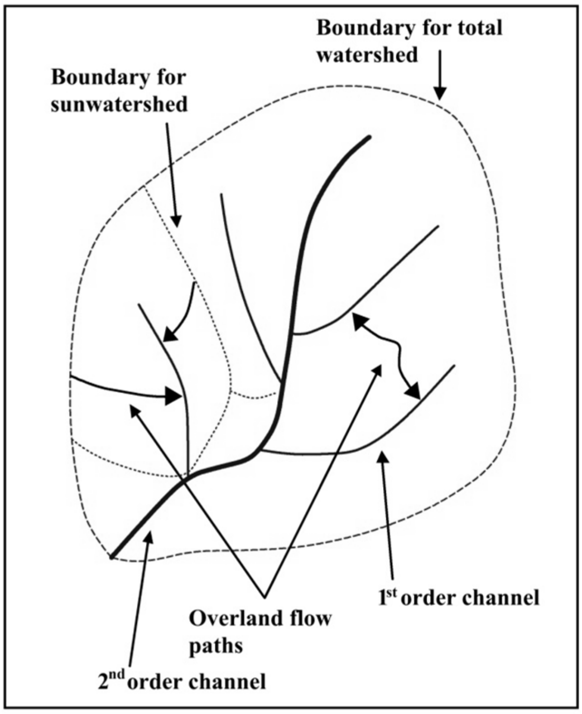


Figure 4.12 Nested hierarchy of gullies and overland flow paths in a watershed

The idea of critical limits, boundary conditions and yield point form an important part of other science disciplines, similar terminology (threshold) constitute only a small part of geomorphic study (Coates and Vitek, 1980). It is refer to such limiting conditions and tolerance level as 'threshold' (Coates and Vitek, 1980). The proceedings volume of "Geomorphology Thresholds", as the central theme for 9th Annual Geomorphology Symposium at Binghamton (October 19 – 21, 1978), provided a timely and comprehensive appraisal of thresholds in geomorphology (Coates and Vitek, 1980). The general definition of a threshold – the point at which a stimulus begins to produce a response – is applicable to those problems (McKerechar, 1980).

4.5.1 Concept of Geomorphic Threshold

Thresholds can be exceeded when input is relatively constant, i.e. the external variables remain relatively constant, yet a progressive change of the system itself renders it unstable and failure occurs (Schumm, 1973 and 1979). A threshold in geomorphology or physical geography is an upper limit to some cumulative process, beyond which that particular sequence of events is terminated, and a totally new sequence introduced (Fairbridge, 1980). In any natural system, a threshold is a turning point or boundary condition that separates two distinct phases of inter-connected process, a dynamic system that is powered by the same energy source. The study of episodic erosion or deposition reflects that the periods of instability or rapid change occur when a threshold of stress or strength of materials is exceeded (Schumm, 1980). There are two types of thresholds, extrinsic and intrinsic. An extrinsic threshold is a threshold that is exceeded by the application of a force or process external to the system (Schumm, 1980). The other type of threshold is intrinsic, indicating that change occurs without a change in an external variable.

Geomorphic thresholds may be studies in two crucial ways – (1) the first is the establishment of domains for particular process, within which that process is dominant, and (2) the second important aspect of thresholds is the nature of the transition between domains of dominance (Kirkby, 1980). A geomorphic threshold is a point or period of time that separates different modes of operation within part of a landscape system (Bull, 1980). The concept of geomorphic threshold is useful identifying those conditions at which a landform is incipiently unstable (Schumm, 1980). Following this identification, some action can be taken either to prevent failure from occurring or to minimize the effect of the change when it odes occur. Geomorphic thresholds can be defined in terms of ratios, the numerator and denominators of which describe opposing tendencies and which may be simple or complex depending on the needs of the investigator or the complexity of the real world (Bull, 1980; Coates and Vitek, 1980). The part of the system under consideration may be considered to be at a threshold or equilibrium condition when the ratio is equal to 1.0. When the derived value exceeds 1.0, a threshold has been reached. A threshold that described changes in dominant hydro-geomorphic processes is the hillslope runoff threshold (Bull, 1980):

$$\text{Factors that promote runoff} / \text{Factors that promote infiltration} = 1.0$$

Probably, at first Horton (1945) explained the mechanism of channel initiation on a hillslope where after a critical distance from the divide the overland flow exceeds threshold condition to incise a channel (figure 4.13). In western Colorado, Patton and Schumm (1975) have reported on a relation between drainage area and valley floor slope above which incision of the valley floor is likely to take place. This situation provides an excellent example of geomorphic threshold.

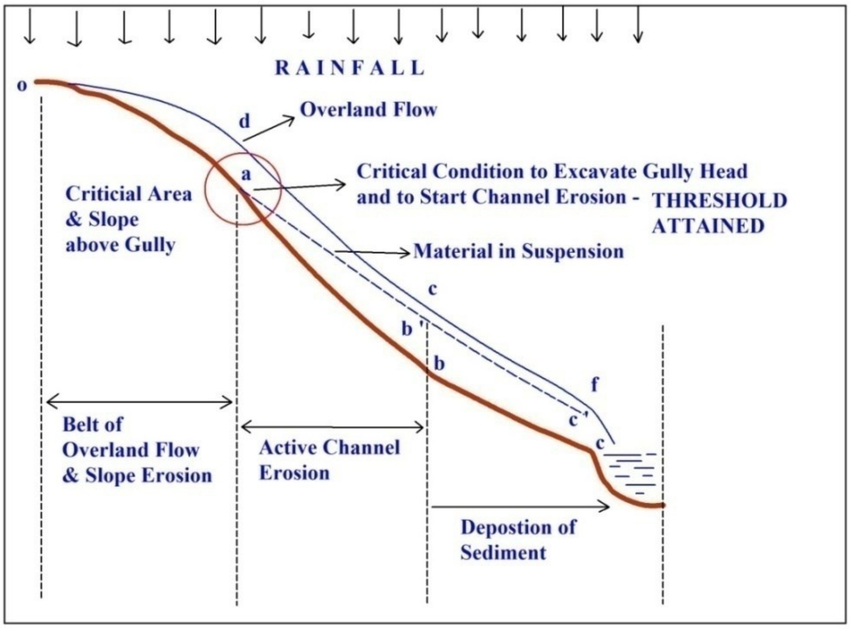


Figure 4.13 Horton's model of channel initiation – a simple model of threshold condition (Horton, 1945)

4.5.2 Methodological Aspect of Geomorphic Threshold

The geomorphic threshold model can be taken as a standardised system for evaluating site susceptibility for gully erosion, linking the susceptibility to local topography, soil types and management practices (Torri and Poesen, 2014). In general, thresholds for gully head position in the landscape traditionally taken into consideration local slope angle (as topographic variable) and gully head drainage area (as runoff variable) (Rossi et al., 2015). Channel initiation by surface processes has been viewed as a threshold phenomenon related to size of contributing area (A) and its slope (S) (Schumm and Hadley, 1957; Patton and Schumm, 1975; Begin and Schumm, 1984; Ebisemiju, 1989; Moeyersons, 2003; Morgan and Mngomezulu, 2003; Montgomery and Dietrich, 2004; Dong et al., 2013; Vandaele et al., 1996; Samni et al., 2009; Araujo and Pejon, 2015). The relation between critical valley slope and drainage basin area ($S = a A^{-b}$, where a = coefficient and b = exponent of relative area) is used as a predictive model to locate those areas of instability within alluvial valleys where gullies will form.

$$S = a A^{-b}$$

This erosion system is assumed to be non-linear because the outputs are not proportional to the inputs across the entire range of the inputs (Philips, 2003, 2006 and 2009). A threshold line is drawn through the lower limit of scatter points and this line represents, for a given area, a critical value for valley slope above which entrenchment of the laterite should occur. This relationship can be written as $SA^{b} > T$ (where T = threshold value, i.e. area ^{b}), defining the limit of threshold value to start gully initiation (Morgan and Mngomezulu, 2003; Torri and Poesen, 2014). A theoretical division of the landscape into process regimes in terms of log S (X axis) and log A (Y axis) signifies different geomorphic thresholds to gully erosion and the resultant critical threshold line is demarcated as Montgomery – Dietrich (M – D) envelope, through A – S threshold (Montgomery and Dietrich, 1988, 1992 and 1994; Vandekerckhove et al., 2000; Moeyersons, 2003; Samni et al., 2009). To depict the role of ground slope and to identify critical slopes (i.e. potential for gully incision) 146 valley-side slopes has been selected randomly in this lateritic terrain, including gullied and un-gullied slope segments. Sprinter 150 m of Leica Geosystem and ASTER DEM were used to measure the angle of slope facets. Drainage area above gully head is calculated from the flow direction and flow accumulation algorithm of Arc GIS 9.3 using drainage lines (digitized from toposheets) and DEM.

4.5.3 Estimating Geomorphic Threshold

Based on the data of slopes (S) and drainage areas (A) of 118 gully-head catchments an empirical power regression is adopted which can be used as geomorphic intrinsic threshold for gully initiation on this lateritic terrain. The upstream slopes above gully heads are negatively correlated ($r = -0.55$) with upstream drainage areas which are used as surrogate for the volume of runoff yield in the study area. A significant line is fitted through the lower-most scatter points for the study sites which are incised to form gully heads. This empirical straight line ($S = 17.419\, A^{-0.2517}$, with R^2 of 0.52) represents an approximation to critical slope – area threshold relationship for gully incision (figure 4.14). Any site (may be un-trenched or trenched by gullies) lying above this critical line is much prone to gully erosion on this terrain of laterites. It is derived that mean critical threshold slope for the initiation of gullies is 2.34°.

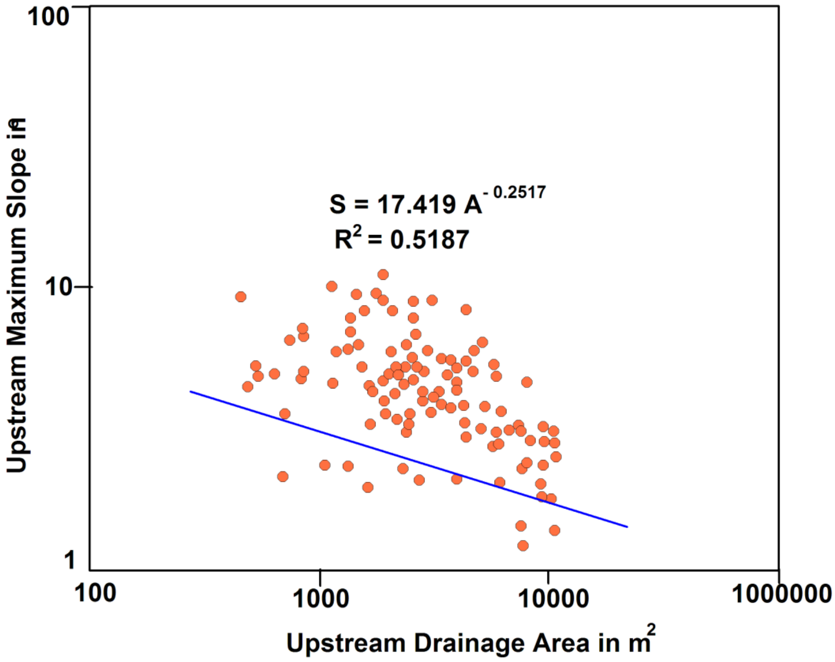


Figure 4.14 Establishing critical slope-area threshold relation (S = 17.419 A -0.2517) for the gullies of lateritic terrain on the basis of intrinsic thresholds S (in degree) and A (m^2)

The high value of *a* (i.e. 17.419) signifies the initiation of gullies by high volume of overland flow and landslideing at micro scale in the study sites (Morgan and Mngomezulu, 2003). Most importantly the constant *b* is variously interpreted as relative area exponent or relative shear stress indicator (Bengin and Schumm, 1984; Morgan and Mngomezulu, 2003). The negative value of *b* (i.e. -0.2517) and in general consideration *b*>0.2 is considered to identify the dominancy of overland flow erosion over sub-surface processes in the study area (Vandaele et al., 1996; Vandekerckhove et al., 1998; Morgan and Mngomezulu, 2003; Samni et al., 2009; Dong et al., 2013). The slope – area relationship is recognized here as geomorphic threshold – intrinsic to the system to initiate abrupt changes as the primary condition of gully formation in this lateritic landscape. Development of numerous gullies on laterites reflects geomorphic instability in the landform itself when the critical hydro-geomorphic situation crossed the threshold limit, i.e. $SA^{0.2715} > T$ (*T* is the threshold value, i.e. 17.42 for this study site). It is estimated that critical drainage area for slope 2.34° is about 2908 m^2 to initiate gully. Here result of S – A threshold relation is compared with the results of various studies conducted in a range of different environments (figure 4.15). It is found that our S – A critical line of threshold is placed below the other lines, signifying a minimum geomorphic threshold to gully incision in this tropical sub-humid monsoon climate and other geographical conditions.

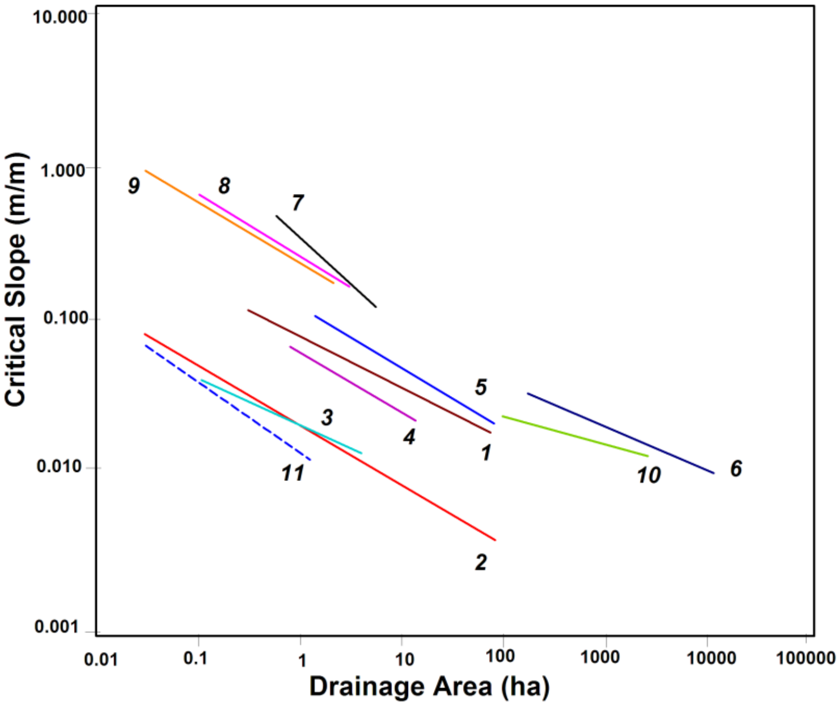


Figure 4.15 Comparing the calculated critical slope and drainage area threshold line (dotted line 11) with threshold lines (1 to 10) of other studies for understanding incipient gully development in a variety of environments (abroad of India), locations of study areas: (1) Central Belgium, (2) Central Belgium, (3) Portugal, (4) France, (5) South Downs UK, (6), (7) Sierra Nevada USA, (8) California USA, (9) Oregon, USA, and (10) New South Wales Australia (modified from Patton and Schumm, 1975; Montgomery and Dietrich, 1994; Vandaele et al., 1996; Boardman, 1992; Poesen et al., 2003)

4.5.4 Statistical Test and Model Validation

To judge the slope – area relation (i.e. statistically fit or not) we have performed two statistical techniques, viz., (1) Student's *t* test of correlation coefficient (*r*) and (2) significance test of standard error of b (S_E) (Sarkar, 2013).

Student's $t = r\sqrt{(N-2)} / \sqrt{(1-r^2)}$

where, *r* is Pearson product moment correlation coefficient, N is total number of sample and N – 2 is the degree of freedom.

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

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

The null hypothesis (H_O) is that there is no significant correlation between the two variables. For 116 degree of freedom (N – 2) the tabulated *t* value is 3.29 in 0.01 significance level (twotailed) but our calculated t value (7.09) much greater that tabulated *t*. Thus H_O is rejected and alternative hypothesis is accepted, which favours a significant inter-relation between S and A in the geomorphic system of gully erosion. The calculated confidence limit of calculated S_E of b (0.271 to 0.232) does not include zero (i.e. zero gradient). It signifies that the power regression($S = 17.419\ A^{-0.2517}$) is certainly significant at five percent level. Therefore, this slope – area threshold equation of channel initiation is valid statistically and can be applied in the other erosion prone lateritic areas of *Rarh* Bengal.

. The performance of this model is validated by the value of model efficiency coefficient (MEC) which was developed by Nash and Sutcliffe (1970) and this equation is applied successfully by Morgan and Duzant (2008) and Cao et al. (2013) in soil erosion research.

$$MEC = 1 - \Sigma\ (Q_{obs} - Q_{pred})^2 / (Q_{obs} - Q'_{obs})^2$$

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

Through inserting the values of drainage area (Q_{obs}) in the equation of $S = 17.419\ A^{-0.2517}$ the predicated slope values (Q_{pred}) of each gully is calculated. The mean slope of sample gullies (Q'_{obs}) is 4.6°. EC is estimated in the case of slope prediction and its value is greater than 0.63 (greater than 0.5) which is generally interpreted to denote that this model performs satisfactorily (Morgan and Duzant, 2008). Therefore, this model is validated in the study area. Now the S – A model is applied in the 82 gully heads of Masra – Jatla area (24°06′37′′ to 24°08′15′′ N, 87°39′38′′ to 87°41′14′′ E) and Bolpur – Santiniketan area (23°40′47′′ to 23°41′46′′ N, 87°39′47′′ to 87°40′36′′ E) of Birbhum district. In this badlands of laterites, two distinct threshold equations of $S = 14.368\ A^{-0.236}$ (R^2 of 0.44) for Masra – Jatla area and $S = 112.48\ A^{-0.473}$ (R^2 of 0.85) for Bolpur – Santiniketan area are derived respectively. In both cases the dominancy of overland flow erosion is identified from significant *b* value (i.e. > 0.2). In these two regions we have found that the value of MEC varies from 0.54 to 0.77, depicting a good performance of S – A model.

4.6 M – D Envelope and Dominancy of Erosion Processes

The trend line of A – S empirical relationship and regression slope (*b* value)can determine relative importance of overland flow erosion, subsurface flow erosion, diffusive erosion and mass movement or landsliding erosion (figure 4.16). Here on the basis of slope (*X axis*) and drainage area (*Y axis*) we have classified the gully heads to determine erosion dominancy which is clearly depicted through a threshold line, i.e. called Montgomery – Dietrich (M – D) Envelope. The estimated M – D envelope distinguishes mass movement dominated gullies from hydraulic erosion dominated gullies. In this study area 52.51 percent of gullies are affected by overland flow erosion (S – 1.2° to 5.2° and A – 2129.1 to 10513.9 m^2) while 27.96 percent belongs to landslide erosion (S – 5.2° to 9.5° and A – 457.1 to 5702.5 m^2).Only 15.25 percent of gullies (S – 2.2 to 4.6° and A – 685.5 to 3843.7 m^2) are affected by tunnel erosion or seepage erosion (table 4.3).

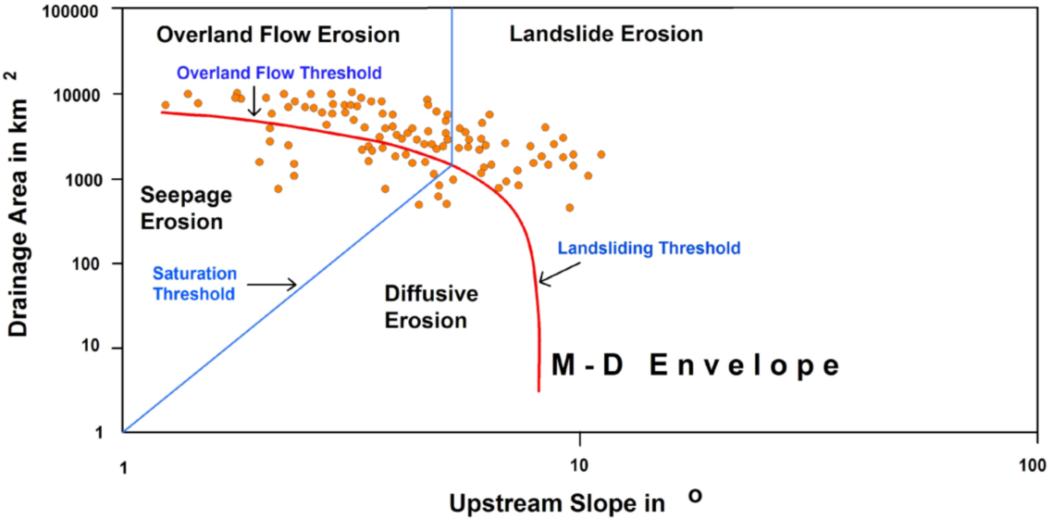


Figure 4.16 The diagram showing S (in °) – A (in m^2) scatter plot in M – D Envelope (i.e. red curve) to depict erosion dominant gullies in the study area

In the study sites the gullies are established by the deepening of rills and slumping of side slopes through the shearing effect of concentrated overland flow, increase in pore-water pressure and decreases in soil strength along seepage lines close to the streams (Lal, 1992). Gully development in the vicinity of concentrated flow is facilitated in the lateritic soils with predominantly coarse-textured A horizon (i.e. secondary duricrust of loose ferruginous nodules) abruptly overlying a compact, less permeable mottle clay or kaolinite pallid zone (B horizon). Therefore, based on the comparison with M – D envelope we can take preventive measures to check active processes in the gully sites. Also we can predict the un-trenched slope facets which have chances to initiate gully heads on the laterites of *Rarh* Bengal. As this lateritic landscape is affected by overland flow erosion, we can say that above the M – D envelope the excess runoff and critical shear stress are progressively increased whereas below that line, the effect of rainfall intensity and infiltration capacity is increased (Montgomery and Dietrich, 1994).

