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Pravat Kumar Shit · Hamid Reza Pourghasemi
Gouri Sankar Bhunia *Editors*

Gully Erosion Studies from India and Surrounding Regions

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Gully Erosion Studies from India and Surrounding Regions

Springer

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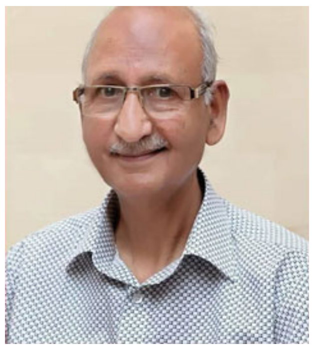
Dedicated to beloved teachers and parents

Foreword



I am happy to learn that Springer-Nature Publishing Company is bringing out a book on "Gully Erosion Studies from India and Surrounding Regions" under the Advances in Science, Technology & Innovation (ASTI) series on Sustainable Development. The book is jointly edited by Pravat Kumar Shit, Hamid Reza Pourghasemi, and Gouri Sankar Bhunia who are eminent scholars and researchers in the field of geomorphology and advanced geospatial technology.

Gully erosion is the erosion process whereby runoff water accumulates and sediment production is varied in various temporal and spatial scales and under the different climatic conditions and land-use patterns. Soil is the most fundamental and basic resource that provides food, fodder, fuel, and fiber. It underpins food security and environmental quality. The essentiality of soil to human well-being is often not realized until the production of food drops is jeopardized when the soil is severely eroded or degraded to the level that it loses its inherent resilience.

India and its surrounding regions are experiencing major problems in land degradation and mismanagement in land-use practices. By contrast, mismanagement and also the sustainability of the current and future soil and land resource allocation are other concerns. Thus, it is important to use the newest technologies and tools to improve and properly develop sustainable management. In this context, the book has been very effectively organized into thematic sections, covering the fundamental concepts of the gully classification system, erosion processes, and prediction, modeling, and sustainable management strategies.

It is a cohesive effort of a number of authors, researchers, and experts in the field of geomorphology across the country and other parts of the world. The editors have done an exemplary job in collecting, compiling, and editing the papers in a book form. The quality of this interdisciplinary research can be realized by readers by going through chapters in this enriched volume. This book will be very much beneficial for geomorphologists, hydrologists, soil scientists, students, scientists, ecologists, and policymakers.

I extend my warm greetings to all those associated with the publication and congratulate Springer-Nature Publishing Company for launching this book.

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Preface

Gully erosion is the removal of soil along constricted channels via the accretion of surface runoff, which tends to yield more sediment loss than other types of soil erosion, such as overland drift or rilling. Gully erosion is physiographically prevalent and is recognized by numerous terms in various regions. Gullies cause widespread destruction to infrastructures and susceptible cultivated lands and adulterate water by confiscation and aggradation of soil elements and chemicals from manure. Gullies are everlasting erosional practices that grow in several areas of the biosphere, predominantly in arid and semiarid zones. Unscientific land-use practices and mismanagement of land use and strategies may accelerate gully development by head cutting, sidewall breakdown, piercing, floor corrosion, and other procedures, which bring about extensive land deprivation and probable mutilation to human erections and activities.

Gully erosion has worldwide effects on agricultural, financial, and sociopolitical circumstances; nevertheless, statistics concerning the amount of these influences have been principally unpredictable. This book emphasizes the reciprocal interactions of gully deprivation, management, and remediation. It highlights the instantaneous and long-lasting effects of gully degradation in association with the geospatial technology in arid and semiarid environments.

The collection of thirty-one chapters draws on the research of an international group of scholars and practitioners who work in college, universities, government sectors, private consultancies, and research centers. Their expertise is in the field of applied geomorphology, hydrology, sedimentology, ecology, and engineering. Their methods include intensive field investigations, laboratory experimentation, geospatial technology, and modeling of gully susceptibility mapping, monitoring, and management.

This book addresses the core subjects associated with morphology and development of rill-gully, restoration strategies of gully and ravine land, gully collapsing in lateritic belt, risk estimation of rill and gully erosion by random forest model, geomorphic threshold and SCS-CN-based runoff-sediment yield modeling, Bayesian weight of evidence, RUSLE, and SDR model, hydraulic flume experiment, SWAT model, plant roots—an experimental insight, MARS model, SVM machine learning algorithm, etc. Research results are presented in this book that forms the scientific basis for the extensive evaluation of gully erosion, control and greening for livelihood, and environmental sustainability. The book covers a wide range of vital topics in the areas of gully erosion and water erosion at lateritic uplands of India and its surrounding regions. Additionally, the book offers GIS-based advanced cartographic techniques for students to recognize both simple and classy concepts of applied geomorphology. It is an ardent challenge to efficiently guide the aspirants who are involved in research and development in applied geomorphology. Chapter-end references, which are recent and resourceful, shed light on topics mentioned in this book.

We thank all the authors who have meticulously completed their chapters at short notice and contributed in building this edifying and beneficial publication. We believe this book will be of great value to geographers, geologists, agricultural engineers, hydrologists, soil scientists, ecologists, research scholars, environmentalists, and policymakers.

Medinipur, West Bengal, India

Pravat Kumar Shit
Hamid Reza Pourghasemi
Gouri Sankar Bhunia

Acknowledgments

The preparation of this book has been guided by several geomorphologic pioneers. We are obliged to these experts for providing their time to evaluate the chapters required updation in this book. We are very much thankful to our respected teachers, Dr. Ramkrishna Maiti, Dr. Ashis Kumar Paul, Dr. Dilip Kr. Pal, Dr. Sunando Bandyopadhyay, Dr. Lakshminarayan Satpati, Dr. Malay Mukhopadhyay, Dr. Joyti Shankar Bandopadhay, Dr. Soumendu Chatterjee, Dr. Nilanjana Das Chatterjee, and Dr. Ratan Kumar Samanta, for their guidance, suggestions, encouragement, and immense support throughout the work.

We thank the anonymous reviewers for their constructive comments that led to substantial improvements to the quality of this manuscript.

We also thank Ranita and Debjani, whose love, encouragement, and support have motivated us to make this book a reality. Because this book was a number of years in the making, we want to thank our family and friends for their continued support.

Dr. Pravat Kumar Shit thanks Dr. Jayasree Laha, Principal, Raja N.L. Khan Women's College (Autonomous), Midnapore, for her administrative support to carry on this project. We also acknowledge the Department of Geography of this college for providing logistic support and infrastructure facilities.

Dr. Hamid Reza Pourghasemi thanks College of Agriculture, Shiraz University, and Watershed Management Society of Iran for supporting during the preparation of this book.

This work would not have been possible without constant inspiration from our students, knowledge from our teachers, enthusiasm from our colleagues and collaborators, and support from our family.

Finally, we also thank our publisher and its publishing editor Dr. Nabil Khélifi, the Middle East and North Africa, Springer Heidelberg, for their continuous support in the publication of this book.

Disclaimer

The authors of individual chapters are solely responsible for ideas, views, data, figures, and geographical boundaries presented in the respective chapters of this book, and these have not been endorsed, in any form, by the publisher, the editor, and the authors of forewords, preambles, or other chapters.

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About the Editors

Pravat Kumar Shit received his Ph.D. in Geography (Applied Geomorphology) from Vidyasagar University (India) in 2013, M.Sc. in Geography and Environment Management from Vidyasagar University in 2005, and PG Diploma in Remote Sensing & GIS from Sambalpur University in 2015. He is Assistant Professor in the Department of Geography, Raja N. L. Khan Women's College (Autonomous), Gope Palace, Midnapore, West Bengal, India. His main fields of research are soil erosion spatial modeling, badland geomorphology, gully morphology, water resources and natural resources mapping, and modeling and has published more than 45 international and national research articles in various renowned journals; also, he has published three books. His research work has been funded by the University Grants Commission (UGC), India, and Higher Education Science and Technology and Biotechnology, Government of West Bengal. He is Associate Editor and on the editorial boards of three international journals in geography and earth environmental sciences.

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He has published more than 90 peer-reviewed papers in high-quality journals, with three chapters in Springer. Also, he has published two books for Springer (https://www.springer.com/gp/book/9783319733821) and Elsevier (https://www.elsevier.com/books/spatial-modeling-in-gis-and-r-for-earth-and-environmental-science/pourghasemi/978-0-12-815226-3).

Gouri Sankar Bhunia received his Ph.D. from the University of Calcutta, India, in 2015. His Ph.D. dissertation work focused on environmental control measures of infectious disease (visceral leishmaniasis or kala-azar) using geospatial technology. His research interests include kala-azar disease transmission modeling, environmental modeling, risk assessment, data mining, and information retrieval using geospatial technology. He is Associate Editor and on the editorial boards of three international journals in health GIS and geosciences. He worked as a "Resource Scientist" in Bihar Remote Sensing Application Centre, Patna (Bihar, India). He is the recipient of the Senior Research Fellow (SRF) from the Rajendra Memorial Research Institute of Medical Sciences (ICMR, India) and has contributed to multiple research programs: kala-azar disease transmission modeling, development of customized GIS software for kala-azar "risk" and "non-risk" area, and entomological study.

Abbreviations

AGNPS	Agricultural Non-Point Source Pollution Model
AHP	Analytical Hierarchy Process
AMC	Antecedent Moisture Condition
ANSWERS	Areal Nonpoint Source Watershed Environment Response Simulation
AS	Anti-scourbility
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AUC	Area under the curve
BOD	Biological Oxygen Demand
BT	Brightness temperature
CEC	Cation Exchange Capacity
CF	Causative factors
CFSR	Climate Forecast System Reanalysis
COR	Calculation of correlation
CR	Consistency ratio
CWC	Central Water Commission
DEM	Digital Elevation Model
DN	Digital number
DPM	Dherua Paschim Medinipur
DT	Decision tree
EGEM	Ephemeral Gully Erosion Model
EPIC	Erosion Productivity Impact Calculator
FR	Frequency ratio
GCP	Ground Control Point
GE	Gully erosion
GEIM	Gully erosion inventory mapping
GESM	Gully erosion susceptibility mapping
GG	Gangani Garhbeta
GIS	Geographical Information System
GSI	Geological Survey of India
HRU	Hydrological Response Units
HSPF	Hydrologic Simulation Program-Fortran
IDW	Inverse Distance Weighted
ILP	Iranian Loess Plateau
IMD	India Meteorological Department
IWD	Irrigation and Waterways Department
Kc	Soil anti-disintegration index
LL	Liquid Limit
LMT	Logistic model tree
LS	Slope Length
LST	Land surface temperature
LULC	Land Use and Land Cover