Table 4.3 Distribution of gully heads in respect of dominant erosion process using M – D Envelope

Dominant Gully Erosion Process	Percentage of Gully Heads	Slope Range	Area Range
1. Overland Flow Erosion	52.51%	1.2 to 5.2°	2129.1 to 10513.9 m^2
2. Seepage Erosion	15.25%	2.2 to 4.6°	685.5 to 3843.7 m^2
3. Landslide Erosion	27.96%	5.2 to 9.5°	457.1 to 5702.5 m^2
4. Diffusive Erosion	4.28%	4.4 to 5.3°	483.2 to 879.9 m^2

Chapter 5.0

5.1 Erosion Estimation and Modelling

Gully erosion represents a major sediment producing process, generating between 10 and 95 percent of total sediment mass at catchment scale whereas the gully channels often occupy less than 5 percent of total catchment area (Poesen et al., 2003; Valentin et al., 2005). Headwall retreat, vertical erosion and sidewall erosion are the chief processes of erosion in the gullies. Because gully erosion involves both hillslope (e.g. rainsplash and mass movement) and channel (e.g. sediment transport) processes that may be affected by many environmental factors, such as topographic threshold, land use change and climate change, quantifying the mechanics controlling gully initiation and estimation of erosion are extremely difficult task. Generally, the physical based models have been used to estimate gully erosion, but the mathematical complexity and data availability are the major hindrances. So, here gully erosion is estimated in two parts – (1) estimating channel erosion and (2) estimating bank failure. The rill and inter-rill erosion is estimated using empirical models.

5.2 Gully Erosion Estimation

To estimate gully erosion a simple approach of transverse cross-profile survey was performed in three sample catchments, viz. gully catchment 1, 2 and 3. The cross-profile wise erosion estimation includes both channel and side-wall erosion in a gully. The main approach is to calculate the eroded area between two transect profiles and then to estimate volume, multiplying the area with length between two transect. The loss of earth materials between two transects is the ratio between bulk density of earth materials (i.e. laterites) and volume of each segment. The calculated average bulk density of laterite samples is 2.205 gm cm^{-3}.

In the gully catchment 1, the estimation of land loss due to gully erosion is based on the eight transverse cross-sectional areas at different interval of distance along the gully floor. The average volume of cross-sections ranges in between 1504.66 m^3 to 9973.37 m^3, whereas the amount of land loss varies from 3317.78 tonne to 21,991.28 tonne (table 5.1). It is calculated that all total 79,188.16 tonne of lateritic land is permanently eroded due to gully erosion in this catchment 1. Similarly, in the gully catchment 2 ten consecutive cross-sections reveal that the average volume of gully channel varies from 114.12 m^3 to 1807.34 m^3 and the amount of land loss varies from 251.64 tonne to 3985.19 tonne. In this catchment all total 21,534.58 tonne of lateritic land is lost due to gully erosion till now. In the gully catchment 3 the analysis of six cross-sections reveals that the volume of gully channel ranges in between 3052.35 m^3 and

73,177.0 m^3 and 6730.43 tonne to 1,61,356.46 tonne of land is eroded along the gully channel. All total 9,48,501.18 tonne of land is permanently lost by this gully.

Table 5.1 Estimation of gully erosion using the cross-profiles across gully

Channel in between	Distance in between (m)	Average Volume in between (m^3)	Weight of Materials Eroded (tonne)
Gully Catchment 1			
O to AA'	21.37	1504.66	3317.779
AA'to BB'	44.37	3173.12	6996.73
BB'to CC'	84.63	4713.46	10393.28
CC'to DD'	20.12	1328.92	2930.281
DD'to EE'	92.67	5635.72	12426.78
EE'to FF'	142	9973.37	21991.28
FF'to GG'	53.21	4689.92	10341.29
GG'to HH'	54.36	4893.76	10790.74
Gully Catchment 2			
O to AA'	13.27	114.12	251.639
AA'to BB'	21.31	458.96	1012.015
BB'to CC'	28.56	930.27	2051.475
CC'to DD'	18.59	1000.04	2205.108
DD'to EE'	23.08	1290.56	2845.694
EE'to FF'	54.2	1233.05	2718.875
FF'to GG'	59.21	609.86	1344.747
GG'to HH'	66.87	1678.43	3700.933
HH'to II'	65.2	1807.34	3985.193
II'to JJ'	31.29	643.94	1419.905
Gully Catchment 3			
O to AA'	23.8	3052.35	6730.431
AA'to BB'	29.2	5764.08	12709.796
BB'to CC'	54.07	12,794.30	28211.431
CC'to DD'	53.34	9179.81	20241.489
DD'to EE'	98.93	73,177.53	161356.457
EE'to FF'	68.33	8730.8	19251.578

Note: Bulk Density of Laterite – 2.205 gm cm^{-3}

Analyzing the bank morphology of gully (selecting erosion prone bank), it is found that average width of tension cracks in bank sidewall varies from 0.05 to 0.18 m and the gradient of wall varies from 70° 21′ to 85° 15′ in the selected sites. Using Leica Disto S910 instrument the area of irregular bank sidewall is measured with the help of 3D geometry tool. The estimated area ranges in between 3.566 m^2 to 13.225 m^2. The weight of bank materials is estimated using bulk density of laterite profile (i.e. 2.205 gm cm-3) and volume of cracked bank. The results show that the weight of bank materials (i.e. potential loss of land) varies from 457.23 kg to 1913.72 kg (table 5.2). This amount of land mass is vulnerable to next bank failure in the gully catchments. The key processes of bank failure are the weathering and tension crack formation, rill erosion, mass movement and undercutting by ephemeral flow.

Table 5.2 Estimating potential bank erosion in terms of losing weight

Bank Site	**GPS Location**	**Avg. width of mass from crack (m)**	**Slope from Base (°)**	**Area (m^2)**	**Weight to be lost (kg)**
B1	24°09’43’’N, 87°41’11’E	0.16	82°50’	3.566	1258.08
B2	24°09’41’’N, 87°41’12’E	0.18	85°15’	1.152	457.23
B3	24°10’27’’N, 87°42’35’E	0.18	74°17’	13.225	5249.15
B4	24°010’26’’N, 87°42’34’E	0.11	80°30’	7.890	1913.72
B5	24°10’59’’N, 87°41’49’E	0.05	70°21’	14.435	1591.46
B6	24°10’58’’N, 87°41’55’E	0.10	80°42’	6.094	1343.73

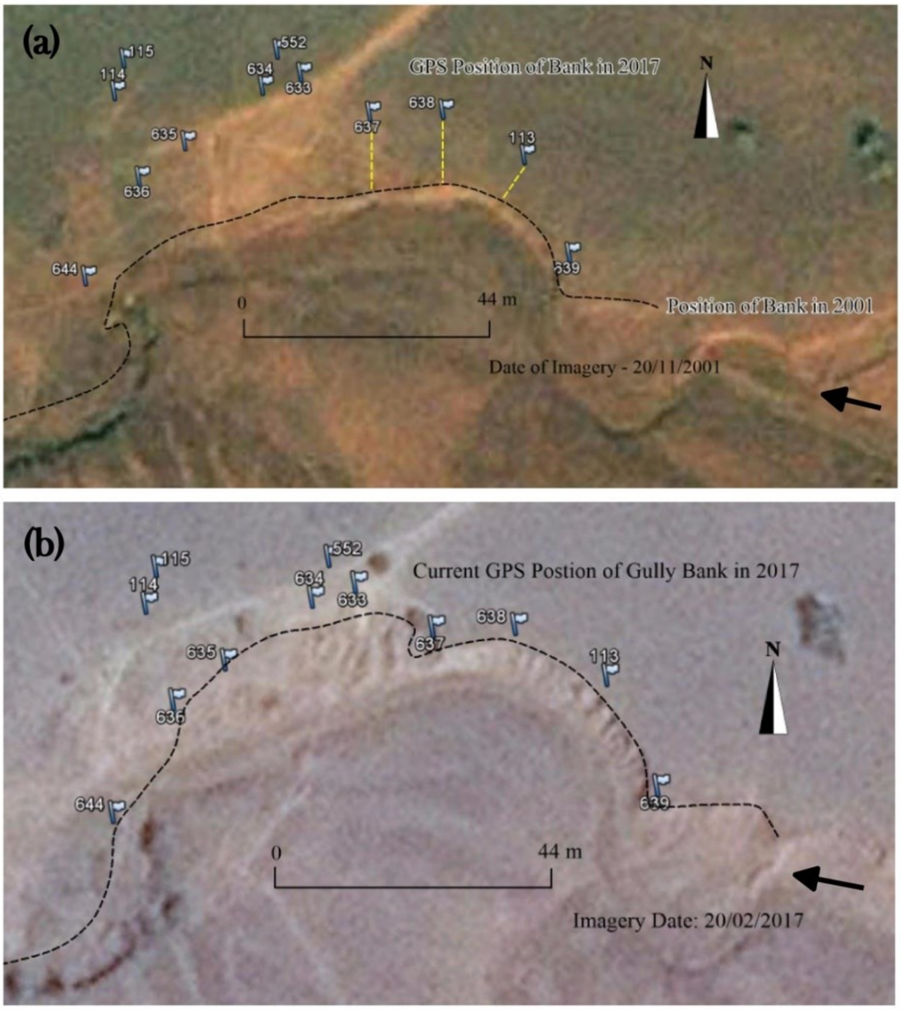


Figure 5.1 GPS-based measurement of bank retreat from Google Earth image of (a) 20th November, 2006 and (b) 20th February, 2017

Due to bank erosion the gully is expanded and the position of bank is recessed. So this geomorphic unit of gully is identified as the active erosion prone sites where the yearly rate of bank retreat (i.e. loss of land due to bank erosion) can be measured. A GPS based study of bank retreat was done in the gully catchment 3, selecting six permanent locations along the gully sidewall. The GPS positions of 2017 were recorded at the six locations and these locations were compared with Google Earth Image of 2001, through overlaying the GIS layer (UTM WGS 84 projection). The average recession (2001 to 2017) of bank was estimated using the ruler tool of Google Earth. The analysis reveals that in between 2001 and 2017 the mean rate of bank retreat varies from 0.231 m yr^{-1} to 0.681 m yr^{-1} in the gully catchment 3. A similar experiment was performed in the 116 gully heads using GPS locations of 2017 (figure 5.1) and the retrieve data was compared with the Google Earth Image of 2001. The analysis reveals that average rate of gully head migration varies from 0.07 m yr^{-1} to 1.14 m yr^{-1} (table 5.3).

Table 5.3 Measuring bank retreat rate using GPS and Google Earth

Bank Site	GPS Location	Avg. Recession of Bank (2001 – 2017) (m)	Avg. Rate of Bank Retreat per year (m/yr)
B1	24°09’43’’N, 87°41’11’E	4.29	**0.268**
B2	24°09’41’’N, 87°41’12’E	4.65	**0.29**
B3	24°10’27’’N, 87°42’35’E	6.22	**0.388**
B4	24°010’26’’N, 87°42’34’E	3.71	**0.231**
B5	24°10’59’’N, 87°41’49’E	7.68	**0.48**
B6	24°10’58’’N, 87°41’55’E	10.9	**0.681**

5.3 Soil Erosion Model

In the soil erosion study, the development of a model is associated with the erosion-prediction perspective which is a powerful tool used for more than half a century in policy development, erosion inventories, conservation planning and engineering design. There are at least three reasons for modelling erosion (Nearing et al., 1994):

1. Erosion models can be used as predictive tools for assessing soil loss for conservation planning, project planning, soil erosion inventories and for regulation;
2. Physically-based mathematical models can predict where and when erosion is occurring, thus helping the conservation planner’s efforts to reduce erosion; and
3. Models can be used as tools for understanding erosion processes and their interactions and for setting research priorities.

Most of the models used in soil erosion studies are of the empirical grey-box type (Morgan, 2005). A grey-box model includes some understanding of the relationships between input and output, for example, that the effect of rainfall on erosion alters according to slope steepness and vegetation cover. They are based on defining the most important factors through the use of observation, measurement, experiment and statistical techniques, relating them to soil loss. In the present study RUSLE (Renard et al., 1997) and RMMF (Morgan, 2001) models are chosen to estimate annual rate of soil loss in hillslope scale. In general these models have same temporal and spatial scale of study having standard boundary conditions and incorporating erosivity factors, erodibility factors, topographic factors, land use and land cover factors and erosion protection factors. The prime objective is to estimate annual mean potential soil erosion rate above gully heads in a catchment and to validate the models in comparison to soil loss tolerance limit and observed results in a year.

Here the catchment of gully is considered where minimum interference of human are noticed, because it is the purpose to study slope erosion processes and variable interaction of soil – land use factors in the normal and natural condition. In this lateritic terrain a high erosion risk catchment of gully is selected, i.e. Gully Catchment 1 which has well defined basin area (about 1,09,250m^2) and dense network of gullies (8.33 km km^{-2}). Maintaining a certain distance from active gully head, six check dams have been developed (denoting Dam 1 to Dam 6) at the base (i.e. gully floor) of representative slope elements to trap eroded sediments coming from upslope in a year (2016 – 2017). The databases of soil and dam site sedimentation were prepared (table 5.4 and 5.5). The prime task is that applying models we have to examine the estimated and observed values of erosion rate and later, to justify the applicable erosion model in this area.

Table 5.4 Textural data of sample soils in the study area

Sample Site	Location	Sand %	Silt %	Clay %	Organic matter %	Soil texture
1	24°11´06´´N, 87°42´40´´E	65.3	24.6	10.1	0.61	Sandy loam
2	24°10´57´´N, 87°42´49´´E	64.0	22.4	13.6	0.68	Sandy loam
3	24°11´23´´N, 87°42´40´´E	52.6	28.3	19.1	0.21	Sandy clay loam
4	24°11´51´´N, 87°42´41´´E	70.2	19.1	10.7	0.57	Sandy loam

Table 5.5 A brief summary of dam's parameters and rate of erosion at six dam sites

Check Dam	Width cm	Height cm	Sedimentation Depth m	Sediment Volume cm^3	Measured Sedimentation kg	Rate of Erosion kg/m^2
Dam 1	100	45	0.13	3,31,410	566	14.10
Dam 2	112	46	0.2	3,59,093	614	19.94
Dam 3	92	48	0.25	12,89,205	2204	24.27
Dam 4	100	47	0.15	11,00,079	1881	14.45
Dam 5	190	55	0.11	6,24,680	1068	10.50
Dam 6	117	40	0.23	13,66,624	3583	24.01

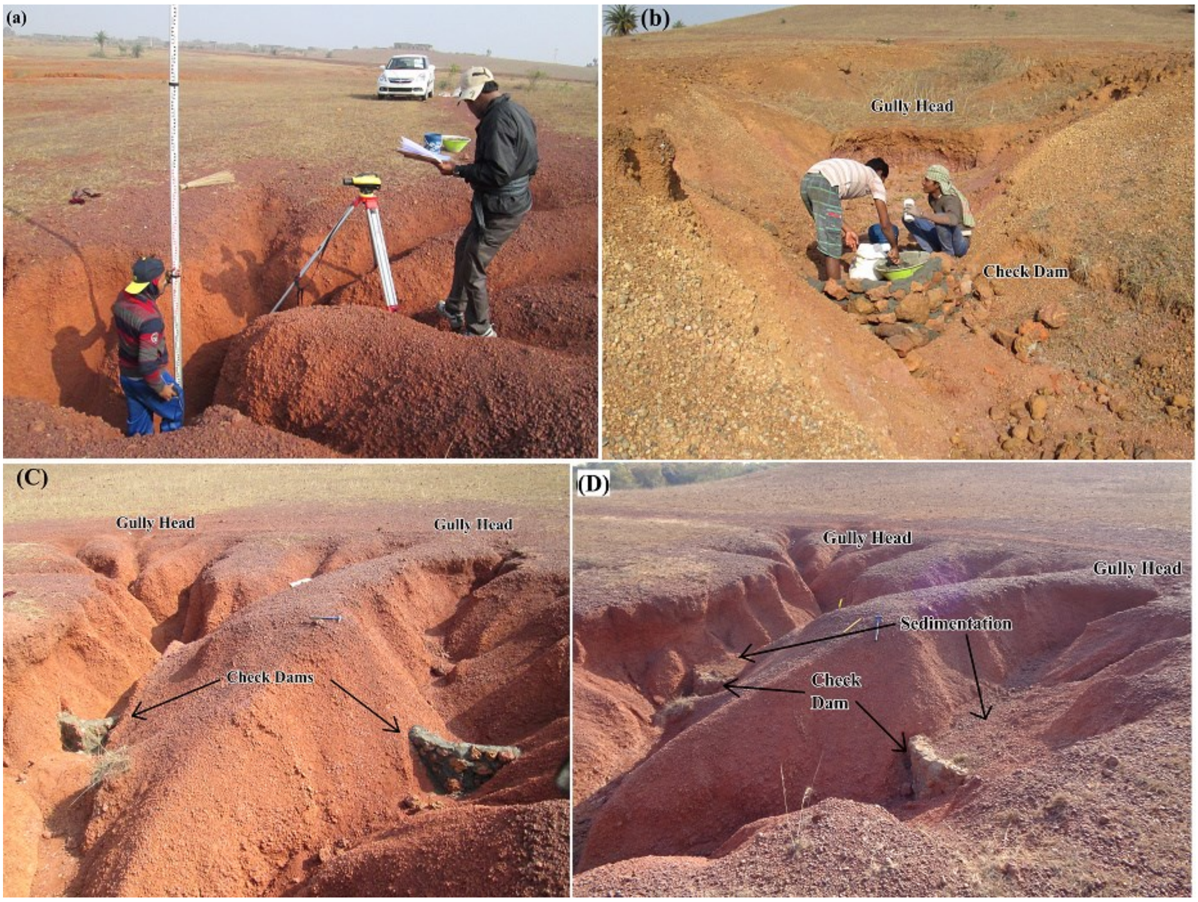


Figure 5.2 (a) Field survey during preparation of dam site using Leica Sprinter 150 m and staff, (b) construction of check dam 5 on January, 2017, (c) initial condition of check dam site 2 and 3 on January, 2017, and (d) post-dam condition of dam site 2 and 3, and sedimentation behind the dam on January, 2018

5.3.1 Revised Universal Soil Loss Equation and Result

Revised Universal Soil Equation (RUSLE) is the modified version of old USLE (figure 7.3), but the basic structure remains same as previous. The USLE is an erosion model designed to compute long-time average soil loss from sheet and rill erosion under specified conditions, but it does not predict deposition and does not compute sediment yields from gully erosion (Wischmeier and Smith, 1978). The Wischmeier and Smith (1972 and 1978) version of USLE is mentioned as follows.

$$A = R\ K\ L\ S\ C\ P$$

where,

- A is the computed soil loss per unit area (tons per acre per year); it can transformed into SI unit
- R, the rainfall and runoff factor, is the number of rainfall erosion index units, i.e, EI_{30}
- K, the soil erodibility factor, is the soil loss rate per erosion index unit for a specified soil as measured on a unit-plot, which defined as a 72.6 ft length of uniform 9-percent slope continuously in clean-tilled fallow
- L, the slope-length factor, is the ratio of soil loss from the field slope length to that from a 72.6 ft length under identical conditions
- S, the slope-steepness factor, is the ratio of soil loss from the field slope gradient to that from a 9 percent slope under otherwise identical conditions
- C, the cover and management factor, is the ratio of soil loss from an area with specified cover and management to that from an identical area in tilled continuous fallow
- P, the support practice factor, is the ratio of soil loss with a support practice like contouring, strip cropping or terracing to that with straight-row farming up and down the slope.

There are few changes in the Revised Universal Soil Equation (RUSLE) which are summarized as follows (Renard et al., 2011).

(1) EI values of rainfall erosivity factor (R) are developed as case specific for different climate zones.
(2) USDA has identified K values for specific soils through wide range of soil surveys.
(3) Soil loss is found to be much more sensitive to changes in slope steepness than to errors in slope length.

(4) C factor is computed as function of five sub-factors, viz., prior land use sub-factor, canopy cover sub-factor, surface cover sub-factor, surface roughness sub-factor and soil moisture sub-factor.

(5) P factor is computed as a function of four sub-factor, viz., contouring sub-factor, strip-cropping sub-factor, terracing sib-factor and sub-surface drainage sub-factor.

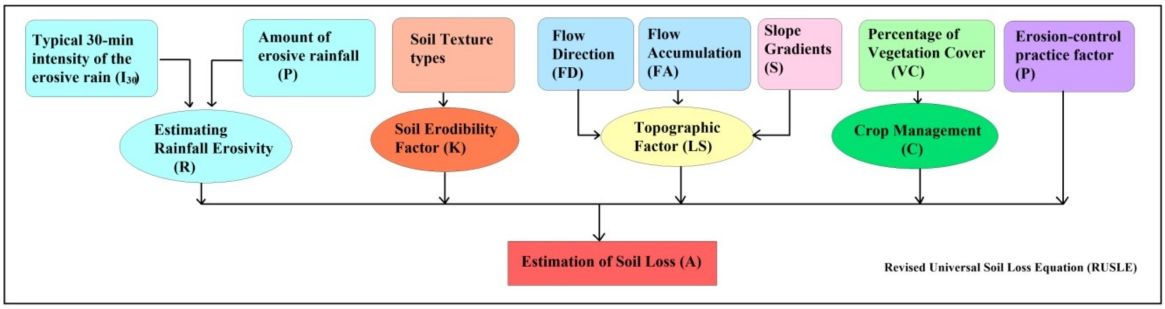


Figure 5.3 Flowchart of data input and methods for RUSLE based soil erosion modelling (modifier form Morgan, 2011 and Bayramov et al., 2013)

In USDA Agriculture Handbook No. 703 (Renard and Ferreira, 1993; Renard et al., 1994 and 1997) the details of RUSLE are incorporated as erosion model predicting long-term soil loss due to raindrop splash and runoff from a hillslope under wide range of input database. We have used the flowing equations of RUSLE which are applied by Renard et al. (1997), Jha and Paudel (2010), Rahaman et al. (2015), Bayramov et al. (2013) and Ganasri and Ramesh (2016).

$$R_1 = P\,(0.119 + 0.0873 \log_{10} I_m) \text{ x } \log_{10} I_{30}$$

$$R_2 = 79 + 0.363\,P$$

$$R = (R_1 + R_2) / 2$$

$$K = 1.2917\,[2.1 \text{ x } 10^{-4}\,(12 - OM)\,M^{1.14} + 3.25\,(s - 2) + 2.5\,(p - 3)] / 100$$

$$M = \%\ silt\ (100 - \%\ clay)$$

$$LS = (L/22.13)^{0.5}.(0.065 + 0.045\,\theta + 0.0065\,\theta^2)$$

where, P is the mean annual rainfall, I_m is the average rainfall intensity (i.e. 25.21 mm hr^{-1}), I_{30} is the maximum30 minute rainfall intensity (i.e. 75 mm hr^{-1}, recommended by Wischmeier and Smith, 1978), OM is the percentage of organic matter in soil, M is the particle size parameter, s is the soil structure code and p is permeability code (table 5.6), L is the slope length andθ is slope steepness in percent.

C and P factors (table 5.7 and 5.8) are firstly computed from the rational input databases of RUSLE (Renard et al., 1997; Morgan, 2005; Sarkar et al., 2005) in different crop and management practices and erosion control practices, and then these values are weighted in respect of current soil – land use pattern of six slope elements.

Table 5.6 Soil structure code and permeability code to determine K factor in RUSLE (Wischmeier and Smith, 1978)

Soil Structure (b)	Code	Soil Permeability (C)	Code
Very fine granular	1	Very Slow	6
Fine granular	2	Slow	5
Coarse granular	3	Slow to moderate	4
Blocky, platy or massive	4	Moderate	3
		Moderate to Rapid	2
		Rapid	1

Table 5.7 C-factor values for RUSLE (Sarkar et al., 2005)

Land Use and Land Cover	C-factor value
Forest (fully stocked and tea garden)	0.01
Forest (moderately stocked)	0.05
Degraded forest / bushy forest	0.10 - 0.14
Grassland	0.01 - 0.025
Crop lands (Tista-Mahanandaand Lower Ganga Plain)	0.20 - 0.30
Crop lands (hillslope / red and lateritic region)	0.40
Degraded or waste land	0.50
Bare Soil	1.0

Table 5.8 P-factor values for RUSLE (Sarkar et al., 2005)

Erosion Control Practices	P-factor value

Terracing	0.10
Contour bunding	0.20
Field bunding (nearly level land)	0.30-0.40
Field bunding (gently sloping and undulating lands; active floodplain)	0.50
Tea cultivation	0.70-1.0

The input parameters of RUSLE are mean annual rainfall (P), average rainfall intensity (I_m), soil erodibility (K), crop cover and management factor (C) and erosion control factor (P). Based on the average data of three rain-gauge stations the mean P is calculated as 1510 mm in 2016 and the I_m is estimated as 25.21 mm hr^{-1} for this climatic region. The K-factor is estimated as average condition of the gully catchment 1, i.e. 0.21 for the sandy loam soils. High percentage of sand (> 60 %) in the top soils makes the low value of K. In general coarse granular soil structure ($b = 3$) and moderate soil permeability ($c = 3$) are observed in the lateritic soils. In the saturation condition of peak monsoon and cyclonic rainfall period, surface crusting (i.e. Fe-Al clay closes the pore spaces of top soils) and less canopy cover on bare soil promotes high overland flow on the slope elements. The slope elements of this catchment have maximum angle of 11°06′ and minimum angle of 5°58′ at the head slope of gully. LS-factor varies from 1.16 to 1.53 and erosion is very sensitive to slope steepness and slope length. The strip areas of slope elements have maximum bare lateritic surface (> 80 %) with ferruginous nodules. Upper convex part of slope has the little grass cover (7 – 17 %) which is effective to check runoff erosion. The C-factor is estimated as weighted value in respect of land use condition in each slope element and it varies from 0.83 to 0.91. The most importantly no artificial erosion control measure has been taken in this catchment. So P-factor is regarded as 1.0 in this region.

Based on the above estimates of inputs, we have then multiplied R, K, LS, C and P factors are taken to get potential predicted values (SE_P) of annual soil erosion rate (Kg $m^{-2}yr^{-1}$). SE_P varies from 13.22Kg $m^{-2}yr^{-1}$ to 17.71 Kg $m^{-2}yr^{-1}$which depicts the soil loss rate due to rainsplash, rill and inter-rill erosion in the sample slope elements in 2016 (table 5.9). On an average the gully catchment 1 has annual rate of soil loss of the S6 slope has maximum SE_P of 17.71 Kg $m^{-2}yr^{-1}$, having slope angle of 9.44 percent, slope length of 45.4 m and high LS factor of 1.50. The slope element S4 depicts minimum potential SE_P value of 13.22 Kg $m^{-2}yr^{-1}$with LS factor of 1.16. As the T value (soli loss tolerance value) is only 0.5 Kg $m^{-2}yr^{-1}$for this region, so it can be that the lateritic terrain is in high risk of erosion. The productivity of land is much less, because erosion beyond acceptable limit does not favour soil formation or soil stability and growth of luxurious vegetation, i.e. prone to land degradation.

Table 5.9 Estimated input parameters and annual erosion rate in RUSLE modelling

Sample Slope	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
Grassland Cover (%)	13	7	11	17	9	14
Bare Lateritic Cover (%)	87	93	89	83	91	86
Slope Length m	20.1	15.4	45.4	65.1	74.6	50.9
Slope Angle	10°9′	11°6′	8°30′	6°11′	5°58′	8°5′
Slope Angle in %	11.27	12.33	9.44	6.85	6.63	8.89
LS	1.33	1.34	1.53	1.16	1.19	1.5
Weighted C	0.87	0.93	0.89	0.83	0.91	0.86
R	654					
K	0.21					
P	1.0					
Annual Rate of Soil Loss (A) Kg m^{-2}yr^{-1}	15.89	17.11	18.7	13.22	14.87	17.71
Observed Erosion Rate Kg m^{-2}yr^{-1}	14.1	19.94	24.27	14.45	10.5	24.01

To justify the model applicability and to estimate error in model values, the values of RUSLE model (SE$_P$) and observed values of erosion rate (SE$_O$) are compared (table 5.10). In general the absolute error varies from + 6.3 to – 4.37Kg m^{-2}yr^{-1} in the sample sites and RMS-error is about 9.56 in respect of observed values. Now applying the equation of MEC (model efficiency coefficient) the value of 0.37 is obtained (MEC > greater than 0.5, i.e. highly good performance of model) which depicts low to moderate accuracy and performance of RUSLE model in the gully catchment 1. In general it is observed that the values ofSE$_P$ are very much close to SE$_O$. In slope elements of S1, S2 and S4 the difference between RUSLE and observed values varies from 1.23 to 2.83Kg m^{-2}yr^{-1}.

Table 5.10 Error and RUSLE model validation in comparison with observed values

(SE_P) Predicted Erosion Rate Kg $m^{-2}yr^{-1}$	(SE_O) Observed Erosion Rate Kg $m^{-2}yr^{-1}$	Error	RMS-error	MEC
15.89	14.1	-1.79	9.56	0.37
17.11	19.94	2.83		
18.7	24.27	5.57		
13.22	14.45	1.23		
14.87	10.5	-4.37		
17.71	24.01	6.3		

5.3.2 Revised Morgan, Morgan and Finney Model and Result

Bringing together the results of research by geomorphologists and agricultural engineers, Morgan, Morgan and Finney (1984) developed a model to predict annual soil loss from the field-sized areas on hillslopes which, whilst endeavouring to retain the simplicity of the USLE. Initially MMF model comprises fifteen input parameters and six operating functions. The model comprises a water phase and a sediment phase. Rainfall energy and runoff volume are estimated from annual rainfall amount in the water phase (Morgan et al., 1984; Morgan, 1986). In the sediment phase, erosion is taken to result from the detachment of soil particles by rainsplash and their transport by runoff (Morgan et al., 1984; Morgan, 1986).

Morgan (2001) presents a revised version of MMF model (RMMF) which takes account of the need to improve the description of the processes of erosion and the requirement of users for better guidance on the choice of input parameter values. In RMMF seventeen parameters and all total fourteen equations are incorporated to predict soil loss on a hillslope. Further modifications are made to the RMMF erosion prediction model to enable the effects of crop and other vegetation cover on a hillslope to be expressed through measurable plant parameters (Morgan and Duzant, 2008).

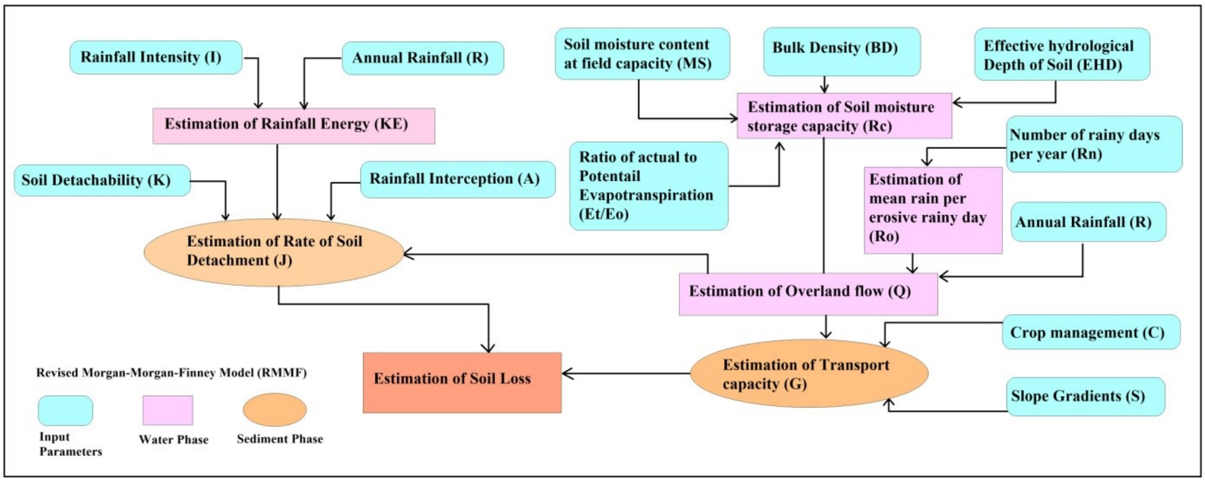


Figure 5.4 Flowchart of data input and methods for RMMF based soil erosion modelling (modifier form Morgan, 2005 and Bayramov et al., 2013)

The RMMF model (figure 5.4) is applied at catchment scale to plot scale for predictions of annual soil loss in variable topographic and climatic conditions by Jasrotia and Singh (2006), Vigiak et al. (2006), Lopez-Vicente and Navas (2010), Jha and Paudel (2010), Fernandez et al. (2010) and Boyramov et al. (2013). Now the description of two phase erosion, input parameters and employed equations of RMMF model (Morgan, 1986, 2001 and 2005) are summarized as below (table 5.11).

Table 5.11 Input parameters to the RMMF model of predicting soil loss and estimated values (Morgan, 2001 and 2005)

Factors	Input Parameters	Descriptions	Estimated Value
Climate	R	Mean annual rainfall (mm)	1510 mm
	R_n	Number of rain days per year	88 days
	R_o	Average daily rainfall in rainy days (mm)	17.48 mm
	I	Typical value for intensity of erosive rain (mm hr^{-1})	25.21 mm hr^{-1}
Soil	MS	Soil moisture content at filed capacity (wt%)	0.28%
	BD	Bulk density of the top soil layer (Mg m^{-3})	1.20 Mg m^{-3}
	EHD	Effective hydrological depth of soil (m)	0.114 m
	K	Soil detachability index (g J^{-1})	0.70 g J^{-1}
	COH	Cohesion of the surface soil (KPa) as measured with a torvane under saturated conditions	2.0KPa
	SD	Total soil depth (m) defined of soil surface to bedrock	0.65 m
	Slope	Slope steepness in degree	Measured in field

Landform and Land Cover	A	Proportion (between 0 and 1) of the rainfall intercepted by the vegetation or crop cover	Weighted value based on soil - land use condition in each slope element (table 7.13)
	E_t/E_o	Ratio of actual (E_t) to potential (E_o) evapotranspiration	
	C	Crop cover management factor	
	CC	Proportion of canopy cover (between 0 and 1)	
	GC	Proportion of ground cover (between 0 and 1)	
	PH	Plant height (m), representing the height from which raindrops fall from vegetation to the ground surface	
Time	N	Number of consecutive years for which the model is to operate	1 year

(1) Water Phase – The basic input parameters to the water phase are the annual rainfall (R), rainfall interception by vegetation cover (A) and percentage of canopy cover (CC). Initially the RMMF model takes annual rainfall total and computes the proportion (between 0 and 1) which reaches the ground surface after allowing for rainfall interception to give the effective rainfall (ER). Then, ER split into two, which reaches the ground surface as direct through fall (DT) and as leaf drainage (LD). The kinetic energy of DT is determined as a function of erosive rainfall intensity (I) and the amount of DT. The kinetic energy of LD is dependent upon the height of the plant canopy (PH). The total energy of effective rainfall (KE) is the summation of kinetic energy of DT and LD.

It is assumed that runoff (Q) occurs when the daily rainfall total exceeds a critical value which represents the soil moisture storage capacity (R_c) of the soil – land use combination and that daily rainfall amounts (R_o) approximate an exponential frequency distribution. R_c is a function of soil moisture content at field capacity (MS), bulk density of soil (BD), effective hydrological depth of the soil (EHD) and the ratio of actual to potential evapotranspiration (E_t/E_o) (table 7.11). The typical values for the soil and land use parameters are given by Morgan (2001 and 2005).

$$ER = R\,(1 - A)$$

$$LD = (ER - CC),\ DT = (ER - LD)$$

$$KE\,(DT) = DT\,(11.9 + 8.7 \log I)$$

$$KE\,(LD) = LD\,[(15.8 - PH^{0.5}) - 5.87]$$

$$KE = KE\,(DT) + KE\,(LD)$$

$$R_c = 1000\ MS.BD.RD\ (E_t/E_o)^{0.5}$$

$$R_o = R/R_n$$

$$Q = R\ \exp(-R_c/R_o)$$

(2) Sediment Phase – The RMMF model simplified the erosion processes of sediment phase into two parts: (i) detachment of soil particles from the soil mass (kg m^{-2}) by raindrop impact and runoff (J) and (ii) transport of those particles (kg m^{-2}) by runoff (G). Previously the detachment by runoff was ignored but now it includes in the model. The raindrop impact (F) is a function of soil erodibility and total kinetic energy of effective rainfall (KE). On other side, runoff impact (H) is considered as a function of runoff, slope steepness (S) and the resistance of the soil (Z) (which is dependent on cohesion of soil, COH). The total amount of soil particle detachment is the summation of F and H.

The transport capacity of overland flow (G) depends on the volume of overland flow slope steepness (sine function of S) and crop or plant cover factor (C) (table 7.12), The model allows the effect of agronomic measures of soil conservation which will bring about changes in R_c, E_t/E_o and C factor and it will further affect respectively Q, J and G (Morgan 2001 and 2005).

$$F = K\ .\ KE\ .10^{-3}$$

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

$$Z = 1\ /\ 0.5\ COH$$

$$J = F + H$$

$$G = C\ Q^2\ \sin S.10^{-3}$$

The model compares the predictions of detachment by rainfall – runoff (J) and the transport capacity of the runoff (G). it assigns the lower of the two values as the annual rate of soil, thereby denoting whether detachment or transport is the limiting factor, as described in Meyer and Wischmeier model (1969).

Table 5.12 Typical values for soil parameters used in RMMF model (Morgan, 2005)

Soil Texture Type	MS	BD	K	COH
Loam	0.2	1.3	0.8	3
Sandy Loam	0.28	1.2	0.7	2
Sandy Clay Loam			0.1	3
Silt Loam	0.25	1.3	0.9	3
Clay Loam	0.4	1.3	0.7	10

Table 5.13 Typical values for effective hydrological depth and plant parameters used in RMMF model (Morgan, 2005)

Condition/Plant/Crop	EHD	A	E_t/E_o	C
Bare Shallow soils with surface crust	0.05	0	0.05	1.0
Grass	0.12	0.25	0.85-0.87	0.004-0.01
Mature forest and secondary growth	0.2	0.35	0.90-1.00	0.001-0.004
Groundnuts	0.12	0.25	0.50-0.87	0.2-0.8
Rubber	0.15	0.20-0.30	0.9	0.2

The climatic factor of RMMF model has four input parameters – mean annual rainfall of 2016 (R), mean rainfall intensity (I), number of rainy days (R_n) and mean rainfall per rainy day (R_o). R is about 150 mm and I is estimated as 25.21 mm hr^{-1}. In 2016 all total 88 rainy days are calculated, having mean rainfall of 17.48 mm per day. The soil factor has six input parameters, viz., moisture content (MS), bulk density (BD), effective hydrological depth (EHD), soil detachability index (K), soil cohesion (COH) and soil depth (SD). These parametric values are tabulated from the input RMMF database of Morgan (2001 and 2005). For the sandy clay loam texture ferruginous soils, BD, K and COH are estimated as 1.2Mgm^{-3}, 0.7 gJ^{-1} and 2 KPa respectively. SD, MS and EHD are 0.65 m, 0.28 % and 0.114 m respectively. The slope steepness (S) varies from 5°58′ to 11°06′ with variable slope length (20.1 to 74.6 m) between crest and gully head. Based on the slope-wise areal coverage of grassland and bare lateritic soil cover (i.e. major land uses) we have estimated the weighted values of ratio of actual to potential evapotranspiration (E_t/E_o). Vegetation cover (A), crop cover factor (C), proportion of canopy cover (CC), proportion of ground cover (GC) and plant height (PH) etc. (Table 5.12 and 5.13).

Table 5.14 Estimated values of landform - land cover input parameters in RMMF modelling

Sample Slope	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
Grassland Cover (%)	13	7	11	17	9	14
Bare Lateritic Cover (%)	87	93	89	83	91	86
Slope Length m	20.1	15.4	45.4	65.1	74.6	50.9
Slope Angle	10°9′	11°6′	8°30′	6°11′	5°58′	8°5′
Weighted EHD	0.06	0.05	0.06	0.06	0.05	0.06
Weighted A	0.25					
Weighted E_t/E_o	0.156	0.107	0.14	0.19	0.124	0.143
Weighted C	0.87	0.93	0.89	0.83	0.91	0.86
Weighted CC	0.13	0.07	0.11	0.17	0.09	0.14
Weighted PH	0.017	0.009	0.014	0.022	0.011	0.015
Weighted GC	0.13	0.07	0.11	0.17	0.09	0.14

Inputting the above parameters in the water phase of RMMF model the amount of rainfall erosivity (kinetic energy, KE) and runoff depth (Q) are calculated in each slope elements. In six sites, total KE of rainfall detachment varies from 24,530 J m^{-2} to 26,156 J m^{-2} and Q ranges in between 913.83 mm and 1076.88 mm, influenced by soil and land use parameters (table 5.14). When these output values of sediments phases and other input parameters of topography and land cover are inserted in the sediment phase of RMMF, the total rainfall detachment of soil particles (F), runoff detachment of soil particles (H) and transport capacity of runoff (G) are estimated in six slope elements. The total detachment of soil particles on the slope is the summation of F and H values, i.e. denoted as J in the RMMF model. Here J (i.e. maximum potential annual soil loss) ranges from 15.94 Kg $m^{-2}yr^{-1}$to 24.58Kg $m^{-2}yr^{-1}$in the six sites. G is a function of crop cover, runoff and slope steepness and it varies highly from 85.95Kg $m^{-2}yr^{-1}$ to 205.50 Kg $m^{-2}yr^{-1}$. Here J is much less than G and it reflects that the soil erosion is transport limited. Here the supply of eroded soil particles is much less than the transport capacity of runoff. It means that total amount of detached particles (J) is transported by the runoff. So J is the annual rate of soil loss in each six slope elements.

The average erosion rate of RMMF modelling is 20.93Kg $m^{-2}yr^{-1}$ which is much greater than T value. As the T value (soli loss tolerance value) is only 0.5Kg $m^{-2}yr^{-1}$for this region, so we can say that the lateritic terrain is in high risk of erosion. The productivity of land is much less due to intensive rill and gully erosion and this lateritic terrain is prone to land degradation.