MAE	Mean absolute error
MARS	Multivariate Adaptive Regression Splines
ME	Maximum entropy
MIF	Multi-Influencing Factor
MLA	Machine Learning Algorithm
NCEP	National Centre for Environmental Prediction
NDVI	Normalized Difference Vegetation Index
OSM	Open Street Map
PCI	Principal component image
PL	Plastic Limit
PLDZ	Potential Land Degradation Zone
PMSE	Potential Mean Soil Erosion Rate
PSD	Soil Particle Size Distribution
PV	Proportion vegetation
RD	Root Density
RI	Resilience Index
RLD	Root Length Density
RM	Rangamiti Medinipur
RMSE	Root mean square error
ROC	Receiver Operating Characteristic
RS	Remote Sensing
RSAD	Root Surface Area Density
RSC	Road-Stream Crossing
RSD	Relative Soil Detachments
RSP	Relative slope position
RUSLE	Revised Universal Soil Loss Equation
SCS-CN	Soil Conservation Service-Curve Number
SDR	Sediment Delivery Ratio
Sfm-MVS	Structure-from-motion together with multi-view stereo
SOI	Survey of India
SOM	Soil Organic Matter
SPI	Stream Power Index
SVM	Support vector machine
SWAT	Soil and Water Assessment Tool
SY	Sediment Yield
TDS	Total Dissolve Solid
TDS	Total Dissolved Salt
TM	Thematic Mapper
TT	Topographic threshold
TWI	Topographical wetness index
USLE	Universal Soil Loss Equation
UTM	Universal Transverse Mercator
WEPP	Water Erosion Prediction Project
WI	Wetness Index
WLC	Weighted Linear Combination
WoE	Weight of Evidence

Spatial Extent, Formation Process, Reclaimability Classification System and Restoration Strategies of Gully and Ravine Lands in India

1

Gopal Kumar, Partha Pratim Adhikary, and Ch. Jyotiprava Dash

Abstract

Land degradation has been a major global issue due to its adverse effect on food security, environment and ecology. Among different degraded lands, gullied and ravine lands are very important and remained a highly researchable topic. Gullies are continuous depression on the sloping land surface as a result of soil displacement caused by overland water flow and aided by gravity force, whereas ravines are most extreme form of erosion with intricate network of various forms of gullies, having high drainage density and multidirectional slopes. In India, ravines are mostly found in four states such as Uttar Pradesh, Madhya Pradesh, Gujarat and Rajasthan. During 1976, total ravine land in India was 3.67 million ha, which has been reduced to about 60% at present, and the treatable area including peripheral land is likely to be as high as 1.5 times the actual ravine.

High-intensity rainfall, loose, friable soil devoid of organic carbon and vegetation, faulty agricultural practices, removal of vegetation and overgrazing of lands along with upliftment of central highlands, Aravalli range, Bundelkhand and Chhota Nagpur plateau against lowering of Himalayan base are some of the major factors which are responsible for formation and extension of ravine. As these lands are socio-economically very important, they need reclamation. The main objectives of ravine reclamation are to arrest degradation process, promote ecological restoration, positive on-site and off-site hydrological influences and to establish socio-economic balance with a defined benefit-sharing mechanism. Land shaping, levelling and bench terracing along with riser stabilization are recommended for reclamation and productive utilization of narrow ravine systems with depth up to 3 m. Marginal bund of 1.5 m^2 cross section with 0.1–0.2% grades can be constructed at the periphery of agricultural land to regulate entry of runoff into ravine lands. Similarly, for ravine with gullies deeper than 3 m, reclamation process involves stabilization of gully heads, gully bed and side slopes, establishment of protective vegetation with economic importance and encouraging socio-ecological harmony for sustenance of protective measures. Perennial vegetation and wildlife along with eco-tourism can be considered as the best option for most degraded ravines. As the ravine area is ecologically sensitive complex system, its reclamation and sustainable development can be achieved through scientific planning at micro level and socio-eco-friendly policies.

Keywords

Chambal valley · Yamuna valley · Gully · Mahi · Ravine · Rehabilitation · India

1.1 Introduction

Land degradation has been a major global issue during the twentieth century and still remains high on the international agenda in the twenty-first century. The threat of food insecurity and deterioration of environmental quality have kept alive the issue of land degradation in the present century. Land degradation can be considered in terms of the loss of actual or potential productivity or utility of the land; it is the decline in land quality or reduction in its productivity (Eswaran et al. 2001). When the productivity does not match with land quality, the issue of land degradation arises. Principal processes of land degradation include erosion by water and wind, physical deterioration and chemical degradation (Adhikary et al. 2018). Important among physical processes are a decline in soil structure leading to crusting,

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compaction, erosion, desertification, environmental pollution and unsustainable use of natural resources (Singh et al. 2004). The chemical processes responsible for land degradation are acidification and alkalization, salinization, nutrient leaching, decrease in action retention capacity and fertility depletion. The statistics of variously degraded lands in the world are given in Fig. 1.1.

Among the different degraded lands, gullied and ravine lands are very important and remained a highly researchable topic. Gully erosion has been described in a large variety of landscapes throughout the world. In simple terms, gullies may be described as continuous depression on the sloping land surface as a result of soil displacement caused by overland water flow and aided by gravity force. They may extend in length from a few meters at the initiation stage and up to hundreds of meters if the erosion is not checked (Kumar et al. 2018). The commonly accepted definition of gullies is that they are larger than rills, which cannot be ploughed or easily crossed but smaller than streams, creeks or river channels. The most commonly described gullies are the ‘hillslope gullies’, which are present in the upland portions of catchments. Gully erosion and the associated soil loss have caused major environmental disasters worldwide. Many urban and rural communities have been severely affected, while the sustainability of the total landscape has been threatened. Human and animal population, physical infrastructure, agricultural lands and socio-economic system of the land/areas are adversely exposed to multifaceted hazards. In many developing countries, several villages and communities have been displaced and virtually disappeared as a result of the scourges of gully erosion. Gully erosion, which generally starts after sheet erosion if remained unchecked for some time, can render large areas useless. Ravines are a result of formation of the gullies within unconsolidated, relatively loosely bound material such as soft sediments, which can make the land totally unproductive and ruin the livelihood of the people residing nearby (Chaturvedi et al. 2014).