Table 5.15 Calculated water phase and sediment phase in RMMF modelling

	Water Phase							
Sample Slope	**ER mm**	**LD mm**	**DT mm**	**KE(LD) Jm^{-2}**	**KE (DT) Jm^{-2}**	**Total KE Jm^{-2}**	**Rc**	**Q mm**
S1	1132.5	147.225	985.275	1346	23,738	25,084	7.96	957.61
S2		79.275	1053.225	780	25,376	26,156	5.49	1070.1
S3		124.575	1007.925	1223	24,285	25,508	7.54	981
S4		192.525	939.975	1883	22,647	24,530	8.78	913.83
S5		101.925	939.975	1001	24,830	25,831	5.91	1076.88
S6		158.55	973.95	1808	23,466	25,021	7.62	975.53

	Sediment Phase					
Sample Slope	**F** Kg $m^{-2}yr^{-1}$	**H** Kg $m^{-2}yr^{-1}$	**J (F+H)** Kg $m^{-2}yr^{-1}$	**G** Kg $m^{-2}yr^{-1}$	**Predicted Erosion Rate (J < G)** Kg $m^{-2}yr^{-1}$	**Observed Erosion Rate** Kg $m^{-2}yr^{-1}$
S1	17.56	4.54	22.1	140.6	22.10	14.10
S2	18.31	6.27	24.58	205.5	24.58	19.94
S3	17.86	4.04	21.9	126.6	21.90	24.27
S4	17.17	2.46	19.63	85.95	19.63	14.45
S5	18.08	3.34	21.42	109.7	21.42	10.50
S6	12.26	3.68	15.94	115.11	15.94	24.01

Now the calculated erosion rates (J) are compared with observed values (SE_O) to know the deviation in the RMMF model (table 5.15). In general the absolute error varies from + 8.07 to - 10.92 Kg $m^{-2}yr^{-1}$in the sites. The average observed soil loss rate is 17.87 Kg $m^{-2}yr^{-1}$, whereas the RMMF predicts 20.93 Kg $m^{-2}yr^{-1}$in average. RUSLE model predicts average values of 16.25Kg $m^{-2}yr^{-1}$ which is very much close to average SE_O. The RMS-error of RMMF model is estimated as 19.05 which are two times higher than the results of RUSLE (i.e. RMS-error – 9.56). In all cases the predicted values are much deviated than the observed values. To justify the model validation calculated REC is done which near about– 0.87 which reflects that the RMMF model predictions have a higher variation than the observed values. Therefore, the performance of this model is very weak in this condition.

Table 5.16 Error and RMMF model validation in comparison with observed values

(J) Predicted Erosion Rate Kg $m^{-2}yr^{-1}$	(SE_O) Observed Erosion Rate Kg $m^{-2}yr^{-1}$	Error	RMS-error	MEC
22.1	14.1	-8	19.50	-0.87
24.58	19.94	-4.64		
21.9	24.27	2.37		
19.63	14.45	-5.18		
21.42	10.5	-10.92		
15.94	24.01	8.07		

5.4 Comparison between RUSLE and RMMF

A number of studies have been done to judge the applicability and performance of RUSLE and RMFF in different geo-climatic conditions (Fernandez et al., 2010; Jha and Paudel, 2010; Bayramov et al., 2013). Here after sensitivity analysis and model validation part, it can be rationally said that there are significant differences in predictions of erosion rate by RUSLE and RMMF models (table 5.17). In five cases (S1 to S5) the predicted values of RMMF are much greater than the predictions of RUSLE. The average maximum potential annual rate of soil loss is 20.93Kg $m^{-2}yr^{-1}$in the RMMF model, whereas it is 16.25Kg $m^{-2}yr^{-1}$in the RUSLE model. Both these values do not match with the observed field values of erosion rate which is 17.87 Kg $m^{-2}yr^{-1}$in the gully catchment 1 (figure 5.5 a). In six cases, the RMS-error of RUSLE is 9.56, but it is rising up to 19.05 in the RMMF model. Alongside, the MEC value is highly negative (-0.87) for the RMMF model, which means high variations in predictions than the observed values. But the MEC value of RUSLE model is 0.37 which means moderate performance of model in this geo-climatic condition.

Table 5.17Comparing the observed values with the predicted values of RUSLE and RMMF in Gully Catchment 1

RUSLE (SE_P) Predicted Erosion Rate Kg $m^{-2}yr^{-1}$	**RMMF (J) Predicted Erosion Rate Kg $m^{-2}yr^{-1}$**	**Field Data (SE_O) Observed Erosion Rate Kg $m^{-2}yr^{-1}$**	**Average of RUSLE**	**Average of RMMF**	**Average of Observed**
15.89	22.10	14.10	16.25Kg $m^{-2}yr^{-1}$	20.93Kg $m^{-2}yr^{-1}$	17.87 Kg $m^{-2}yr^{-1}$
17.11	24.58	19.94			
18.70	21.90	24.27			
13.22	19.63	14.45			
14.87	21.42	10.50			
17.71	15.94	24.01			

The results of RUSLE show little variation in different segments due to low variability of the input factors in a micro region and the range of the variables are low except length of slope and the soil conservation factor. The input parameters of RUSLE show the average condition of the study area, having simplicity in inter-relationship. But the complexity and high sensitivity of input parameters increases the deviation of output values in the RMMF model and it over-predicts the situation. Also the equations of effect rainfall energy is very much subjective than practical condition in field, and the RMMF model does not include slope length parameter. This region has least crop coverage, high percentage of bare soil cover and lesser extent of slope variation. For those reasons the database of input parameters of soil and land uses are not effectively explain the actual field conditions and also the land use parameters do not show any effect on the checking the soil erosion. This is why the predicted RMMF values are much deviated from the observed values. Also the table values of Morgan (2001 and 2005) are not sufficient and effective in this lateritic region, because the wide-range values of many other inherent parameters are not included in this model. Due to high sensitivity of K, CC, S and P factors it is better to take care of the actual values of these inputs and rational judgment of input values during the RMMF model operation.

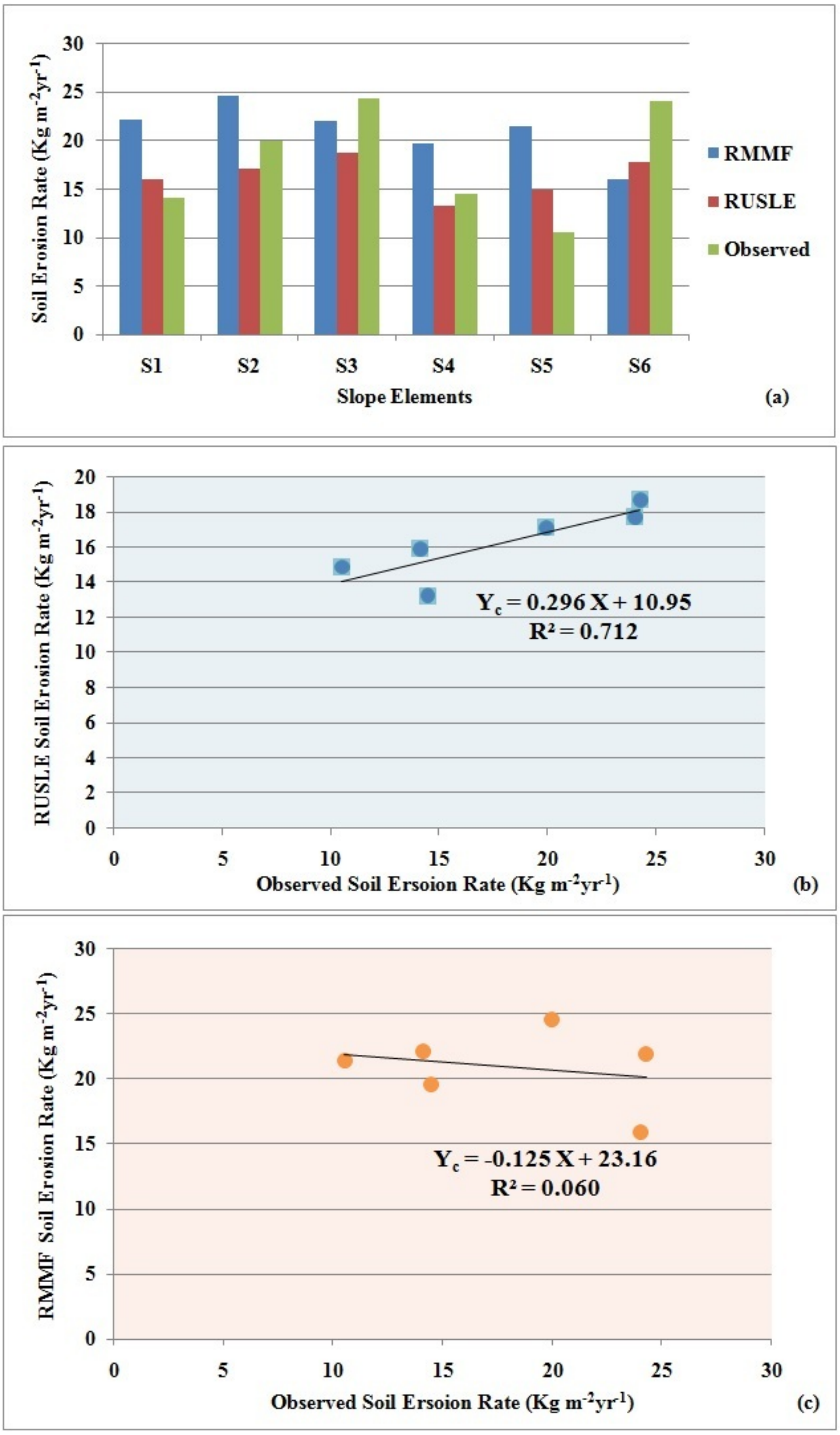


Figure 5.5 (a) comparison among the values of RUSLE, RMMF and observed, (b) linear regression between RUSLE and observed values, and (c) linear regression between RMMF and observed value

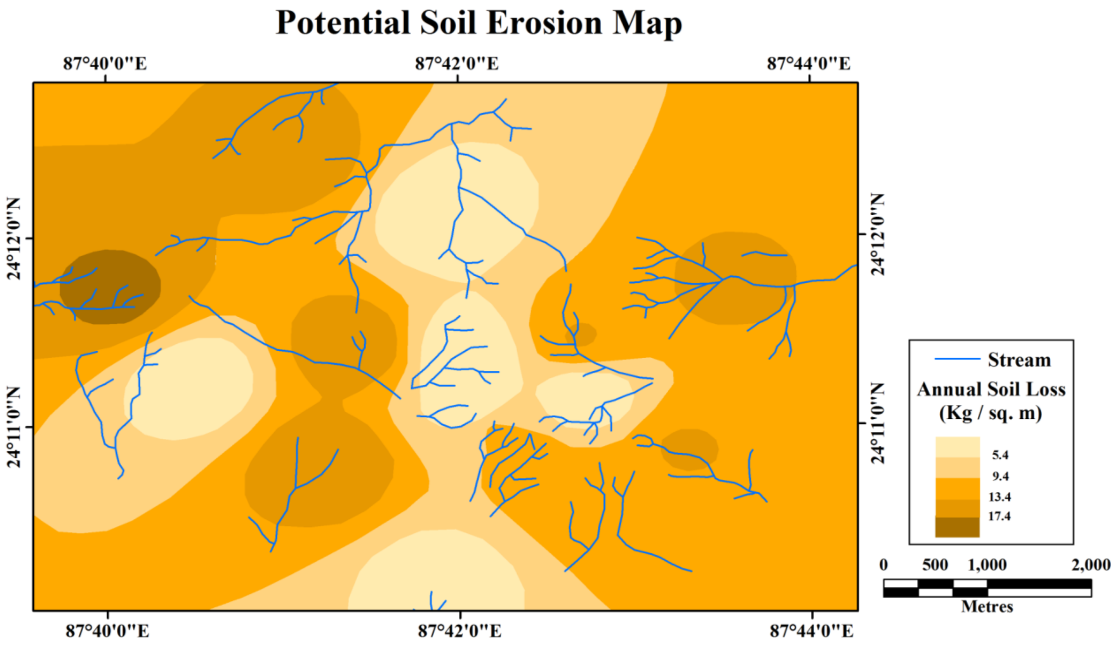


Figure 5.6 RUSLE erosion map depicting (rill and inter-rill erosion) spatial coverage of different zones of annual soil erosion rate (Kg $m^{-2}yr^{-1}$), considering seventeen catchments of gullies

The comparison reflects that when the observed values are high (in S3 and S6) the both values of RUSLE and RMMF are less. It is found that in RMMF model the high slope steepness in short slope length (in S2) predicts more rate of soil loss and in RUSLE high LS factor increases the values of erosion rate in all cases. For better compassion and understanding statistical inter-relationship, a linear regression ($Y_c = a + bX$) is fitted in between the predicted values and observed values in both RUSLE and RMMF models (figure 5.5 b and c). Surprisingly, two different pictures of regression are come to evaluate the model performance. In case of RUSLE model results the predicted values of annual soil loss rate are positively related with the observed values with increasing trend and high degree of coefficient of determination ($R^2 = 0.71$). It means that with increasing observed values (X) the predicted values (Y) of RUSLE are linearly increased in this field experiment ($Y_c = 0.2961\ X + 10.956$). Therefore, the predictions of RUSLE model are very much similar to the actual observed values and it fits the field data. But there is a negative relation between the predicted RMMF values and the observed values, with very low degree of coefficient of determination ($R^2 = 0.06$). The calculated equation of linear regression is $Y_c = -\ 0.125\ X + 23.16$. It reflects that there is an inverse relation between predicted and observed values in the RMMF model. Therefore, it is justified that instead of RMMF model it is better to select RUSLE model for this lateritic region to estimate potential annual rate of soil loss. Therefore, based on the seventeen sub-catchments of gullies (a part of study area) and RUSLE modelling (considering 118 gully head slope) an erosion map is developed here which depicts the potential annual rate of soil loss due to rill and inter-rill erosion in the lateritic region. The erosion map (figure 5.6) shows that the western and eastern part is very much susceptible to soil erosion (greater than 9.4 Kg $m^{-2}yr^{-1}$) due to high LS factor and bare soil cover, but the erosion rate (less than 9.4 Kg $m^{-2}yr^{-1}$) is much lower in the central part, because this part is covered with Acacia plantation, Sal forest, aerodrome pavement and relatively low LS factor. Also it is understood that the whole region is under very high erosion risk, because the erosion rate is beyond the acceptable T value limit (i.e. 0.5 Kg $m^{-2}yr^{-1}$). It is found that the eastern plateau region of West Bengal has very low T value of 5 t ha^{-1} (i.e. 0.5 kg m^{-2}) and the present study area of Birbhum belongs to T value of 10 t ha^{-1} (i.e. 1.0 kg m^{-2}).

Chapter 6.0

6.1 Gully Erosion Dynamics

Gully erosion is determined by many watershed and anthropogenic factors and some factors intensifies the rate of gully erosion and expansion (figure 6.1). There are extrinsic and intrinsic thresholds responsible for gully erosion. Extrinsic thresholds are those where an external variable changes progressively and eventually triggers an abrupt failure within the system, e.g. deforestation, road construction etc. Intrinsic thresholds are within the system and change independently of the external variables, e.g. piping. In the study area few anthropogenic factors (e.g. deforestation, overgrazing, mining, road and associated construction) and watershed factors (e.g. rainfall, overland flow, subsurface flow, soil profile and lithology) are very visible and dominant to induce rill and gully erosion.

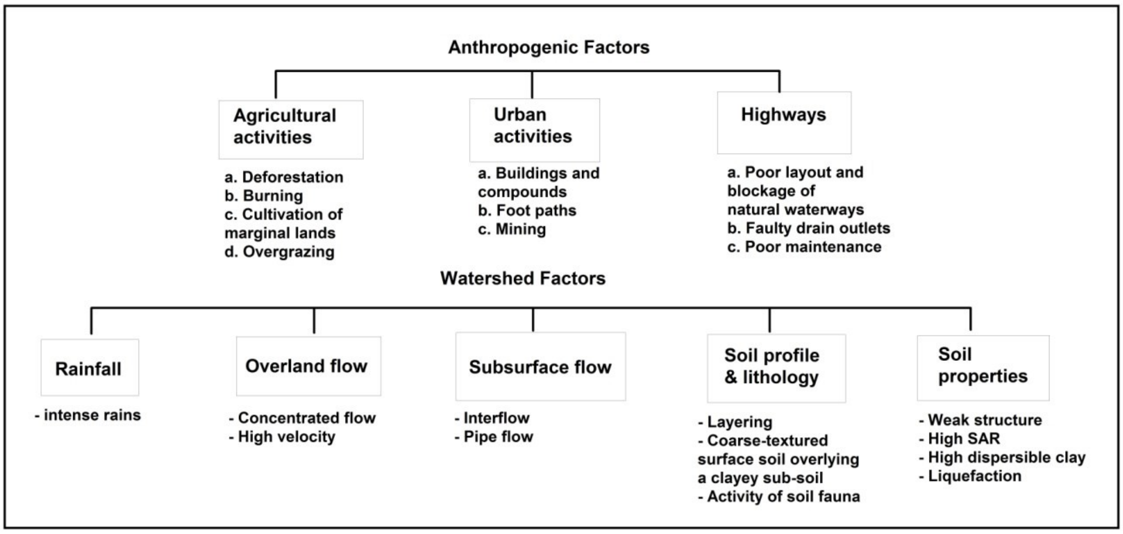


Figure 6.1 Possible anthropogenic and watershed factors of gully erosion (Lal, 1992)

6.2 Dominant Processes of Gully Erosion in Laterites

Kirkby and Bracken (2009) examines the condition of gully formation – a sharp step to initiate a headcut, a sufficiently low effective bedload fraction to evacuate eroded material, and the potential to maintain steep sidewalls, usually dominated by mass movement processes. Gully initiation and development, in contrast to rills, generally involve multiple episodes of channel erosion – (1) downward scour, (2) headward cutting, (3) rapid enlargement and (4) stabilization (Gao, 2013). The first three processes form gully headwalls and create gully channels, which may be further characterized by four stages. Gullies are established by the deepening of rills and slumping of side slopes through the shearing effect of concentrated overland flow, increase in pore-water pressure and decrease in soil strength along the seepage lines close to the streams and rivers, and slumping due to excessive formation of tunnel or pipe flow (Lal, 1992). Just as inter-rill areas deliver runoff and sediment to rill areas, overland flow areas deliver runoff and sediment to concentrated flow areas. An ephemeral gully begins at a finite point in a hollow on a converging landscape where overland flow merges into a single, definable channel (figure 6.2). The processes affecting gully morphology can be divided into overland flow, headcut migration, hillslope infilling, pipe initiation, pipe enlargement by flow, mass failures, sidewall erosion and the magnitude of storm events (Bocco, 1991; Lal, 1992; Bull and Kirkby, 1997; Morgan, 2005; Kirkby and Bracken, 2009; Gao, 2013; Toy et al., 2013).

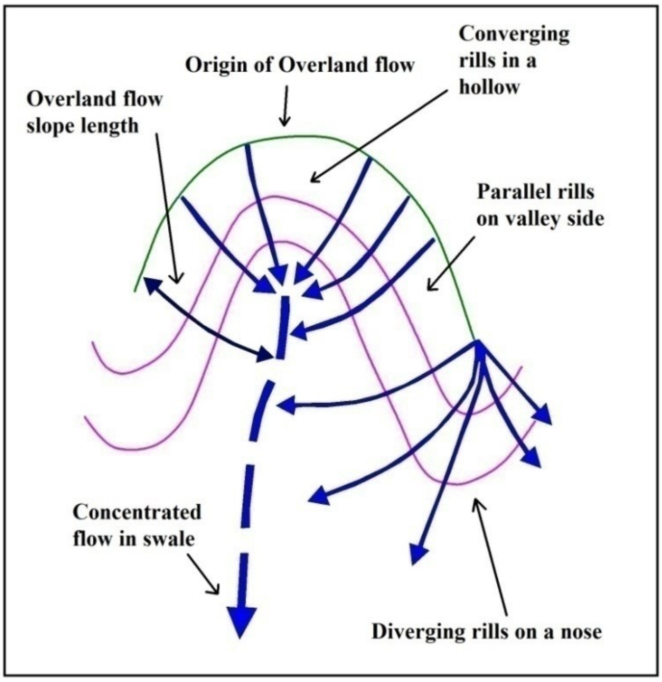


Figure 6.2 Development of ephemeral gully by overland flow (Toy et al., 2013)

6.2.1 Overland Flow –In first stage, surface water concentrates in small depressions caused by localized weakening of vegetation cover and then enlarges until depressions coalesce to form an initial channel. For erosion to occur the rate of rainfall must be sufficient to produce runoff, and the shear stress produced by the moving water must exceed the resistance of the soil surface. There are two styles of overland flow generation – (1) Hortonian overland flow and (2) Saturation overland flow. Hortonian overland flow extends to the catchment divide (occurs during rainfall at an intensity exceeding the infiltration capacity), whereas saturation overland flow is usually confined to base concavities and hollows (exfiltration of sub-surface flow after rainfall).

6.2.2 Headcut Migration – Overland flow may play a significant role in extending steep headcuts by creating a waterfall and plunge pool which undermines the back wall (Bull and Kirkby, 1997). Part of the water falling from the lip forms a backward eddy which directs flow strongly against the foot of the headwall. Sediment carried forwards out of the plunge pool creates a ridge at the downstream end of the plunge pool, defining its form. The gully head extends backward through various mechanisms by the following processes (Lal, 1992).

(1) Undercutting followed by slumping;

(2) Slumping caused by water moving through a vertical crack (figure 6.3a);

(3) Slumping and undercutting caused by tunnelling or pipes in the vicinity of an active gully;

(4) Formation of new headcuts by rapidly expanding waterfall; and

(5) The point where a runoff drops over a vertical height is an important cause of gully head initiation, and the water fall can start the linear incision developing throughflow or interflow aided by burrowing activity and, in the vicinity of a stream, reduced soil strength causing slumping (figure 6.3b).