Gullied and ravine lands are the most degraded and vulnerable eco-system which pose a threat to the livelihood of the peoples residing along with those. Apart from the deterioration of the physical, chemical and biological quality of the lands, gullied lands are the hot spot of the major soil erosion as huge amount of soils are being eroded from these lands, which increases the risk of flooding and sedimentation (Kumar et al. 2018). The subsistence farming practised by the resource-poor farmers in the gullied and ravine lands also contributed to the progressive degradation of this fragile eco-system. Erratic and short-duration high-intense rainfall, loosely bound deep alluvial soils, undulating landscape, faulty agricultural practice, illegal cutting of trees and bushes and overgrazing are some of the factors responsible for the formation of gully and ravine land (Rao et al. 2015).

With increased pressure on the land, attention has been shifted on the so far neglected lands like gullied and ravine lands. Being at very low production baseline, these extremely degraded lands offer an opportunity to improve farmer’s income and livelihood. Ravine is an extreme form of land degradation developed through soil erosion. Most of the Indian workers believe it as work of concentrated flow of runoff which is accelerated by improper land management and poorly consolidated earth materials. There are several hypotheses for ravine formation including neo-tectonic upliftment and intensification of rainfall. With new information and shreds of evidence available, these hypotheses were revisited. The ravine land is not only problematic at the place

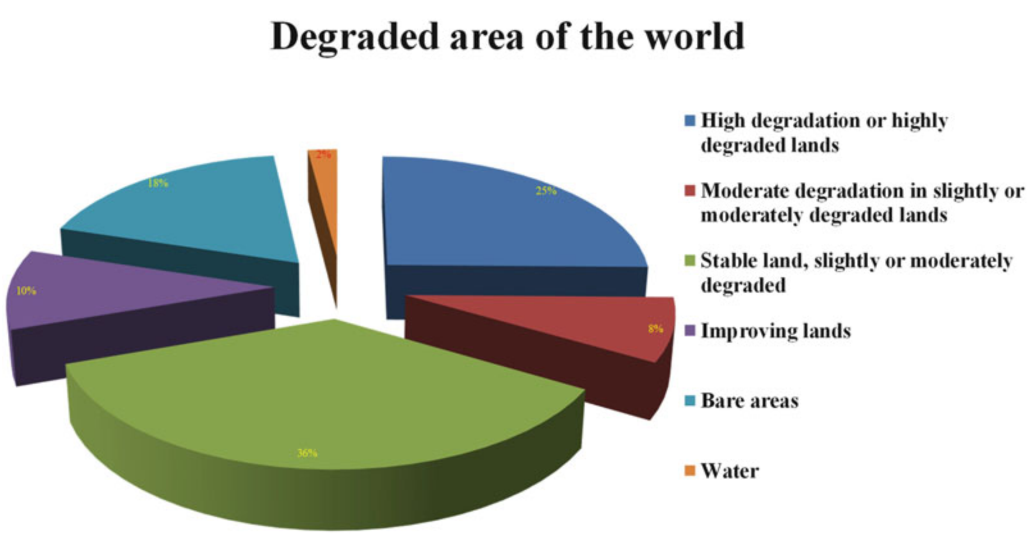

Fig. 1.1 Extent of land degradation in the world (Source: http://www.fao.org/fileadmin/templates/solaw/files/thematic_reports/SOLAW_thematic_report_3_land_degradation.pdf)

of existence but also poses a continuous threat to adjoining tableland. Proper assessment of ravine problem is essential for developing management plan. Therefore, in this article, an attempt has been made to assess the spatial extent of gullied and ravine lands in India. Their formation processes were discussed and reclaimability classification systems were also analysed. As these lands are very potential but are hidden, the various possibilities to restore the gullied and ravenous lands to their ultimate potential were also discussed.

1.2 Spatial Extent of Gully and Ravines in India

India accounts for a meagre 2.4% of the world surface area of 135.79 million km^2, covering 3,287,263 km^2, extending from the snow-covered Himalayan heights in the North to the tropical rain forests of the South. Extensive land degradation in the form of deep gullies has occurred along some of the major river systems of the country in various states. The largest is the Yamuna–Chambal ravine zone. The Chambal ravines flank the River Chambal in a 10-km-wide belt, which extends southwards from the Yamuna confluence to 480 km up to the town of Kota in Rajasthan. Ravines also affect basins of several Chambal tributaries, for example Mej, Morel, Kalisindh, etc. In Gujarat, ravine belt is spread over the southern bank of the Tapti, banks of the Narmada, Watrak, Sabarmati and Mahi basins. Besides these river basins, ravines are also found in Jharkhand (Chhota Nagpur), Bihar and Mahanadi and upper Sone Valley (Fig. 1.2).

The first authentic and reliable assessment of ravine lands in India was published by National Commission on Agriculture (NCA 1976) in which 3.67 million ha of ravine has been reported in India. The states of Uttar Pradesh, Madhya Pradesh, Rajasthan and Gujarat were reported to be the major ravine states, comprising about 75% (2.76 million ha) of the total ravine area of the country. NCA estimate was not on the basis of systematic ground survey and hence the committee suggested further survey and mapping using aerial photographs. Subsequent periodical assessments by National Remote Sensing Centre (NRSC) in 2000, 2003, 2005 and 2008–2009 have shown a sharp reduction in the ravine area of the country. In the backdrop of renewed public interest for reclaiming ravine lands and lack of availability of realistic estimate for the extent of the problem, the Indian Council of Agricultural Research–Indian Institute of Soil and Water Conservation (ICAR-IISWC) regional centres at Kota (Rajasthan) and Vasad (Gujarat) initiated a ravine area delineation project in 2014 with visual delineation approach using high-resolution LISS-IV and Google Earth imageries. Total ravine area delineated in four states of Uttar Pradesh, Madhya Pradesh, Rajasthan and Gujarat is 1.036 million ha. Figure 1.3 shows the spatial extent of the ravine and gullied lands of four states of India, that is Gujarat, Rajasthan, Uttar Pradesh and Madhya Pradesh. The current ravine area assessment indicated about 60% reduction in the total ravine area since 1976 in the four major ravine states. Table 1.1 compares the spatial extent of gullied and ravine lands estimated by different agencies.