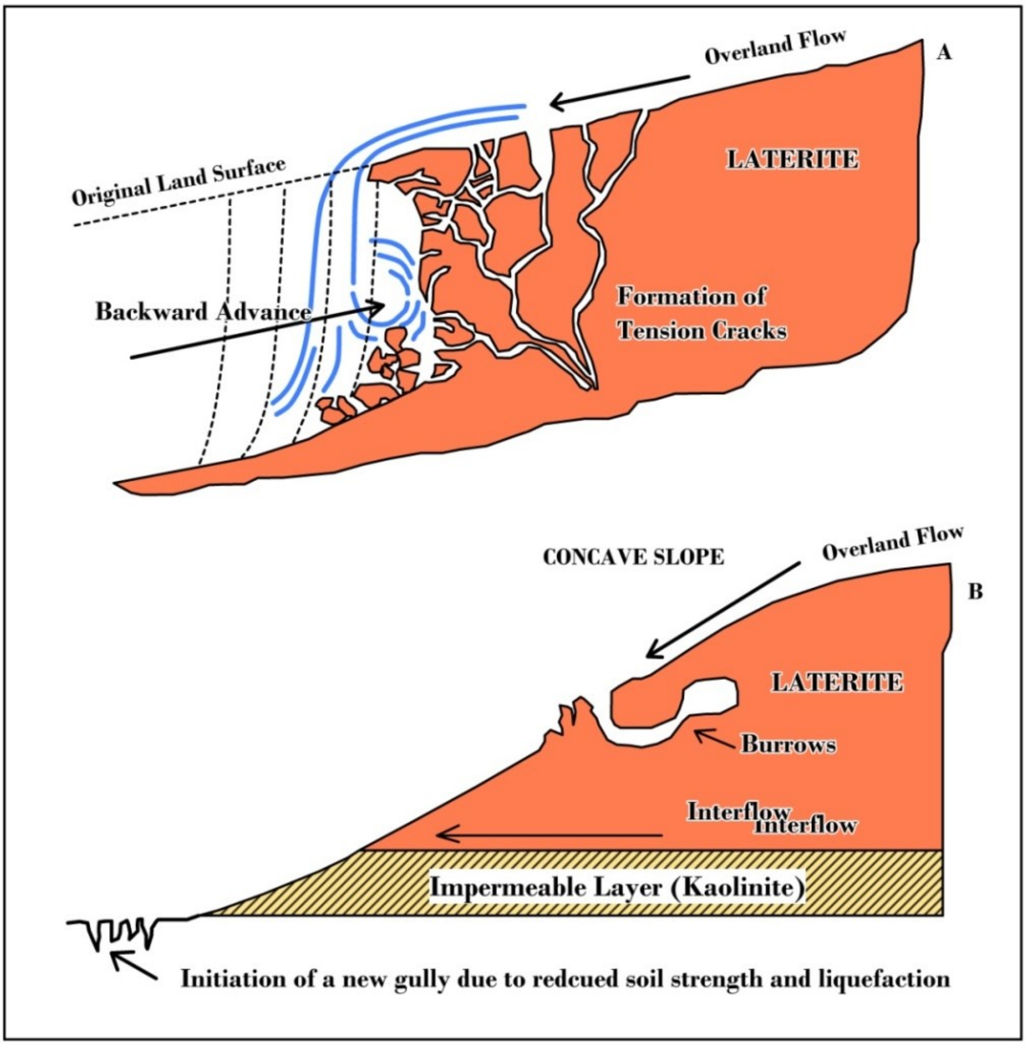


Figure 6.3 Schematic diagram showing (a) the processes of undercutting, slumping and gully head migration, and (b) gully initiation due to liquefaction and reduction in soil strength liquefaction (modified from Lal, 1992)

A soil with a coarse-textured highly permeable surface horizon with an abrupt transition to slowly permeable subsoil is normally prone to gully erosion (Bocco, 1991; Lal, 1992). Subsoil containing high clay content, high moisture retention at low suction and high shrinkage limit indicate that large volume changes could occur during wetting and drying cycles. Gully erosion could occur in soils with an almost zero shrinkage limit. In the profile of secondary laterite there distinct upper zones are identified – (1) dismantled loose laterite and crust, (2) mottled sandy clay zone and (3) kaolinite pallid zone (figure 6.4). At the gully head the formation of grooves and tension cracks in the laterite curst layer develop several tunnels or pipes as seepage lines into the mottled zone, but the due to presence of impermeable kaolinte clay layer the pipes are restricted only in the upper two zones (figure 4.21). During rainstorm the tunnel erosion expands the pipes and the overhanging mass of laterite is destabilized over the pallid zone. The roof of gully head has been collapsed and slumped in the gully floor, enhancing the upward migration of head. According to Poesen et al. (2002) gully head and gully wall collapse are a composite and cyclical process resulting from downslope creep, tension crack development, crack saturation by overland flow, head or wall collapse followed by debris erosion which facilities the next failure.

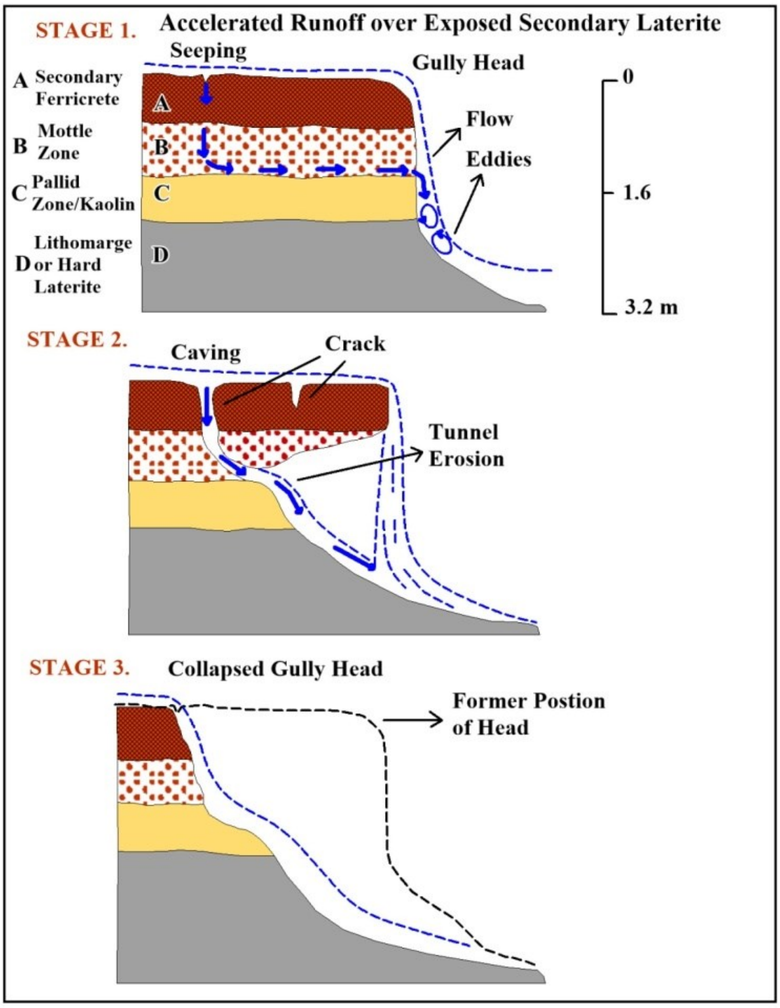


Figure 6.4 Cyclic and composite processes of gully head retreat in the study area

6.3 Stages of Gully Development

The concept of stages of (cyclic) gully development includes the life cycle of a gully from initiation phase to gully stabilization phase in a region. Understanding the stages of gully development many planners can take decision to manage the active deepening of gullies and growth of gullies. It is already know that gullies are established by the deepening of rills and slumping of side slopes through the shearing effect of concentrated overland flow, increase in pore-water pressure and decrease in soil strength along seepage lines close to the streams and rivers and slumping due to excessive formation of tunnel or pipeflow. Once gullies are established, they from permanent locations for concentrating the overland flow. Consequently, progressive deepening and widening of the gully continues until the gully has adjusted to a new set of equilibrium conditions. It is therefore important to understand the processes of gully erosion, stages of gully development and the sensitivity of areas to gullying, in order to recommend and adopt preventive measures that will minimize the risks of new gullies and slow or reverse the growth of existing systems (Kirkby and Bracken, 2009).

There are many theories and models of the genesis and development of gullies in different set of geo-climatic environment. The main theories and models were developed by Bryan (1940), Schumm (1968), Leopold et al. (1964), Young (1972), Sharma (1980 and 2011), and Singh and Dubey (2002). Many researchers postulated that when climate shifts from wetter to drier conditions vegetation cover declines, permitting increasing runoff and resulting in channel erosion. Climatic theories of gully genesis reveal that erosion of gully is initiated by a shift from drier to wetter conditions and seasonality of extreme rainfall events and the climate change with intensive grazing and deforestation can trigger gullies. Sharma (1980) provided a rejuvenation theory of ravine and gully in the Indian context. It will be wrong to say that over-grazing, deforestation, climate change or extreme climatic events have not any role in gully erosion, but there must be some common denominator in different areas of gully erosion – upliftment of Peninsular Shield. The erosion surface gained potential energy from neo-tectonism. Potential energy changes to kinetic energy when fluvial erosion initiates. Sharma (2011) proposed four stages of ravine development in the alluvial tract – (1) swallow hole stage, (2) tunneling stage, (3) collapsing stage and (4) recession stage.

Singh and Dubey (2002) also supported the rejuvenation theory of Sharma (1980) and applied a base level theory to gully development in the perspective of Belan River. They said that the ravines of Chambal River had been rejuvenated in the Early Quaternary Period and the present topography has been carved out by the accelerated linear erosion to form 10 to 15 m deep gullies. Based on local base level, the successive stages of gully development are (1) gully initiation, (2) gully headcut and rapid rate of gully enlargement, (3) gully healing, (4) gully stabilization and (5) gully rejuvenation due to fall in base level.

6.3.1 Stages of Gully Development in Study Area

The above said theories of gully development have some merits but the problem lies when it is applied to the lateritic *Rarh* Plain. Many of the mentioned stages are quite observed in the study area and the development of gully does not follow those cyclic stages at all in a single catchment. It reveals that the genesis of gullies and the life cycle can be explained on the basis of integration of those theories. Due to regional variability of laterite thickness, exposure of hard and soft laterites, groundwater, effective rainfall, land use and land cover, soil erodibility, bareness of soil, livestock grazing, local gradient and drainage area etc. there are some variability of rill and gully formation. Consecutive field investigations reveal seven stages of rill and gully development on the laterites of study area – (1) Initiation of sub-parallel rills, (2) Cross-grading and micro piracy, (3) Initiation of gullies, (4) Start of accelerated erosion, (5) Retardation of vertical erosion, (6) Lateral erosion and widening, and (7) Gully stabilization.

(1) Initiation of sub-parallel rills –

Loose soil particles of laterites detached by raindrops may be split into that which is transported in splash droplets. After prolong rainfall (due to thunderstorm or tropical depression) overland flow starts (after satisfying the depression storage) on the watershed line as sheet flow without channels over thin grass cover and bare lateritic soil. Wherever the length of overland flow is greater than the limiting critical distance, a threshold (due to critical slope and drainage area) is reached beyond which significant flow detachment begins to take place. Once this occurs, the flow begins to erode through definable sub-parallel rills along the hillslope direction (figure 6.5). Here flow shear stress overcomes the soil resistance at that distance.

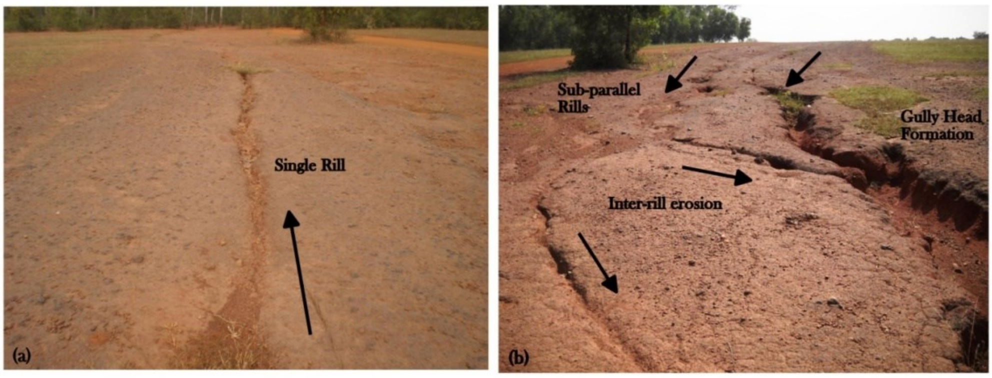


Figure 6.5 Rill erosion on bare laterites – (a) Initiation of a rill at a critical distance from divide and (b) merging of sub-parallel rills to form a gully

(2) Cross-grading and micro piracy –

In the intense rainstorms the tendency of water flow along the resultant slope direction and is a direct consequence of the overtopping and breaking down of the intermediate ridges between rills by overland flow. The divide between two or more rills may be broken down at its weakest point by (a) caving in the divide, (b) erosion by the deeper or lower rill, diverting the higher rill, and (c) overtopping the divide at the low points by the higher rill again diverting it into the lower rill. Development of the lateral component of slope towards the master rill across the main slope along the long profile of the rills is called cross-grading (figure 6.6). The process by which water from a rill is diverted to another rill by either overtopping or erosion of the divide between adjacent rills is called micro piracy. In these processes a master rill is developed on the hillslope. As the inter-rill divides are obliterated, the lateral component of flow towards the master rill will increase.

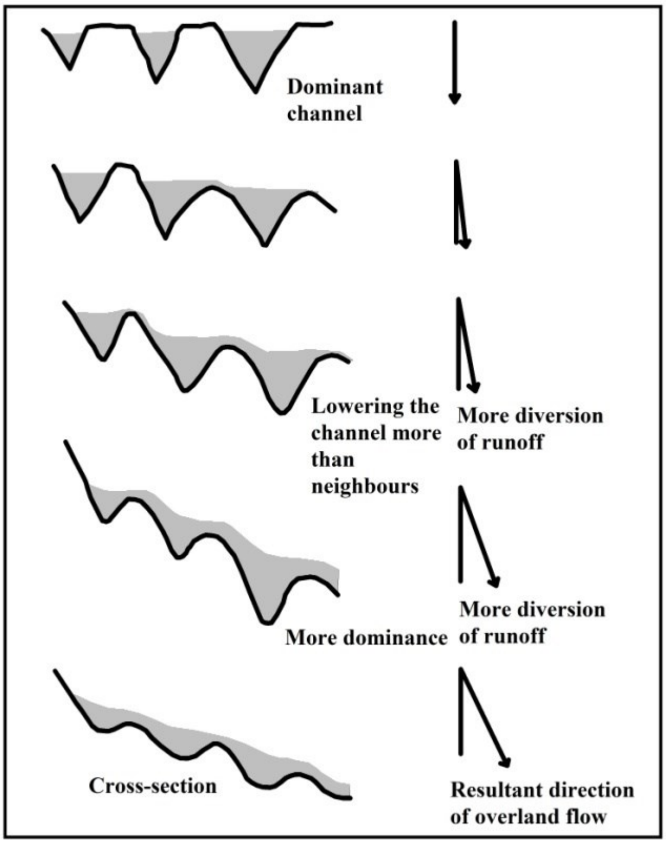


Figure 6.6 Cross-grading of channels and micro piracy (modified from Horton, 1945)

(3) Initiation of gullies –

A gully is established downslope by the further deep incision of rills and slumping of side slope through the shearing effect of concentrated overland flow, increase in pore-water pressure, decrease in soil strength along the seepage lines and formation of tunnel or pipe flow (figure 6.7). Here small depression or groves on the surface or breaks in vegetation cover help to initiate gully headcut. The crust formation at surface favours more runoff and less infiltration. At certain slope the excessive runoff concentration at the weakest points trigger gully. In many parts of study area many rills are coalescence at a swale of landscape to form next higher order gully.

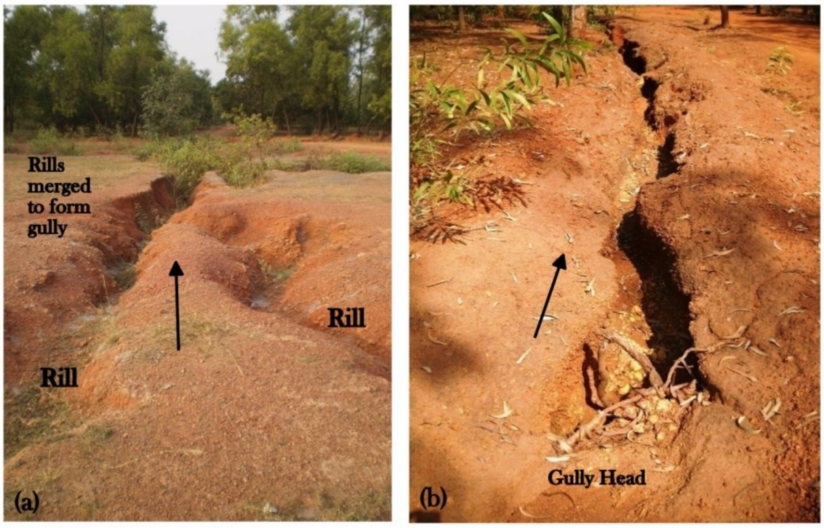


Figure 6.7 (a) Initiation of a gully due to coalescence of rills and (b) start of vertical erosion from gully head

(4) Start of accelerated erosion –

Once gullies are established, these form permanent channels and locations where the concentration of overland flow is converged and then channelized. Upstream migration of secondary knick points, slumping soil mass in headward section, slope failure due to collapse of pipe flow and flute, further scouring of gully floor by transporting sediment are the principal processes of accelerated gully erosion and headward migration. It forms V-shaped gullies at the initial phase with bare soil cover at head and sidewall (figure 6.8). A natural and vertical drop in channel-bed elevation is a headcut where the dissipation of kinetic flow energy of the flowing water at the drop causes excessive erosion and forms plunge pools with headcut retreat. The eroding action of the waterfall and its splash (with eddies) deepens a round or parabolic plunge pool into the subsoil.

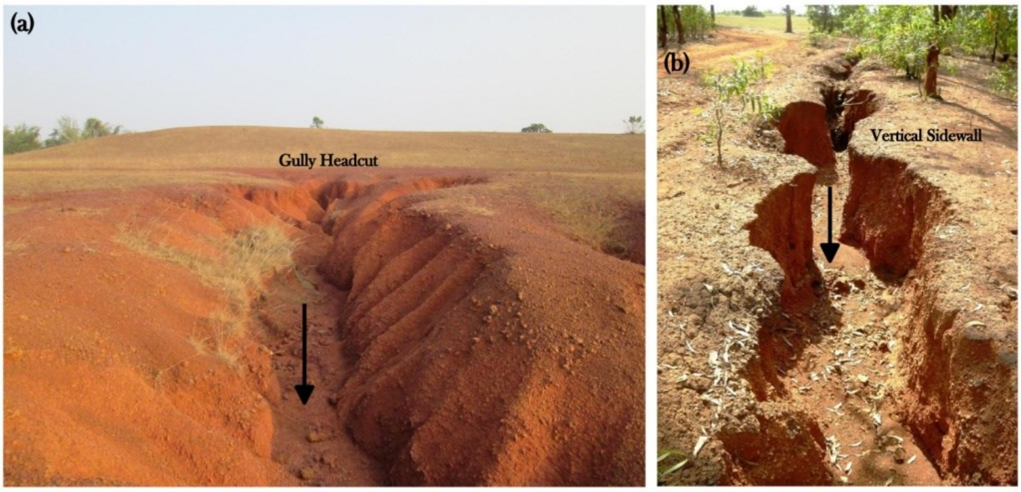


Figure 6.8 (a) Deeply incised V-shaped gully showing vertical erosion and (b) steep sidewall of gully due to vertical incision

(5) Retardation of vertical erosion –

Vertical erosion continues until stopped by a base that can be of different type:

- Any plain where the velocity of the stream does not permit further erosion
- The water level of a lake or a river
- A solid sub-layer of soil bedrock

Eventually a state of balance is reached between erosion and deposition even if the gully floor is not quite stable. Downstream of gully head the runoff water loses its energy and starts to deposit the sediments. Due to exposure of hard laterites the runoff water of channel unable to erode further, but the sidewall is scoured due to undermining of runoff water. As a result, the gully bottom becomes a wider floor and gets filled with sediments. It forms a U-shaped valley which represents a stage of maturity in the gully development (figure 6.9).