Development and dissemination of technologies for reclamation and productive utilization of ravine lands through field demonstration and capacity-building programmes conducted by ICAR-IISWC regional centres located at Kota (Rajasthan), Vasad (Gujarat) and Agra (Uttar Pradesh) has helped reclamation of about 1.7 million ha of ravine land in four major ravine states of UP, MP, Rajasthan and Gujarat as indicated by nearly 62.5% reduction in ravine land since 1976 in a recent estimate by ICAR-IISWC (Kumar et al. 2018). This reclamation largely comprises shallow ravines that too not to the level of potential production. As per remote sensing-based estimate by ICAR-IISWC, un-reclaimed ravine (rugged land only) spread in the states of Uttar Pradesh, Rajasthan, Gujarat and Madhya Pradesh was 1.036 million ha. The treatable area including peripheral land is likely to be as high as 1.5 times the actual ravine. The ravine reclamation packages developed and recommended by the ICAR-IISWC can transform these wastelands into productive land by encouraging sediment entrapment and water harvesting.

Despite extreme form of degradation, these lands offer potential for productive utilization and economic upliftment of the ravine dwellers. The production potential estimated of ravine areas in Uttar Pradesh, Madhya Pradesh and Rajasthan was estimated long back (1960s) to be 3 million tonnes of food grains annually. With the advent of new tools, cultivation practices and technologies generated for reclamation and productive utilization, this figure can conveniently be proportionately higher per unit land. In addition, fruits, fodder, fuel, timber and raw material for industrial can be produced. By not reclaiming these ravines, the revenue loss was estimated by Planning Commission to be about Rs. 157 crores a year. The reclamation strategy for a ravine land largely depends on degree of terrain deformation, soil quality, accessibility to water and other resources. The target of ravine reclamation is to arrest degradation process, promote ecological restoration, positive on-site and off-site hydrological influences and to establish socio-economic balance with a defined benefit-sharing mechanism.

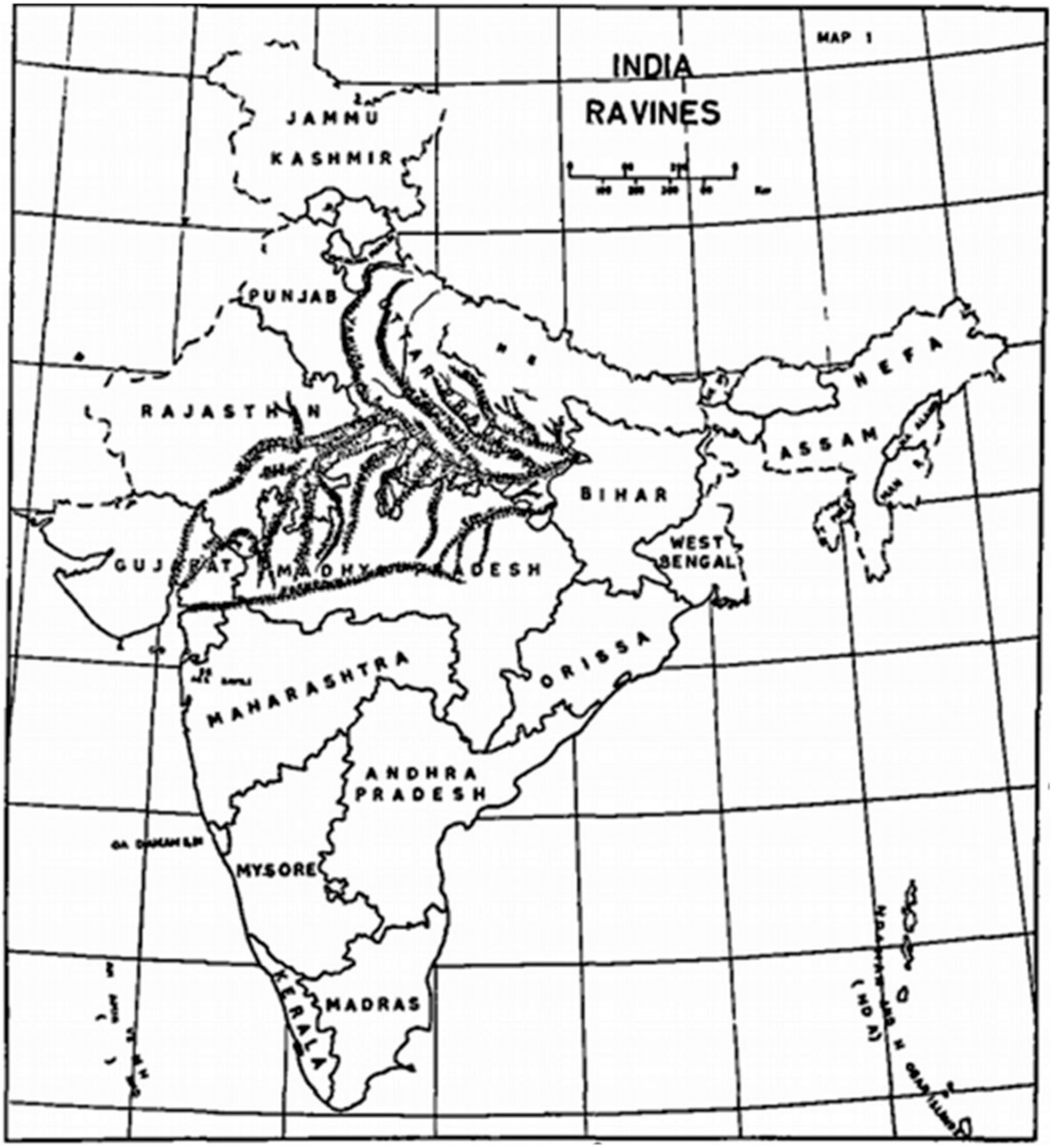

Fig. 1.2 Geographical position of major gullied and ravine lands in India (Source: Sharma 1980)