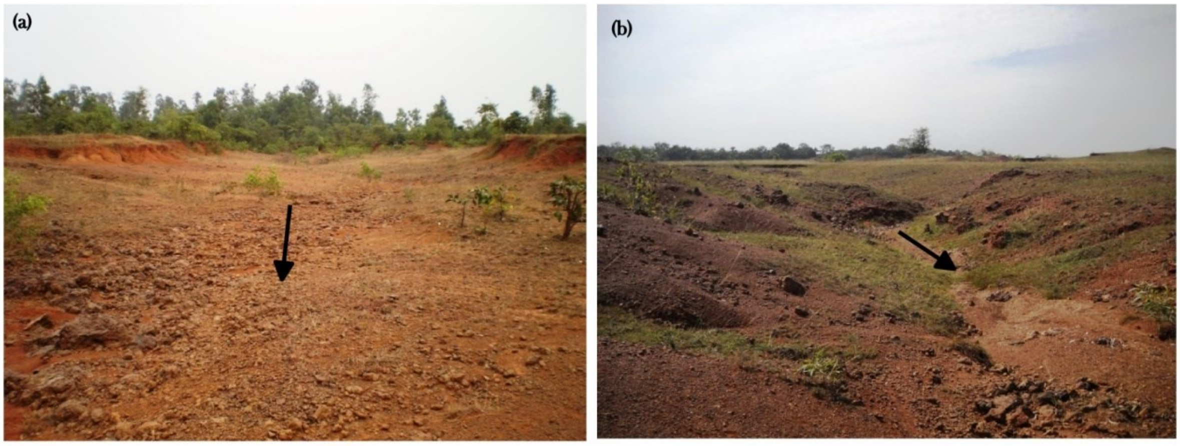


Figure 6.9 (a) Retardation of vertical erosion and deposition at gully floor and (b) widening of V-shaped gully

(6) Lateral erosion and widening –

With the passage of time and distance the flow energy is redirected on the lateral erosion having sinuous channel course and point bar deposition in a wide valley. The gully heads and sidewall are subject to three forces:

- The weight of the saturated soil
- The weight of water added by infiltration or a rise in water table
- Seepage forces of percolating water

Gullies with homogenous, cohesive banks may expand by progressive, continuous failure through creep over long time periods or by catastrophic shear failure of the bank. The rill erosion and initiation of bank gullies widen the valley and it is more prominent in the outer bends of gullies (figure 6.10). When large volume of coarse sands, gravels and ferruginous materials are transported by the gullies, the bars of coarse materials can cause meandering of main active course due to flow resistance. The deep incision of base of sidewalls makes the gully side more unstable and causes mass movement during heavy rains. The valley of gullies can also be widened through branches by tributary flows, collapsed tunnels and slumping of sidewalls. In this ways many newly developed networks of rills and gullies are extended at side slope and upslope. Eventually, these processes dissect the smooth rolling lateritic uplands into badlands (figure 6.11).

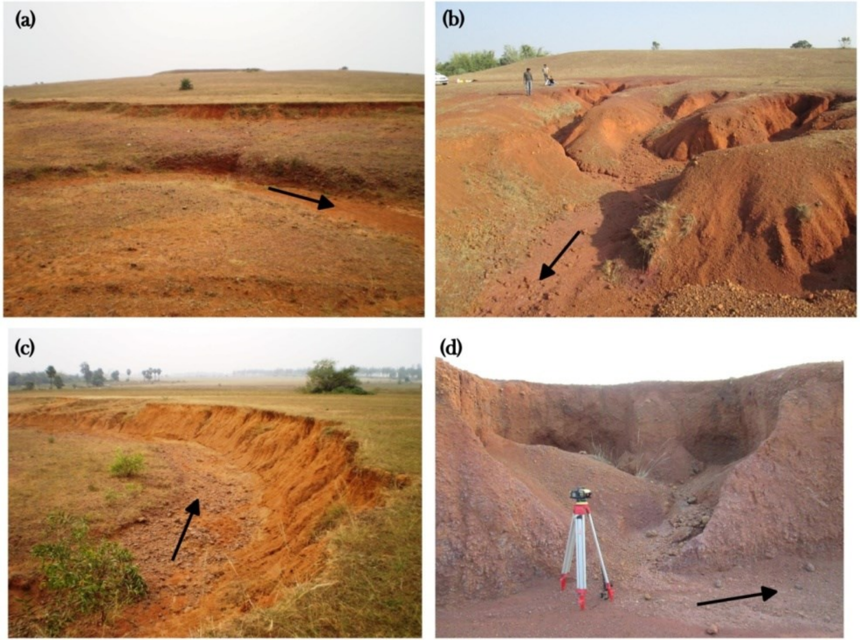


Figure 6.10 (a) Gully widening due to sinuous course of active channel, (b) development of bank gullies, (c) rill erosion and undercutting of channel at gully sidewall, and (d) collapse of gully bank due to mass failure

Figure 6.11 (a) Deeply dissected laterites by gullies and (b) development of badlands on laterites in gully catchment 3

(7) Gully Stabilisation –

The stage of healing and readjustment, which follows the period of most active cutting, is a time of delicate balance in the regimen of the gully. If there are no unusually heavy rains to cause excessive washing, no drought years to weaken or hill the vegetation as it tries to get a foothold, and no human or animal interference in the area, this stage should progress smoothly, and the gully should approach rapidly a stabilized condition. Gully stabilisation means that gullies are not active in vertical or sidewall erosion (without change in gully morphology further) and the vegetation is grown within the valley to stop headward migration and mass failure also (figure 6.12). As down-cutting is retarded and headward retreat is stopped, the walls can become graded to a gentle slope suitable for the growth of vegetation. As the plant cover increases and the root mat become denser, the deposition of runoff transported materials is increased. A stabilized gully should be able to resist normal flow of water in the rainy seasons, but there is always the danger that excessive concentration of overland flow may cause renewed cutting or rejuvenation in the old channel.

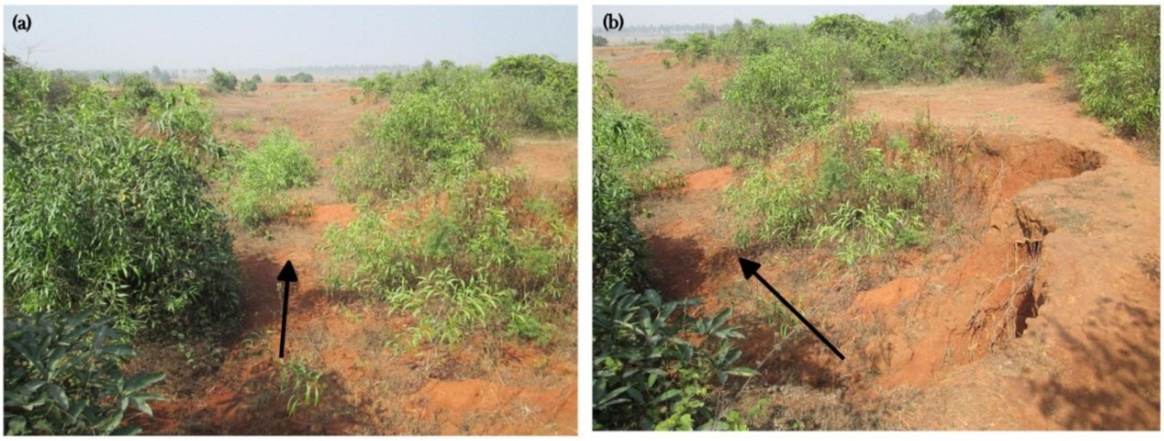


Figure 6.12 Stabilization of (a) gully floor and (b) gully headcut due to vegetation growth

Chapter 7.0

7.1 Erosion Management

Based on the field study it is clear that the exposures of secondary laterites are very much prone to erosion and the major problem is linear erosion through dense network of rills and gullies. The sediment delivery through rills and gullies occur, if proper erosion and sediment control practices are not installed and maintained. In case no parts of study area are under any erosion control measures except few plantation patches. In broad way, soil conservation is the selection of erosion and sediment control practices that provide the desired control while allowing the desired land use and land cover.

7.2 Principles and Strategies

The principles of soil erosion control provide the ultimate basis for understanding erosion and sediment control practices, strategies and steps for management. Before applying any engineering structures and other conservation measures it is utmost necessary to follow the principles firstly in the erosion prone land. These principles are summarized as follows (Morgan, 2005; Toy et al., 2013, Osman, 2014):

1. **Maintain Vegetative Cover** – Wide vegetative cover over barren land reduces water erosion by providing canopy, plant litter for ground cover and incorporation into the soil and root network.

2. **Maintain Ground Cover** – Keeping the ground cover by leaving last year’s crop residue on the surface, growing plants that produce a high level of litter, is highly effective for controlling erosion.

3. **Protection against Erosivity** – It is better to maintain these covers during the monsoon periods and rainstorm events when rainfall erosivity is highest, if cover cannot be maintained at all times during the year.

4. **Incorporate Biomass into the Soil** – Adding to and incorporating organic material such as manure, sewage sludge (biosloids), or paper mill waste in the erodible land can reduce erosion significantly due to increase in soil cohesion.

(5) **Checking Soil Disturbance** – Soil disturbance should be minimized, but if the soil is disturbed mechanical process, it is better to leave the soil surface rough, with large clods.

(6) **Add Supporting Practices** – To minimize the effect of runoff erosivity the ridges (any barriers) can be developed orientation of which will be perpendicular to the direction of runoff. If infiltration is increased through bio-engineering measures in the upper catchment, then the linear erosion downslope can be checked easily.

(7) **Slope Modification –** Rill erosion should be prevented by avoiding long, steep slopes and water convergence. Where ever possible, modification is necessary especially to avoid convex segments at the end of hillslope profiles. To induce deposition it is preferable to develop long concave slope with little steepness at the end.

The strategies for soil conservation and erosion management must be based on: covering the soil to protect it from raindrop impact; increasing infiltration capacity of the soil to reduce runoff; improving the aggregate stability of the soil; and increasing surface roughness to decrease the velocity of runoff (Morgan, 2005). There are three main types of conservation techniques – (1) vegetative and agronomic measures, (2) soil management, and (3) mechanical methods. Agronomic and vegetative measures combined with good soil treatment can influence both the detachment and transport phases of erosion, whereas mechanical methods are effective in controlling the transport phase but do little to prevent soil detachment (Morgan, 2005). Therefore, agronomic and vegetative measures are more easily fitted into existing land uses and more relevant to maintain the biodiversity of plant communities, whereas the mechanical works are costly to install and maintain (table 7.1).

Table 7.1 Effect of various soil conservation practices on the detachment and transport phases of water erosion (Morgan, 2005)

Practice		**Control Cover**			
		Rainsplash		**Runoff**	
		D	**T**	**D**	**T**
Agronomic & Vegetative Measures	Covering soil surface	*	*	*	*
	Increasing surface roughness	–	–	*	*
	Increasing surface depression storage	+	+	*	*
	Increasing infiltration	–	–	+	*
	Soil management	+	+	–	–
	Fertilizers, manures	+	+	+	*
	Increasing surface roughness (tillage)	–	–	*	*
	Subsoiling, drainage	–	–	+	*

Mechanical Measures	Contouring, ridging	–	+	+	*
	Terraces	–	+	+	*
	Shelterbelts	–	–	–	–
	Waterways	–	–	–	*

Note: D – detachment, T – Transport, – no control, + moderate control, * strong control

7.3 Control of Flow Erosion and Sediment Transport

Almost all areas of inter-rill and rill erosion re concerns include concentrated-flow areas that collect overland flow in a defined channel network and deliver it to a gully and then a watershed outlet. So, this type of linear erosion should be controlled in a spatial scale of watershed or basin or catchment. In a gully catchment the focus of erosion control should centred on three aspects – (1) reduction of discharge rate, (2) reduction of grade, and (3) control of headcut erosion.

Sediment loss from a site can be controlled in one of two ways. The first way is to control erosion, and the second way is to reduce transport capacity at the boundary of the site, which will lead to deposition of the sediment load (Toy et al., 2013). For increasing rate of sediment deposition, it is necessary to check channel erosion (including bank erosion) and slope erosion (overland flow erosion) in a catchment scale.

7.3.1 Sediment Control for Overland Flow

The field experiment suggests that the barrier type of sediment control is very effective for inter-rill erosion (trapping 90 percent of sediment) and it is done by planting stiff-grass hedges planted in narrow rows about 15 to 18 inches wide (Gray and Sotir, 1996). The stiff grass stands up to the flow to maintain its effectiveness and also the stiff grass can recover after being inundated by deposition.

Gravel bags and hay or straw bales are sometimes used as flow barriers. Gravel bags work better than straw bales, and if placed sufficiently high and have a wide base, they can be more stable during high rainstorm. In the study area the upper catchment should be protected using gravels bags (placing these bags as upper convex shape along the slope) to decrease the effect of flow convergence (figure 7.1).

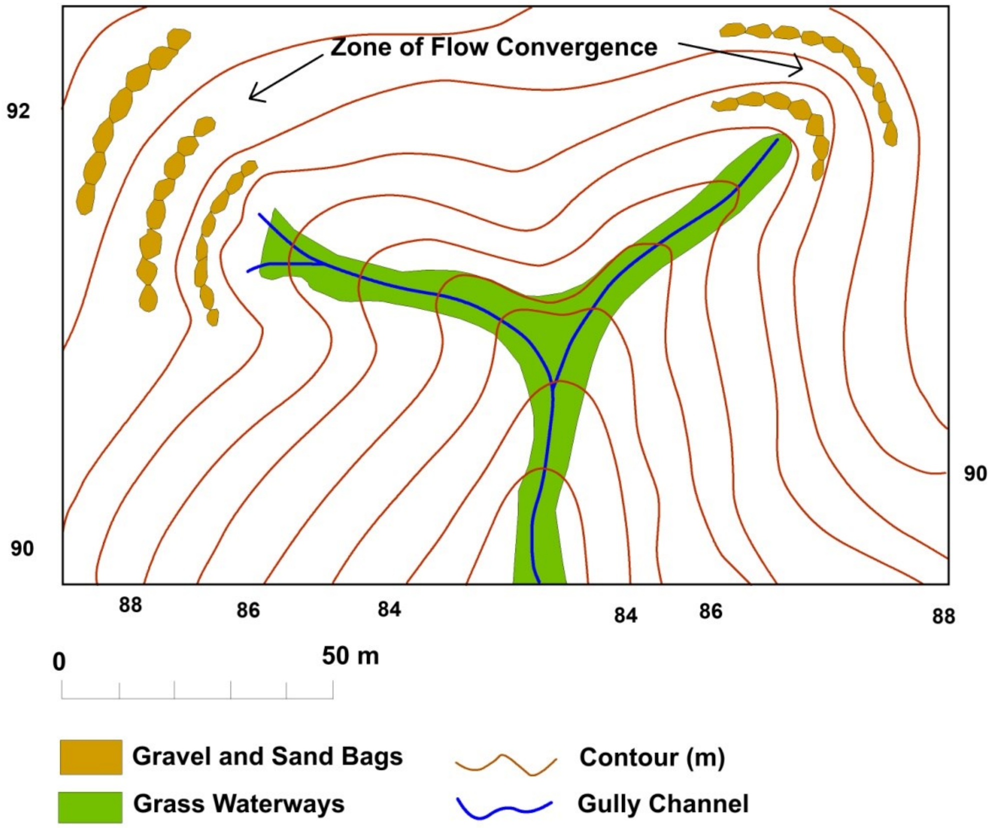


Figure 7.1 A tentative plan to restore gullied land using gravel and sand bags in the sites of flow convergence and development of grass waterways along the gully channel

7.3.2 Sediment Control in Concentrated-Flow Areas

The most effective sediment control device is the sediment control in the drainage basin. When these basins are properly installed, they can trap up to 95 percent of the sediment entering them (figure 7.2). Also, sediment control basins can be put in series, but the second basin is much less effective in trapping sediment, than the first basin because the first removes most of the coarse sediment and the fine sediment leaving the first basin is not easily deposited in the second basin. The basin with fill sediment is good place for the growth of new plants which further can enhance the trap efficiency and stabilization of gully. Only thing is that the contractor should remove the filled sediments and spread the sediments in a suitable place.

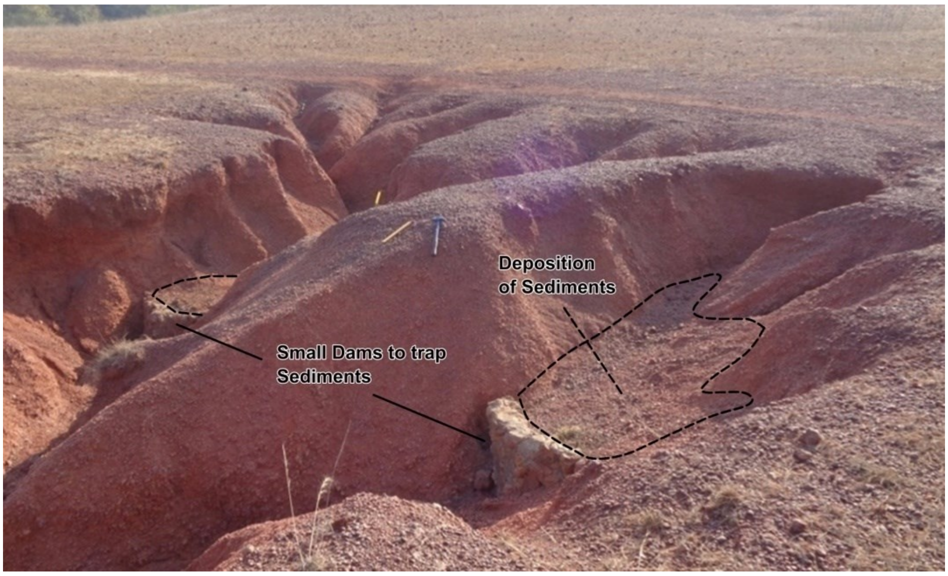


Figure 7.2 Sediment control basin trapping sediment near gully headcut at Maluti, Shikaripara

Small sized and convex-shaped check dams (across the gully) just below the gully headcut is an efficient tool to check the flow erosivity and to increase sedimentation during the high rainstorm events. Small dams, usually 0.4 – 2.0 m in height, made from locally available materials such as laterite clay, laterite boulders, basalt boulders, dry wooden parts and brush wood etc. are built across the gullies to trap sediment and thereby reduce channel depth and slope (figure 7.3 and 7.4). The dams must be provided with a spillway to deal with overtopping during high flow and installed at spacing appropriate to the slope of the channel. Dam spacing should be based on the 'head-to-toe' rule, whereby the top of a downstream dam is level with the lowest elevation of the upstream dam (Morgan, 2005).

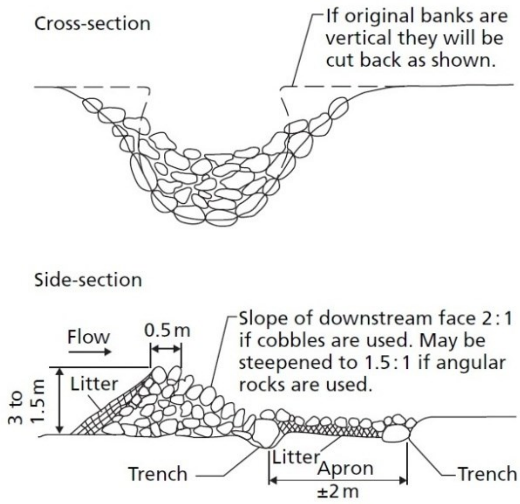


Figure 7.3 A model depicting construction of loose rock dams across gully channel (Morgan, 2005)

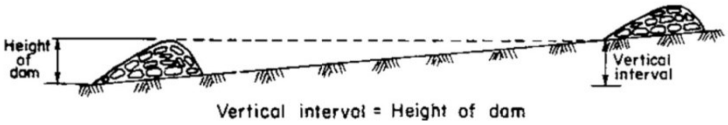


Figure 7.4 Spacing of small dams along the gully floor (Morgan, 2005)

The spacing of the dams can be determined from the following formula (Morgan, 2005):

$$\text{Spacing} = H\,E / K \tan S \cos S$$

where, HE is the dam height, S is the slope angle of the gully floor and K is a constant equal to 0.3 for tan S <0.2 and 0.5 for tan > 0.2. For example, if the slope is 1°00' slope and HE of 1 m, the spacing between two dams will be 190 m in the site.

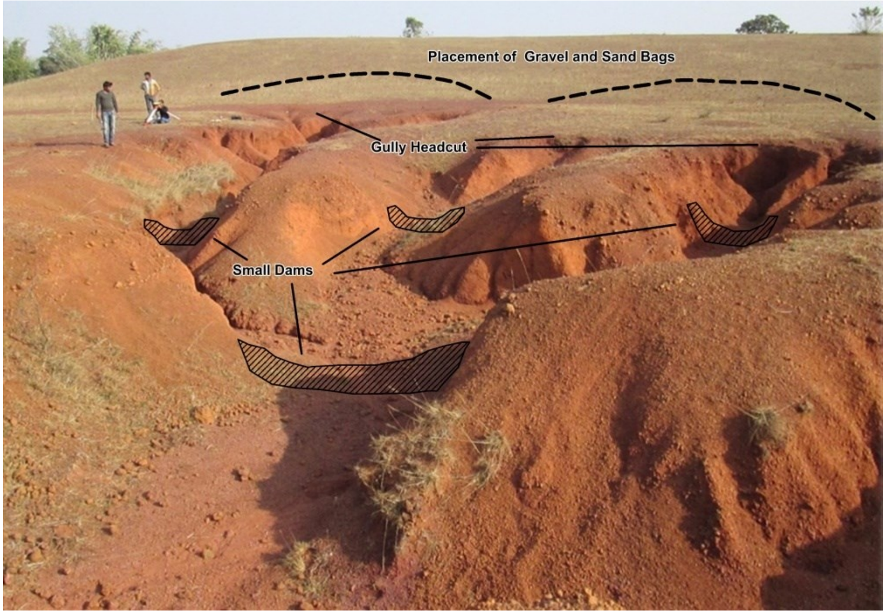


Figure 7.5 A plan to check gully erosion through construction of small check dams and placement of gravel bags in the upper catchment at Maluti, Shikaripara

7.4 Role of Vegetation and Vegetative Measures

Vegetation plays a vital role in the process of erosion control on the gullied areas and re-vegetation of bare surface can control channel and splash erosion to maximum level (figure 7.6). The most challenging task is to grow new plants in the imfertile and heavily eroded surface of laterites where progressive expansion of rills and gullies, surface crusting, water crisis in lean period (November to April) and bareness are the key issues. Before applying any vegetative measures we have to understand the root morphology of plants, criteria of re-vegetation, plant selection and design of plantation.

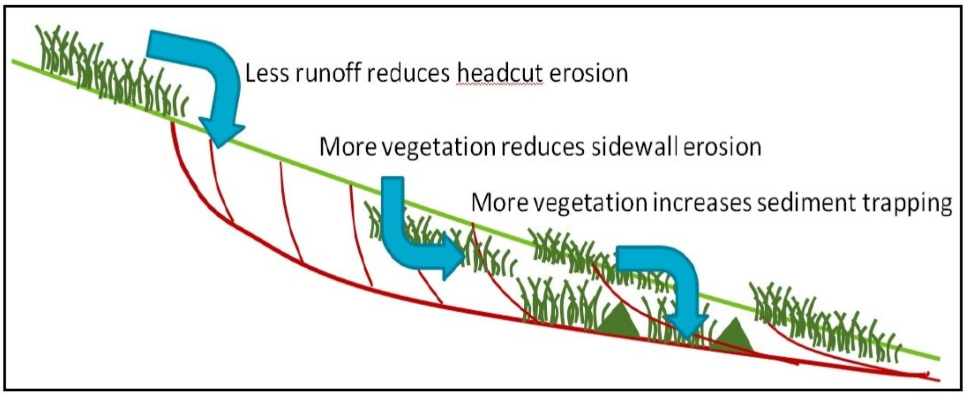


Figure 7.6 Effect of vegetation to reduce gully erosion

Plants exhibit many different forms and structures, but in general the elements that are likely to be useful in eco-technological solutions to slope stability are:

(a) Roots, to provide anchorage and absorb water and nutrients from the soil,

(b) Stems, to support the above-ground parts and capture eroding soil, and

(c) Leaves, to intercept precipitation and irritate evapotranspiration leading to decrease soil moisture levels.

The role of vegetation in reinforcing and anchoring the soil contributes to its stability but is dependent on factors such as root system morphology, root strength, distribution and root-soil interaction (Stokes et al., 2008). Trees have been classified as having three main root system types: plate, heart and tap (figure 7.7). Plate root systems have large lateral roots and vertical sinker roots, heart systems possess many horizontal, oblique and vertical toots, and tap systems possess one large central root and smaller having a mixture of root system types (Gray and Sotir, 1996; Stokes et al., 2008). Trees possessing heart and tap root systems have been classified as being the most resistant to uprooting and plate systems the least resistant.

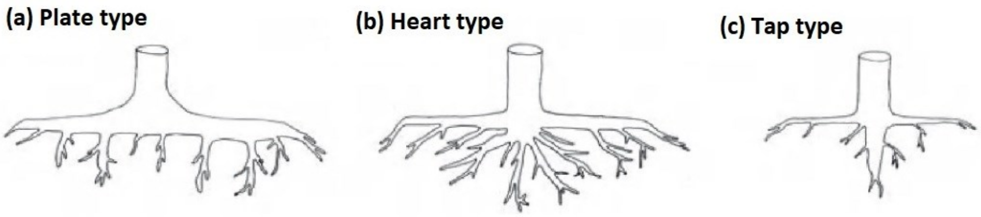


Figure 7.7 Different types of root system architecture (a) plate system with large lateral roots and some smaller vertical roots, (b) heart system with many horizontal and vertical roots, and (c) tap root system with one major central root and smaller horizontal and vertical roots (modified from Gray and Sotir, 1996)

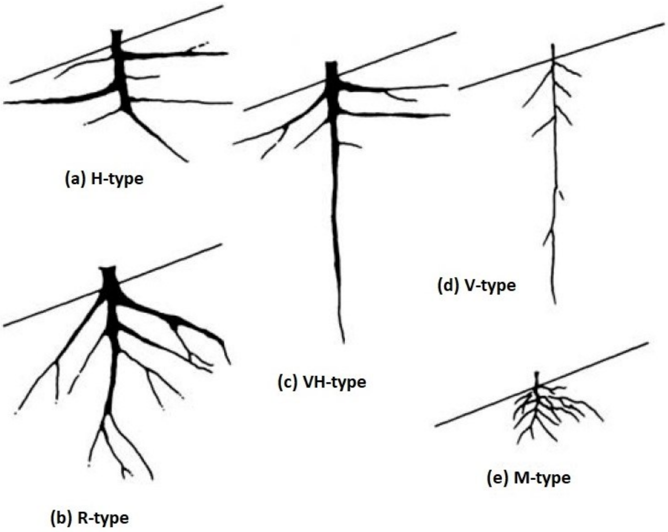


Figure 7.8 Pattern of root growth in trees (a) H-type: maximum root development occurs at moderate depth (80 percent of root matrix in the top 60 cm), (b) R-type: maximum root development is deep (20 percent of root matrix in the top 60 cm), (c) VH-type: maximum root development is moderate (80 percent of root matrix in the top 60 cm), (d) V-type: maximum root development is moderate to deep, and (e) M-type: maximum root development is deep (80 percent of root matrix in the top 60 cm) (modified from Morgan and Rickson, 1995).

Stokes et al. (2008) attempted to classify root systems according to their suitability for stabilizing soil on slopes or their erosion-reducing potential. Types – H and VH (figure 7.8) include root systems with horizontal lateral roots and deep tap roots, respectively. M-type root systems have profusely branching roots in the top soil, but with a narrow lateral extent. *Rhizomatous* species can be envisaged e.g. bamboo as well as clumping grasses and bushy shrubs and they very dense root systems. With regard to water erosion, it is important to determine the types of erosion encountered. For splash and inter-rill erosion, above ground vegetation cover is the most important vegetation parameter and erosion can be reduced by planting e.g. *Rosmarinus* species which provides good ground cover (Stokes et al., 2008). The grasses examined have a high density of fine roots in the top o to 0.2 m soil. It is widely accepted that grasses have the highest erosion-reducing potential in situations where overland flow is severe. In general, dense and lateral spreading root systems would be most useful in fixing soil against rill and gully erosion. The root systems composed of deep tap roots and sinker roots crossing the slip surface of gully wall would be ideal (Norris et al., 2008). Vetiver grass is often used for replanting on shallow slope failures, due to its deep and fibrous root system, which can cross the slip surface. Tap or heart root system have sufficient depth to interact with slip surface at gully head. So, it can reduce the bank failure or other mass movements.

Figure 7.9 (a) Reduction of valley incision and stabilization of gully headcut at Baramasia, Rampurhat, and (b) Re-vegetation induces stabilization of gully floor and enhances sediment deposition at Maluti, Shikaripara

In the barren land or rangeland, a quick establishment of vegetation cover (perennial species) with a fast growth rate, good canopy cover and the ability to improve soil properties should be used. The vegetation with good undergrowth cover of bushes is very much preferred in the upper catchment of gullies, because it protect soils from rain splash and also overflow erosion (figure 7.8). In the problematic rill and gully erosion areas (having chances of intensive linear erosion) vegetation can be planted on spots where the concentrated flow can be expected. Grasses can be used (*Lygeum spartum, Brachypodium restusum* and *Stipa tenacissima*) in combination with deeper rooted trees or shrubs (*Acacia auriculiformis*, *Ziziphus mauritiana*, *Atriplex halimus* and *Salsola genistoides*) along gully walls (Coppin and Stiles, 1995).

To decrease the amount of overland flow and flow convergence no part of upper gully catchment (above gully headcut) should be left barren. The barren lateritic land signifies active erosion phases, so this land can be protected through grass plantation using flow barriers. Alongside, bamboo plant should be planted on the convex part of catchment. Grass stems reduce runoff velocity and grass roots increase topsoil resistance to concentrated flow erosion and can prevent movement of soil blocks by increasing soil cohesion (Norris et al., 2008). On steep slopes, shrubs e.g. *Salsola genistoides* would be useful. *Brachypodium retusum* and reed species e.g. *Juncus acutus* could be planted to vegetate drainage paths whereas for stabilizing gully floors a combination of Vetiver grasses and deep rooted tress e.g. Indian Jujube (*Ziziphus mauritiana*) should be considered. It is found in the field that if vegetation gets chance to grown in the gully floor, the whole gully system is stabilized upstream (figure 7.9).

Chapter 8.0

8.1 Major Findings

In the lateritic *Rarh* Plain the development of gully channels on-site causes a significant decrease in soil quality through very high soil losses and through the enhanced drainage and dissection of the inter-gully areas which may lead to limited soil water availability and significant crop yield reductions in the wet-dry monsoon environment. In addition, the erosion channels lower the free growth of biotic species and enhance the land degradation and desertification also. The active network of rills and gullies engulf the land resource through expansion of badlands and it increases an extra cost for land planners and farmers.

Field-based evidence in the study area suggests that soil losses from sheet and rill erosion as measured on basin scale are much less than gully erosion. Typically, gully channels occupy less than 5 percent of a catchment area, but their contribution to total catchment sediment yield is well above this percentage, i.e. from 10 percent to 90 percent depending upon environmental controls (high intensity rainfall during thunderstorms, wet-dry seasons, soil resistance, topographic thresholds, land use etc.) as well as on the spatial and temporal scales considered. In the study area most of gullies are classic and permanent type which is actively lowering the laterite surface before human interference. Moreover, once gullies develop, the eroded channels increase the connectivity for runoff and sediment within a catchment significantly, leading to a rapid transfer of eroded soil from the uplands to lowlands, hence contributing significantly to floods and to pond and reservoir siltation. It is observed that the infertile ferruginous materials are deposited in the arable land and it affects the productivity and surface crusting problem.

This research work on soil erosion has mainly tried to unearth the spoken and unspoken voices of gully erosion, estimation and conservation on the surface of laterites. The chapters of this project work explore various pedo-geomorphic aspects of gully erosion in details and now to conclude it is utmost necessity to summarize the major outcomes and lessons from this work.

- The evolution of secondary laterites is associated with the neo-tectonic uplift (due to presence of Chotanagpur Foothill Fault, Medinipur Farraka Fault or Pingla Fault and Damodar Fault), resultant erosion of high level primary laterites, deposition as alluvial fan to fan-deltaic formation and re-cementation of ferruginous materials under the favourable tropical wet-dry climatic conditions.

- Due to inherent character of laterites the gully morphology varies significantly and many forms or types of gullies are developed during the different stages of gully evolution. The successive profiles of gully channels reflect that initially V-shape gullies are formed and at a distance these two or more gullies are joined to form a single incised channel with wide valley floor, having U-shape form.
- In the present investigation one fundamental unit of study is hillslope to estimate energy distribution along the slope. The erosion begins from that point and it enhances the upward migration of gully headcut. The hillslope profile has two crucial intrinsic factors – (1) elevation difference or vertical fall (influencing potential energy) and (2) gradient or steepness (influencing kinetic energy).
- In this investigation geomorphic threshold model is taken as a standardised system for evaluating site susceptibility for gully erosion, linking the susceptibility to local topography, soil types and management practices. The exponential relation between critical valley slope and drainage basin area ($S = a A^{-b}$, where a = coefficient and b = exponent of relative area) is used as a predictive threshold model to locate those areas of instability within alluvial valleys where gullies will form. The negative value of b (i.e. -0.2517) with a general consideration $b>0.2$ is considered to identify the dominancy of overland flow erosion over sub-surface processes in the study area.
- The estimated M – D envelope distinguishes mass movement dominated gullies from hydraulic erosion dominated gullies. In this study area 52.51 percent of gullies are affected by overland flow erosion while 27.96 percent belongs to landslide erosion. Only 15.25 percent of gullies are affected by tunnel erosion or seepage erosion.
- There is always a need to study the geomorphic processes as a system approach. In this research only grey-box models (e.g. RUSLE and RMMF models) are used based on data availability and instrumentation. The average maximum potential annual rate of soil loss is 20.93Kg $m^{-2}y^{r-1}$in the RMMF model, whereas it is 16.25Kg $m^{-2}y^{r-1}$in the RUSLE model. Both these values do not match with the observed field values of erosion rate which is 17.87 Kg $m^{-2}y^{r-1}$in the gully catchment 1.
- In six cases, the RMS-error of RUSLE is 9.56, but it is rising up to 19.05 in the RMMF model. Alongside, the MEC (Model Efficiency Coefficient) value is highly negative (-0.87) for the RMMF model, which means high variations in predictions than the observed values.

But the MEC value of RUSLE model is 0.37 which means moderate performance of model in this geo-climatic condition.

- Based on the empirical study it is clear that the exposures of secondary laterites are very much prone to erosion and the major problem is linear erosion through dense network of rills and gullies. The sediment delivery through rills and gullies occurs, if proper erosion and sediment control practices are not installed and maintained.

8.2 Concluding Remarks

Accelerated soil erosion of *Rarh* Plain is a grave problem that must be solved to ensure the welfare of future generations. Although erosion and erosion-control research during the past 70 years provides a solid understanding of erosion processes and a variety of erosion-control practices, much more remains to be done. Changing technologies present new challenges and also offer new possibilities. The erosion-prediction technologies with GIS inputs now expand to database of erosion rate in the remote areas. In the economically backward region of study area the adaptation of erosion control technologies is very crucial steps. To check gully erosion, the technology must satisfy a number of requirements – (a) a high and quick financial return, (b) a reduction in risk, (3) no loss of existing benefits, (4) economic and social acceptability of native plant species used in the erosion management, and (5) accessibility to the farmer in terms of extra inputs of labour and capital.

Controlling gully erosion can be an elusive process and the rate of success in any conservation scheme depends on the planning, design and techniques employed. Exact gully control rules are difficult to establish because gullies are not similar even in the same area. It is possible to achieve gully stabilization if the vegetation growth overtakes the vertical and lateral erosion in the gully channels. Once the gully floor and head are rendered, then the stabilisation is established upward. Small check dams or sedimentation tanks and selective vegetation (e.g. bushes and grasses with deep dense root system) play a vital role in the process of erosion control on the gullied areas and re-vegetation of bare laterite surface can control channel and splash erosion of upper catchment to maximum level. Concentrated-flow areas within the natural landscape may be on such a steep grade that erosion occurs in them and these areas are the key locations of gully initiation. Drop structures with loose rocks at those points are the possible management strategies to avoid flow concentration and with time it increase deposition and vegetation growth.

Soil erosion is an integral part of the natural and cultural environment; its rate and spatial and temporal distribution depend on the interaction of physical and human circumstances. Archaeological and historical studies show how the nature of this interaction has changed over time. Since the 1970s, there has been increasing concern about the environmental damage caused by erosion. Although much of this damage is associated with sediment derived from agricultural areas and the chemicals adsorbed to it, problems can also arise from erosion on road banks, barren land newly developed built-up area and recreational areas. The people whose activities may contribute to gully erosion and who may be affected by any damage are now a much wider group than farmers. Erosion affects whole communities. As the climate changes and human activities are the most active factors in the environment, the erosion dynamics is likely to change in future. Areas that traditionally have not experienced erosion problems may well do so in the future.

References

Ahmad E (1970). Distribution and Causes of Gully Erosion in India. In: Chatterjee SP, Das Gupta SP (ed.), *Selected papers Vol.1 Physical Geography, 21st International Geographical Congres*,Calcutta, National Committee for Geography, pp. 1 – 3.

Araujo TP, Pejon OJ (2015) Topographic threshold to trigger gully erosion in a Tropical region – Brazil. In: Lollino G, Arattano M, Rinaldi M, Giustolisi O, Marechal JC, Grant GE (eds), Engineering Geology for Society and Territory. Springer, Switzerland, pp. 627 – 630.

Bakshi AK (1995) Petrogenesis and timing of volcanism in the Rajmahal flood basalt province, north-eastern India. *Chemical Geology*, 121: 73 – 90.

Baksi AK, Barman TR, Paul DK, Farrar E (1987) Widespread Early Cretaceous flood basalt volcanism in eastern India: geochemical data from the Rajmahal – Bengal – Sylhet Traps. *Chemical Geology*, 63: 133 – 141.

Ball V (1877) *Geology of Rajmahal Hills*. Memoir of Geological Survey of India No. 5, 13 (2), pp. 1 – 94.

Bandyopadhyay S (1987) Man-initiated gullying and slope formation in a laterite terrain at Santiniketan, West Bengal. Geographical Review of India, 49 (4): 21 – 26.

Bandyopadhyay S (1988) Drainage evolution in a badland terrain at Gangani in Medinipur district, West Bengal. Geographical Review of India 50 (3): 10 – 20.

Bayramov E, Buchroithner MF, McGurty E (2013) Differences of MMF and USLE models for soil loss prediction along BTC and SCP pipelines. Journal of Pipeline Systems Engineering and Practice, 4 (1): 81 – 96.

Begin ZB, Schumm SA (1984) Gradational thresholds and landform singularity; significance for quaternary morphology, Geological Society of American Bulletin 56 (3): 267 – 274.

Behera P, Durga Rao KHV, Das KK (2005). Soil Erosion Modelling using MMF model – A Remote Sensing and GIS Perspective. *Journal of Indian Society of Remote Sensing*, 33 (1): 165-175

Bhan C (2009). Yamuna and Chambal Ravines: Mechanism of Gully Formation. In: H.S. Sharma HS, Kale VS (ed), *Geomorphology in India,* PrayagPustakBhavan, Allahabad, pp. 459-472.

Biswas A (1987) Laterities and Lateritoids of Bengal. In: Datye VS, Diddee J, Jog SR, Patial C (eds), Exploration in the Tropics. K.R.Dikshit Felicatiobn Committee, Pune, pp. 157-167.

Blanco H, Lal R (2008). *Principles of Soil Conservation and Management*. Springer, New York.

Bocco G (1991) Gully erosion: processes and models. *Progress in Physical Geography*, 15 (4): 392 – 406.

Bull LJ, Kirkby MJ (1997) Gully processes and modelling. Progress in Physical Geography, 21 (3): 354 – 374.

Bull WB (1980) Geomorphic thresholds as defined by ratios. In: Coates DR, Vitek JD (eds), Threshold in Geomorphology, George Allen & Unwin, pp. 259 – 263.

Carey B (2006). *Gully Erosion*. Retrieved from http://www.derm.qld.gov.au/factsheets/pdf/land/l81.pdf

Cerda A, Gimenez-Morera A, Bodi MB (2009) Soil and water loess from new citrus orchards growing on sloped soils in the western Mediterranean basin. *Earth Surface Processes and Landforms*, 34:1822 – 1830.
Charlton R (2008). *Fundamentals of Fluvial Geomorphology*. Routledge, London.

Chmelova R,Sarapatka B (2002). Soil Erosion by Water: Contemporary Research Methods and Their Use. *Geographica*, 37: 23-30.

Chorley RJ, Schumm SA, Sugden (1984) *Geomorphology*. Methuen, London.

Coates DR, Vitek JD (1980) Perspectives on geomorphic thresholds. In: Coates DR, Vitek JD (eds), Threshold in Geomorphology, George Allen & Unwin, pp. 3 – 23.

Cooke R U,Doornkamp J C (1987). *Geomorphology in Environmental Management*. Clarendon Press, Oxford.

Dai Q, Liu Z, Shao H, Yang Z (2015). Karst bare slope soil erosion and soil quality: A simulation case study.Solid Earth, 6 (3): 985-995.

Das Gupta AB, Mukherjee B (2006) *Geology of N.W. Bengal Basin*. Geological Society of India, Bangalore.

Das Gupta S (1996) Bentonite deposits intercalated with the Rajmahal volcanic rocks of eastern India. *Journal of Southeast Asian Earth Sciences*, 13 (2): 133 – 137.

Das K, Bandyopadhyay S (1996). Badland development in alateritic terrain: Santiniketan, West Bengal. National Geographer, XXXI (1 & 2): 87 – 103.

Dong Y, Xiong D, Su Z, Li J, Yang D, Zhai J, Lu X, Liu G, Shi L (2013) Critical topographic threshold of gully erosion in Yuanmou dry – hot valley in southwestern China. Physical Geography 34 (1): 50 – 59.

Douglas I (1976). Erosion Rates and Climate: Geomorphological Implications. In: Derbyshire E (ed.) *Geomorphology and Climate*, John Wiley & Sons, London, pp. 269-285.

Ebisemiju FS (1989) Thresholds of gully erosion in a lateritic terrain, Guyana. Singapore Journal of Tropical Geography, 10 (2): 136 – 143.

Eggleton T,Taylor G (2000). *Selected Thoughts on 'Laterite'*. Retrieved from www.crcleme.org.au/Pubs/monographs/.../18_eggleton%26taylor.pdf

El-Swaify SA, Dangler EW,Armstrong CL (1982). *Soil Erosion by Water in the Tropics*. University of Hawaii, Hawaii. Retrieved from http://www.pdf.usaid.gov/pdf_docs/PNAAR134.pdf

Erskine ED(2005). Gully erosion. In: LehrJ, Keeley J, Lehr J, Kingery TB (eds), Water Encyclopaedia: Surface and Agricultural Water, Wiley, New York, pp. 183 – 188.

Eswaran H, Lal R, Reich PF (2001) Land Degradation: an overview. In: Bridges EM, Hannam ID, Oldeman LR, Pening de Vries FWT,Scherr SJ, Sompatpanit S (eds.), Responses to Land Degradation, Proceeding 2nd International Conference on Land Degradation and Desertification, New Delhi, Oxford, pp. 20 – 35.

Fairbridge RW (1980) Thresholds and energy transfer in geomoprhology. In: Coates DR, Vitek JD (eds), Threshold in Geomorphology, George Allen & Unwin, pp. 43 – 49.

Ganasri BP, Ramesh H (2016) Assessment of soil erosion by RUSLE model using remote sensing and GIS – a case study of Nethravathi Basin. Geoscience Frontiers, 7: 953 – 961.

Gao P (2013) Rill and gully development processes. In: Marston RA, Stoffel M (eds), *Treatise on Geomorphology – Mountain and Hillslope Geomorphology* Volume 7, Academic Press, San Diego, pp. 122 – 131.