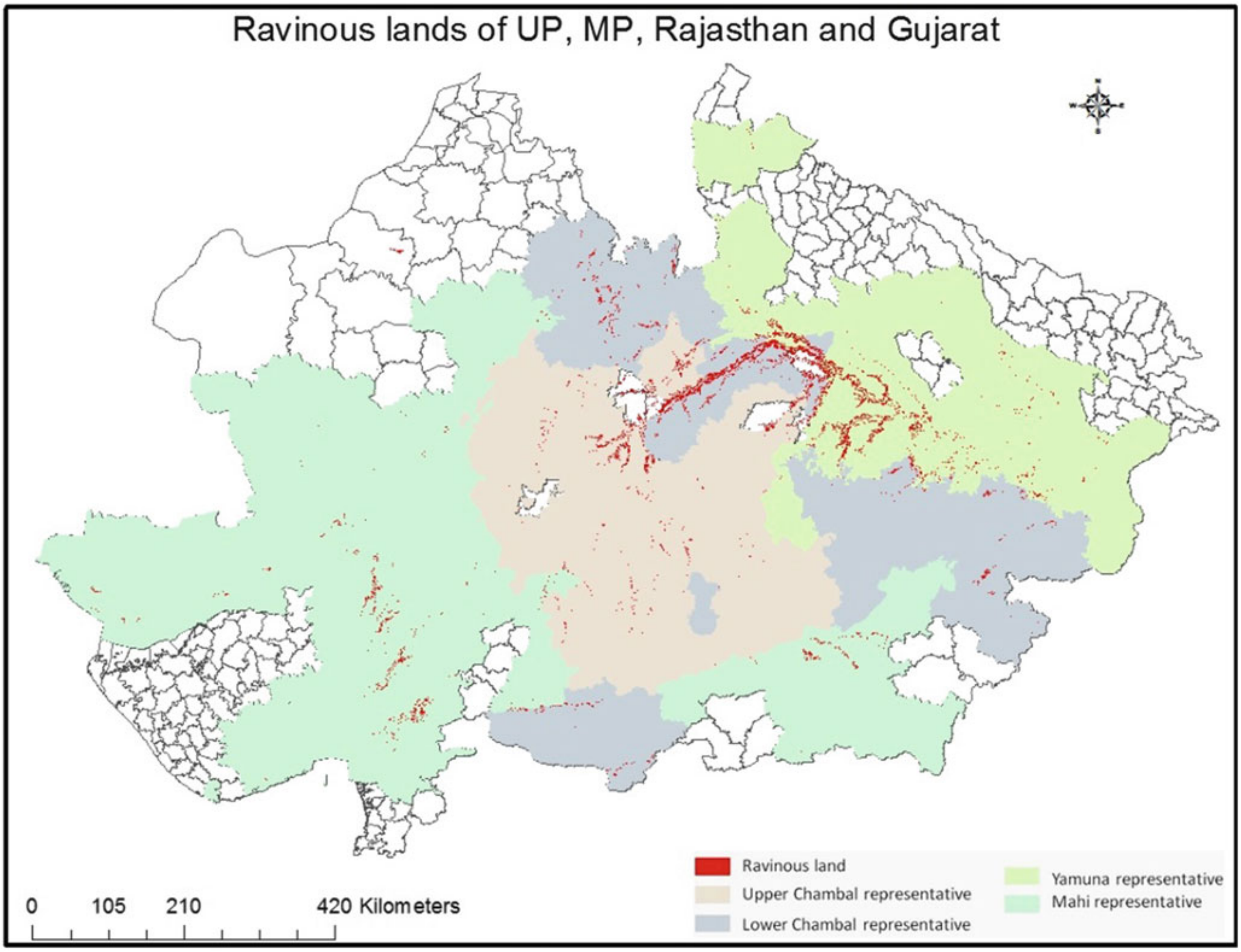

Fig. 1.3 Spatial distribution of gullied ravinous lands of Uttar Pradesh, Madhya Pradesh, Rajasthan and Gujarat (Source: Kumar et al. 2018)

Table 1.1 Estimate of spatial extent of ravine area (lakh hectare) in different states of India by different sources

S. no.	State	NCA (1976)	Chaturvedi et al. (2014)	NRSC (2000)	NRSC (2008)	Kumar et al. (2018)
1	Uttar Pradesh	12.30	12.30	3.25	1.199	3.40
2	Madhya Pradesh[a]	6.83	6.83	5.274	1.453	3.12
3	Rajasthan	4.52	4.52	6.6	1.525	2.74
4	Gujarat	4.00	4.00	0.39	0.339	1.101
5	Maharashtra	0.20	0.20			
6	Punjab	1.20	1.20			
7	Bihar[b]	6.00	6.00			
8	Tamil Nadu	0.60	0.60			
9	West Bengal	1.04	1.04			
	Odisha	–	0.11			
	Others	–	0.19			
Total		36.69	39.8			

[a]Area included: Chhattisgarh
[b]Area included: Jharkhand

1.3 Gully and Ravine Formation Process and Hypothesis

1.3.1 Gully and Ravine Formation Process

Soil material displacement by water initially results in loss of top-soil, but if left unattended may lead to terrain deformation through splash, sheet and rill erosion. Gully erosion is an advanced stage of rill erosion where rills get widened and deepened enough that it cannot be obliterated by normal tillage operations. In the initial active phase, gully erosion may surpass rill and sheet erosion; however, with time, it gets stabilized and causes less erosion than sheet or rill erosion. Gullies occur when runoff flows over land concentrate and cut a channel through the soil. Continuous undercut and resulting collapsing of gully head triggers the upslope extension of most of the gullies but sidewalls slumping and collapsing contribute the higher proportion of soil loss. Gully may start from any depression such as cart tracks and cattle trails if neglected for long. The soil instability at gully banks leads to sloughing and cave in the bank slope. Most of the Indian workers considered the gully erosion, as described above, responsible for ravine formation. Also land-use-induced concentrated runoff (Gupta 1973; Ali 1974; Gupta and Prajapati 1983), poor management of runoff (Prajapati et al. 1982), poor land management, or high-intensity rainfall (Babu et al. 1978) were considered responsible. However, some geologists (Sharma 1968, 1976; Ahmed 1973) put alternate explanation and additional geological factor, including tectonic uplift. With varied perception, an attempt is made to discuss gully under two categories.

Category I: Gully which is formed by concentrated flow through several stages of erosion and is an advance phase of rill erosion. This type of gully is observed in moderate-to-high land slope area, including hills. The rate of gully extension primarily depends on runoff producing characteristics of catchment including alignment, size and shape of the gully, soil characteristic, bank and bed slopes.

Category II: Gully which is formed by progressing slope failure or other mechanism but not essentially by concentrated flow and cannot be considered as an advanced stage of sheet or rill erosion as there may not be an appreciable volume of runoff reaching the gully. Gullies of ravine systems in alluvial soils along Chambal, Yamuna, Mahi, Sabarmati and other rivers are in this category. These gullies are developed on land with gentle slope but high elevation difference (almost vertical drops along the riverbank) between ground level (higher) and main drainage system (riverbed).

Land with loose structured soil, no or poor vegetation and poor soil organic matter ends up to a gully easily when runoff is concentrated (Table 1.2). Rarely any distinction was made in these gullies despite different mechanisms operating. Most often, Category I has been focused on and reported.

1.3.2 Hypothesis of Gully and Ravine Formation

1.3.2.1 Climate and Land-Use Theory

It is difficult to ascertain when the land deterioration started but most popular hypothesis put by Indian workers including hydrologists considers indiscriminate use of land as the main reason. High-intensity rainfall, loose and friable soil devoid of organic carbon and vegetation, erratic, faulty agricultural practices, removal of vegetation, overgrazing of lands and other biotic interference might have aggravated the situation, and continue to be the main factor of gully and ravine extension.

1.3.2.2 Tectonic Upliftment Theory

Another explanation for ravine formation comes from the hypothesis of upliftment of central highlands, Aravalli range, Bundelkhand and Chhota Nagpur plateau against lowering of Himalayan base, thus lowering base level of rivers (Ahmed 1973; Sharma 1976). Steepening of stream gradient due to tectonic wrap, deep incision led to high elevation difference between riverbed and adjoining tableland, which might be the reason for regressive slope failure and ravine formation. River backflow during flood also adds up to wide extent erosion by wet slip and removal of eroded materials. Uniform skyline of Aravalli ranges and presence of hard formations like quartz conglomerate on hill slopes and phyllites and schist forming the lowlands in Chambal–Yamuna ravine area are some of the supporting shreds of evidence to upliftment theory.

1.3.2.3 Aggradation and Degradation Theory

Intensification of monsoon rain in the past is also believed as the reason for ravine formation. The polycyclic nature of river floodplain in which floodplains go through aggradational and degradational phases associated with the change in monsoon intensity and ravine is the symptom of degradational phases has been hypothesized (Gibling et al. 2005). The Chambal ravine is considered a late Pleistocene–Holocene degradational landscape. In the aggradational phase, the large amount of sediment gets deposited by the river in the flood plain. This periodic deposition aggrades the floodplain. However, this condition changes, as during longer

Table 1.2 Distinction between two categories of gullies

Category I (high slope area)	Category II (flat alluvium)
Gully joins higher order, almost perpendicularly	Gully joins higher order from multiple directions
No or less crisscrossing or networking.	Networks of gullies are main features
Runoff is main cutting agent	Role of runoff is more in removing eroded materials instead of active cutting
Human factors including land-use changes and runoff mismanagement are important	Natural factors dominate; however, human activities can accelerate the process
Tunnelling/piping is less observed as mechanism for head extension	Tunnelling/piping is frequently associated to head extension and also along bank slope
Factors affecting: • Improper land use, forest cutting, shifting cultivation, hill cutting for road and rail construction, livestock and vehicle trails, nature of soils • Rainfall intensity is more important than durations • Catchment characteristics: Topography, slope, shape and size of catchment have influence on runoff rate and quantity which ultimately effect gully erosion • Runoff management including diversion and safe disposal through spillways are important	Factors affecting: • Elevation difference with very steep slope, left unattended without conservation measures Unconsolidated soil with poor cementing materials or very fine materials (black soils), lack of vegetation • Rainfall: High duration (wet period) is relatively more important than high intensity • Catchment is usually small, and thus catchment characteristics are not a prime factor • Slope stabilization is more important; however, at sites of substantial runoff, spillways are required
Generally observed in high annual rainfall usually more than 1000 mm	Generally observed in poor-to-moderate annual rainfall (300–1200 mm)
Have deeper channels down slope until the point where deposition or local base level limits extent	No such clear distinction, but ravines are generally deeper close to stream
Loose geological material, poor vegetation, poor soil organic matter and lack of conservation measures are common to both the categories	

wet periods and increased rain intensity, river discharge increases and sediments are not deposited locally, but are carried out of the system to the sea. The rivers cut its own deposits and the channels become deep and remain detached from its floodplain. In this situation, the flood plain not only gets starved of sediment, but the elevation difference created between tableland and riverbed due to deep incision leaves the area vulnerable to wet as well as dry slips and slope failure. In this phase, the floodplain degrades due to bank erosion along the main channel which ingresses gradually or sometimes abruptly into tableland; once inside the tableland, this slope failure moves in multiple directions creating a network of the gully which forms ravine. The runoff generated over adjoining tableland (which depends on runoff-generating properties of catchment) catchment of gully also aggravates the degradation process. Loose and friable soil type, poor organic carbon content, poor vegetation and biotic interference add to the pace of gully head extension.