Gerrard AJ (1981). *Soil and Landforms: An Integration of Geomorphology and Pedology*. George Allen & Unwin, London.

Ghose NC, Singh SP, Singh RN, Mukherjee D (1996) Flow stratigraphy of selected sections of the Rajmahal basalts, eastern India. *Journal of Southeast Asian Earth Sciences*, 13 (2): 83 – 93.

Ghosh S, Bhattacharya K (2012). Multivariate erosion risk assessment of lateritic badlands of Birbhum (West Bengal, India): a case study. *Journal of Earth System Science*, 121 (6): 1441 – 1454.

Ghosh S, Ghosh S (2003). Land Degradation due to Indiscriminate 'Murrum' Extraction near Durgapur Town, West Bengal. In:JhaVC (ed.), *Land Degradation and Desertification*,Rawat Publications, Jaipur, pp. 255-267.

Ghosh S, Guchhait S (2015) Chraterization and evolution of primary and secondary laterites in northwestern Bengal Basin, West Bengal, India. *Journal of Palaeogeography*, 4 (2): 203 – 230.

Ghosh S,Bhattacharya K (2012). Multivariate erosion risk assessment of lateritic badlands of Birbhum (West Bengal, India): a case study. *Journal of Earth System Science*, 121 (6): 1441 – 1454.

Ghosh S,Guchhait SK (2012). Soil loss estimation through USLE and MMF methods in the lateritic tracts of eastern plateau fringe of Rajmahal Traps, India. *Ethiopian Journal of Environmental Studies and Management*, 5 (4): 529 – 541.

Gilbert GK (1970). Land Sculpture in the Henry Mountains. In:Dury GH (ed.), *River and River Terraces* MacMillan, London, pp. 95-116.

Hajgh MJ (1984). Ravine Erosion and Reclamation in India. *Geoforum*, 15 (4): 543-561

Horton RE (1945) Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. Geological Society of America Bulletin, 56, 275 – 370.

Horton RE (1970). Erosional Development of Streams: Quantitative Physiographic Factors. In:Dury GH (ed.), *River and River Terraces,* MacMillan, London, pp. 117-163.

Hudson NW (1984). *Soil Conservation*. English language Book Society, London.

Hunday A,Banerjee S (1967). *Geology and Mineral Resources of West Bengal*. Memoirs of the Geological Survey of India, Delhi.

ICAR (2010) Degraded and wastelands of India: status and spatial distribution. Indian Council of Agricultural Research, New Delhi.

Jha MK, Paudel RC (2010) Erosion predictions by empirical models in a mountainous watershed in Nepal. Journal of Spatial Hydrology, 10 (1): 89 – 102.

Jha VC, Kapat S (2003). Assessment of Soil Erosion and Degraded Land; A Case Study of Dumka Subdivision, Jharkhand. In: In:Jha VC (ed.), *Land Degradation and Desertification*,Rawat Publications, Jaipur, pp. 156-178).

Jha VC,Kapat S (2009). Rill and Gully Erosion Risk of Lateritic Terrain in South Western Birbhum District, West Bengal, India.*Sociedade&Natureza,* Uberlandia, 21 (2): 141-158.

Jha VC,Kapat S (2011). Degraded Lateritic Soils Cape and Land Uses in Birbhum District, West Bengal, India. *Sociedade&Natureza,* Uberlandia, 23 (3): 545-558.

Kale VS, Joshi V, Kelkar N (1994). Morphology and Origin of Valley-Side Gullies on Colluvium, Western Upland Maharashtra. In: Dikshit KR, Kale VS,Kaul MN (eds.), *India: geomorphological Diversity*,Rawat Publications,Jaipur, pp. 451-468.

Kent W, Saunders AD, Kempton PD, Ghose NC (1996) Rajmahal basalts, eastern India: mantle sources and melt distribution at a volcanic rifted margin. Large Igneous Provinces: Continental, Oceanic and Planetary Flood Volcanism. *Geophysical Monograph*, 100: 145 – 182.

Kinghton D (1998). *Fluvial Forms and Processes*. Arnold Publication, London.

Kirkby MJ (1976). Hydrological Slope Models: The influence of Climate. In: Derbyshire E (ed.) *Geomorphology and Climate*, John Wiley & Sons, London, pp. 247-267.

Kirkby MJ (1980) The stream head as a significant geomorphic threshold. In: Coates DR, Vitek JD (eds), Threshold in Geomorphology, George Allen & Unwin, pp. 53 – 73.

Kirkby MJ, Bracken LJ (2009) Gully processes and gully dynamics. *Earth Surface Processes and Landforms*, 34: 1841 – 1851.

Krishnamurthy, P., Mahoney, J.J., Gopalan, K. and MacDougall, J.D. (2014) Clinopyroxene compositions in the Deccan and Rajmahal Traps and their bearing on magma types and evolution. Journal of Asian Earth Sciences, v.84, pp. 102 – 107.

Kumar A, Dayal AM, Padmakumari VM (2003) Kimberlite from Rajmahal magmatic province: Sr-Ad-Pb isotopic evidence for Kerguelen plume derived magmas. *Geophysical Research Letters*, 30 (20): 2053.

Lal R (1992) Restoring tropical land degraded by fully erosion in the tropics. In: Lal R, Stewart BA (eds), Advances in Soil Science Volume 17 Soil Restoration, Springer-Verlag, New York, pp. 123 – 149.

Lal R (2001). Soil Degradation by Erosion. *Land Degradation & Develo*pment, 12: 519-539.

Leopold LB, Wolman G,Miller JP (1969). *Fluvial Processes in Geomorphology*. Eurasia Publishing House (Pvt.) Ltd., New Delhi.

Mahadevan TM (2002) *Geology of Bihar and Jharkhand*. Geological Society of India, Bangalore.

Maignien R. (1966). *Review of Research on Laterites*. UNESCO, Paris. Retrieved from http://www.unesdoc.unesco.org/images/0007/000711/071101eo.pdf

McFarlane MJ (1976). *Laterite and landscape*. Academic Press, London.

McKerchar AI (1980) Thresholds in deterministic models of the rainfall-runoff process. In: Coates DR, Vitek JD (eds), Threshold in Geomorphology, George Allen & Unwin, pp. 171 – 177.

Mehrotra RC, Shukla A, Srivastava G Tiwari RP (2014) Miocene megaflora of peninsular India: present status and future prospect. *Special Publication of the Palaeontological Society of India*, 5: 273 – 281.

Mekonnen M, Keesstra SD, Baartman JE, Ritsema CJ,Melesse AM (2015). Evaluating sediment storagedams: structural off-site sediment trapping measures in northwest Ethiopia. Cuadernos de InvestigacionGeografica, 41: 7 – 22.

Moeyersons J (2003) The topographic thresholds of hillslope incisions in southwestern Rwanda. Catena 50: 381 – 400.

Montgomery DR, Dietrich WE (1988) Where do channels begin. Nature 336 (6196): 232 – 234.

Montgomery DR, Dietrich WE (1992) Channel initiation and the problem of landscape scale. Science 255: 826 – 830.

Montgomery DR, Dietrich WE (2004) Landscape dissection and drainage area – slope thresholds. In: Kirkby MJ (ed), Process Models and Theoretical Geomorphology. John Wiley & Sons, New York, pp. 221 – 246.

Morgan RPC (1976). The Role of Climate in the Denudation System: A Case Study from West Malaysia. In: Derbyshire E (ed.) *Geomorphology and Climate*, John Wiley & Sons, London, pp. 317-341.

Morgan RPC (2001) A simple approach to soil loss prediction: a revised Morgan-Morgan-Finney model. Catena 44: 305 – 322.

Morgan RPC (2005). *Soil Erosion and Conservation*. Blackwell Publishing, Oxford.

Morgan RPC (2011) Model development: a user's perspective. In: Morgan RPC, Nearing MA (eds), Handbook of Erosion Modelling, Wiley-Blackwell, Oxford, pp. 9 – 32.

Morgan RPC, Duzant JH (2008). Modified MMF Model for Evaluating Effects of Crops and Vegetation Cover on Soil Erosion. *Earth Surface Processes & Landforms*, 32: 90-106.

Morgan RPC, Nearing MA (2011). *Handbook of Erosion Modelling* (ed.). Wiley-Blackwell, New York.

Morgan RPC, Mngomezulu D (2003) Threshold conditions for initiation of valley-side gullies in the Middle Veld of Swaziland. Catena 50: 401 – 414.

Morgan RPC, Morgan DDV, Finney HJ (1984) A predictive model for the assessment of soil erosion risk. Journal of Agricultural Engineering Research, 30: 245 – 253.

Morgan RPC, Quinton JN, Smith RE et al. (1998). The European Soil Erosion Model (EUROSEM): A Dynamic Approach for Predicting Sediment Transport from Fields and Small Catchments. *Earth Surface Process and Landforms*, 23: 527-544.

Mukherjee PK (1971) Petrology of the Rajmahal Traps of the north-eastern Rajmahal Hills, Bihar, India. *Bulletin of Volcanology*, 35 (4): 887 – 906.

Mukhopadhyay M, Verma RK, Ashraf MH (1986) Gravity field and structures of the Rajmahal hills: example of the paleo-mesozoic continental margin in eastern India. *Tectonophysics*, 131: 353 – 367.

Narayana, DVV, Babu R (1983). Estimation of soil erosion in India.*Journal of Irrigation Drainage Engineering*, 109 (4): 419 – 434, 1983.

Nasri M, Feiznia S, Jafri M,Ahmadi H(2008). Using Field Indices of Rill and Gully in order to Erosion Estimating and Sediment Analysis (Case Study: Menderjan Watershed in Isfahan Province, Iran). *World Academy of Science, Engineering and Technology*, 43: 370-376.

Nath SK, Thingbaijam KKS, Vyas JC, Sengupta P, Dev SMSP (2010) Macroseismic-driven site effects in the southern territory of West Bengal, India. *Seismological Research Letters*, 81 (3): 480 – 482.

Nearing MA, Lane LJ, Lopes VL (1994) Modelling soil erosion. In: Lal R (ed), Soil Erosion: Research and Methods, Soil and Water Conservation Society, Ankeny, pp. 127 – 156.

Niyogi D, Mallick S, Sarkar S (1970). A Preliminary Study of Laterites of West Bengal, India. In: Chatterjee SP, Das Gupta SP (ed.), *Selected papers Vol.1 Physical Geography, 21st International Geographical Congress* National Committee for Geography, Calcutta, pp. 443-449.

Novara A, Keesstra S, Cerdà A, Pereira P,Gristina, L (2016) Understanding the role of soil erosion on CO_2-C loss using ^{13}C isotopic signatures in abandoned Mediterranean agricultural land.*Science of the TotalEnvironment*, 550: 330-336.

Pandey A, Mather A, Mishra SK,Mail BC (2009). Soil Erosion Modelling of a Himalayan Watershed Using RS and GIS. *Environmental Earth Science*, 59: 399-410.

Panniza M (1996). *Environmental Geomorphology*. Elsevier,Amsterdam.

Parsons AJ (2005). Erosion and Sediment Transport by Water on Hillslopes. In: Anderson MG (ed.), *Encyclopaedia of Hydrological Sciences*, John Wiley & Sons Ltd., London, pp. 1199-1205.

Pathak P, Wani SP,Sudi R (2005). *Gully Control in SAT Watersheds*. Retrieved from Global Theme on Agroecosystems Report No.15 website:http://www.icrisat.org/journal/agroecosystem/v2i1/v2i1gully.pdf

Paton TR,Williams MAJ (1972). The Concept of Laterite. *Annals of the Association of American Geographers*, 32(1): 42-56.

Patton PC, Schumm SA (1975) Gully erosion, north-western Colorado: a threshold phenomenon. Geology 3: 88 – 90.

Pimentel D (2006) Soil erosion – a food and environmental threat. Environment, Development and Sustainability, 8: 119 – 137.

Pimentel D,Burgess M (2013) Soil erosion threatens food production. Agriculture, 3: 443 – 463.

Poesen J, Nachtergaele J, Verstraeten G, Valentin C (2003) Gully erosion and environmental change: importance and research needs. Catena 50: 91 – 133.

Posen J, Nachtergaele J, Verstraeten G,Valentin C (2003). Gully erosion and environmental change: importance and research needs. *Catena,* 50: 91 – 133.

Radakrishnamurty C, Sahasrabudhe PW.(1958) Remnant magnetism of the Rajmahal Traps of north-eastern India. *Nature*, 181: 830 – 831.

Rahaman SA, Aruchamy S, Jegankumar R, Ajeez SA (2015) Estimation of annual average soil loss, based on RUSLE model in Kallar watershed, Bhavari Basin, Tamil Nadu, India. ISPRS Annals of the Photogrammetry, remote Sensing and Spatial Information Sciences 2: 207 – 214.

Rao GVSP, Rao JM, Rao MV (1996) Palaeomagnetic and geochemical characteristics of the Rajmahal Traps, eastern India. *Journal of Southeast Asian Earth Sciences*, 13 (2): 113 – 122.

Rasool I, Khera KL,Gul F (2011). Proliferation of Gully Erosion in the Submontane Punjab, India. *Asian Journal of Scientific Research*, 4 (4): 287-301.

Raychadhuri SP (1970). Classification of Soils of India. In:Chatterjee SP, Das Gupta SP (ed.), *Selected papers Vol.1 Physical Geography, 21st International Geographical* Congress, National Committee for Geography, Calcutta, pp.450-458.

Raychadhuri SP (1980). The Occurrence, Distribution, Classification and Management of Laterite and Lateritic Soils. *Journee Georges Aubert*, XVIII(3-4): 249-252.

Renard KG, Foster GA, McCool DK, Yoder DC (1997) Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation. USDA Agriculture handbook No. 703.

Renard KG, Yoder DC, Lighthe DT, Dadney SM (2011) Universal soil loss equation and revised universal soil loss equation. In: Morgan RPC, Nearing MA (eds), Handbook of Erosion Modelling, Wiley-Blackwell, Oxford, pp. 137 – 167.

Renard KG, Yoder DC, Lighthe DT, Dadney SM (2011) Universal soil loss equation and revised universal soil loss equation. In: Morgan RPC, Nearing MA (eds), Handbook of Erosion Modelling, Wiley-Blackwell, Oxford, pp. 137 – 167.

Rossi M, Torri D, Santi E (2015) Bias in topographic thresholds for gully heads. Natural Hazards, 79: S51 – S69.

Roy Chowdhury MK, Venkatesh V, Anandalwar MA,Paul DK (1965). *Recent Concepts on the Origin of Indian Laterite*. Retrieved from http://www.new.dli.ernet.in/rawdataupload/upload/..../20005ab9_547.pdf

Samni AN, Ahmadi H, Jafari M, Boggs G, Ghoddousi J, Malekian A (2009) Geomorphic threshold conditions for gully erosion in southwestern Iran (Boushehe – Samal watershed). Journal of Asian Earth Sciences 35 (2): 180 – 189.

Sarkar D, Nayak DC, Dutta D, Dhyani BL (2005). *Soil Erosion of West Bengal*. NBSS & LUP, NBSS Publ.117, Nagpur.

Sarkar D, Nayak DC, Dutta D, Gajbhiye KS (2007). *Optimizing Land Use of Birbhum District (West Bengal) Soil Resource Assessment*. NBSS & LUP, NBSS Publ.130, Nagpur.

Schaetzl RJ,Anderson S (2005). *Soils: Genesis and Geomorphology*. Cambridge University Press, Cambridge.

Schumm SA (1980) Some applications of the concept of geomorphic thresholds. In: Coates DR, Vitek JD (eds), Threshold in Geomorphology, George Allen & Unwin, pp. 473 – 485.

Schumm SA, Hadley RF (1957) Arroys and semi-arid cycle of erosion. American Journal of Science 255: 161 – 174.

Sen J, Sen S, Bandyopadhyay S (2004). Geomorphological Investigation of Badlands: A Case Study at Garhbeta, West Medinipur District, West Bengal, India. In: Singh S, Sharma HS, De SK (eds.), *Geomorphology and Environment*, acb Publications, pp. 195-203.

Sengupta S (1972) Geological framework of the Bhagirathi-Hooghly Basin. In: Bagchi KG (ed), The Bhagirathi-Hooghly Basin: Proceedings of the Interdisciplinary Symposium, Calcutta, pp. 3 – 8.

Sharda VN, Dogra P (2013) Assessment of productivity and monetary losses due to water erosion in rainfed crops across different states of India for prioritization and conservation planning.*Agricultural Research*,2 (4): 382 – 392.

Sharda VN, Dogra P,Prakash C (2010) Assessment of production losses due to water erosion in rainfed areas of India.*Journal of Soil and Water Conservation*, 65 (2): 79 – 91.

Sharma HS (1970). Genesis of Ravines of the Lower Chambal Valley, India. In:Chatterjee SP, Das Gupta SP (ed.), *Selected papers Vol.1 Physical Geography, 21st International Geographical* Congress, National Committee for Geography, Calcutta, pp.114-118).

Sharma HS (1986). *Tropical Geomorphology - A Morphogenetic Study of Rajasthan*. Concept Publishing Company, New Delhi.

Sharma HS (2009). Progress of Researches in Ravines and Gullies Geomorphology in India. In:Sharma HS, KaleVS (ed.), *Geomorphology in India*, PrayagPustakBhavan, Allahabad, pp. 441-458.

Sheth HC, Pande K (2005) Magnetism in India through time. *Earth and Planetary Sciences*, 8 (4): 634 – 636.

Singh AK, Kala S, Dubey SK, Pande VC, Rao BK, Sharma KK,Mahapatra KP (2015). Technology for rehabilitation of Yamuna ravines – cost-effective practices to conserve natural resources through bamboo plantation.*Current Science*, 108 (8): 1527 – 1533.

Singh AP, Kumar N, Singh B (2004) Magmatic underplating beneath the Rajmahal Traps: gravity, signature and derived 3-D configuration. *Journal of Earth System Sciences*, 113 (4): 759 – 769.

Singh G, Babu R, Narain P, Bhushan LS, Abrol IP (1992). Soil erosion rates in India.*Journal of Soil and Water Conservation*, 47(1): 97 – 99.
Singh S, Dubey A (2002). G*ully Erosion and Management: Methods and Application*. New Academic Publishers, New Delhi

Singh S,Agnihotri SP (1987). Rill and Gully Erosion in the Subhumid Tropical Riverine Environment of TeontharTahsil, Madhya Pradesh, India. *GeografiskaAnnaler Series A, Physical Geography*, 69 (1): 227-236.

Stone RP, Hilborn D (2000). *Universal Soil Loss Equation*. Retrieved from http://www.*omafra.gov.on.ca/english/engineer/facts/00-001.pdf*

Strahler AN (1956). The Nature of Induced Erosion and Aggradation. In: Thomas WL (ed.), *Man's Role in Changing Face of the Earth*, University of Chicago Press,Chicago, pp. 621-637.

Strahler AN (1964). Quantitative Geomorphology of Drainage Basins and Channel Networks. In: Chow VT (ed.), *Handbook of Applied Hydrology*, McGraw Hill Book Company, New York, pp. 4-39 – 4-75.

Stroosnijder L (2005). Measurement of Erosion: Is It Possible? Retrieved from http://www.idd.wur.nl/NR/rdonlyres/…./Measurement_of_erosion.pdf

Svorin J (2003). A Test of Three Soil Erosion Models Incorporated into a Geographical Information System. *Hydrological Processes,* 17: 967-977

Telles TS, Guimaraes MF, Dechen SCF (2011). The costs of soil erosion. RevistaBrasileira de Ciencia do Solo, 35: 287 – 298.
Thomas MF (1974). *Tropical Geomorphology – A Study of Weathering and Landform Development in Warm Climate*. MacMillan Press Ltd., London.

Thornbury W D (1969). Principles of Geomorphology. Wiley, New York.

Thorp J, Baldwin M (1940). Laterites in Relation to Soils of Tropics. *Annals of the Association of American Geographers*, 30 (3): 163-194.

Townshend JRG (1970). Geology, Slope Form, and Slope Process, and Their Relation to the Occurrence of Laterite. *The Geographical Journal*, 136 (3): 392-399.

Toy TJ, Foster GR, Renard KG (2013) Soil Erosion: Processes, Prediction, Measurement and Control. John Wiley & Sons, New York.

Tripathi A, Jana BA, Verma O, Singh RK, Singh AK (2013) Early Cretaceous palynomorphs, dinoflagellates and plant megafossils from the Rajmahal Basin, Jharkhand, India. *Journal of the Palaeontological Society of India,* 58 (1): 125 – 134.

Valentin C, Poesen J, Li Yong (2005). Gully Erosion: Impacts, factors and Control. *Catena*, 63: 132-153.

Vandaele K, Poesen J, Govers G, Wesemael B (1996) Geomorphic threshold conditions for ephemeral gully incision. Geomorphology 16 (2): 161 – 173.

Wadia DN (1999). *Geology of India*. Tata McGraw Hill Publishing Company, New Delhi.

Wischmeier WH, Smith DD (1972).*Predicting Rainfall-Erosion Losses from Cropland East of the Rocky Mountains*. USDA, Agricultural Handbook No. 282, pp. 1-46.

Wischmeier WH, Smith DD (1978) Predicting rainfall erosion losses – a guide to conservation planning. USDA Agriculture handbook No. 537.

Yadav RC, Bhushan LS (2002) Conservation of gullies in susceptible riparian areas of alluvial soil regions. *Land Degradation and Development*, 13 (3): 201 – 219.
Young A (1972). *Slopes*. Longman, New York.

Young A (1976). *Tropical Soils and Soil Survey*. Cambridge University Press, Cambridge.

Zachar D (1982). *Soil Erosion*. Elsevier Scientific Publishing Company, Amsterdam.