1.3.2.4 Oceanic Upwelling Theory

Based on the sedimentological and stratigraphic analysis of facies and dating of sediment, it is also suggested that ravine formation coincided with the intensification of the south-west Indian monsoon at the end of the last glacial maximum around 15,000 years ago (Gibling et al. 2005). This degradation process probably got amplified in recent past due to intense human interference including, removal of vegetation and improper land use and management.

The older sediment exposed under the incised main channel of the river and the ravines leds to the evidence of earlier degradational and aggradational episodes coincide with fluctuations in monsoon intensity. The coeval Arabian Sea cores containing variations in pollen abundance which records variation in terrestrial vegetation and planktonic foraminiferal abundance also indicate oceanic upwellings related to monsoonal circulation.

Ahmed (1973) opined that though the gully erosion and ravine formation are not prominently related to sea-level regression, tectonic upliftment during early Holocene may be responsible for quick ravine formation that almost ceased during middle Holocene mainly because of sea-level rise that resulted in the second terrace along riverbank (up to 6 m deep). The marine deposition confined near the riverbank and within old cliffs may be considered supporting evidence. Incision of the lower terrace can be attributed to the phase of tectonic upliftment that probably continues even today. Ravine erosion perhaps extended to the older marine terrace (second surface).

1.3.2.5 Concave Riverbank Elevation Theory

Western theory relates gully and ravine formation with climate, mainly rainfall intensification, which may be valid for gully in high-slope hills (Category I) but found very little logic in alluvial ravine of India, as high concentration of ravine is found in poor rainfall (500–600 mm annual rainfall) areas. Indian soil conservation workers have preferred explanations couched in land-use terms along with high

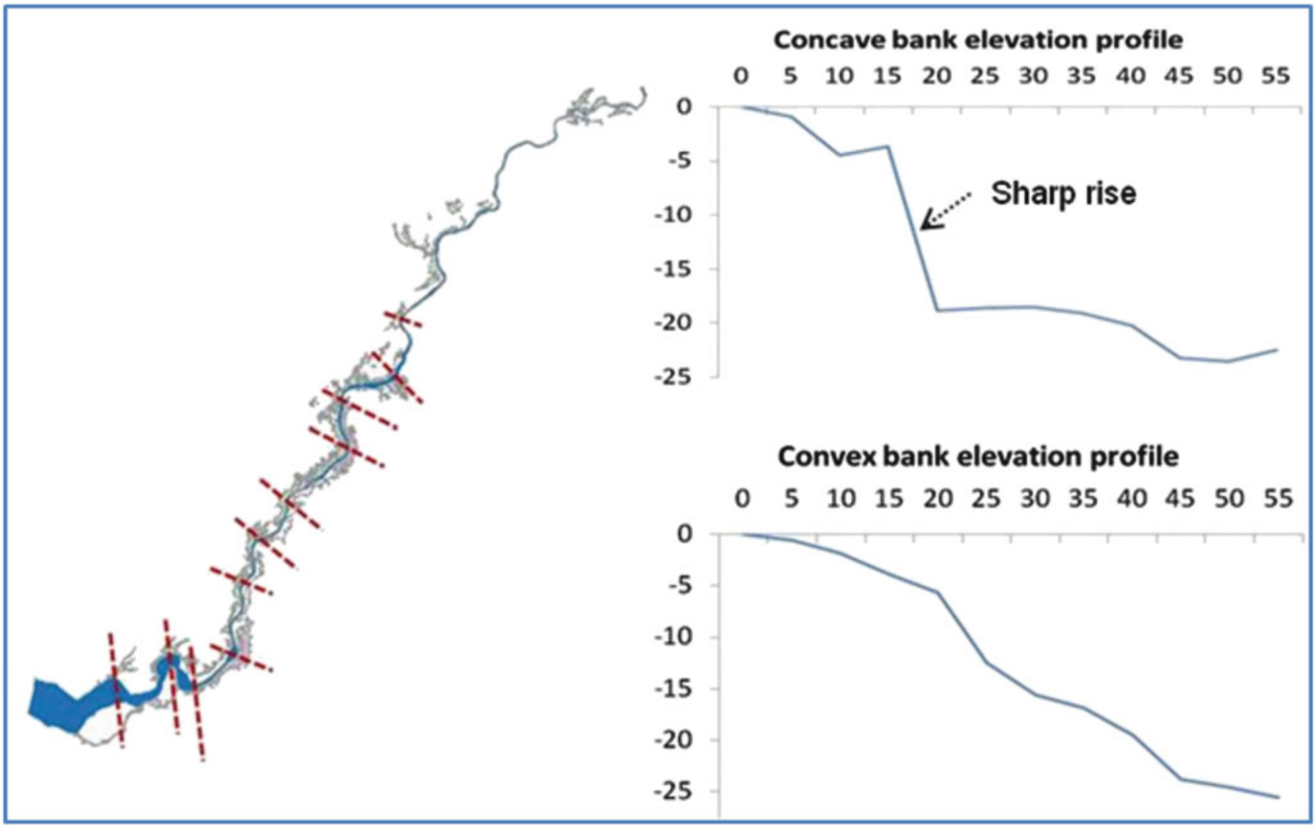

Fig. 1.4 Association of concave bank with ravine formation and elevation profile and concave and convex bank of Mahi ravine

intensity and concentration of rainfall during monsoon. High erodibility of the deep, alluvial soil was also pointed as responsible for ravine formation. Forest thinning and indiscriminate use that led to disturbed hydrological balance have been the other reasons found in Indian studies.

In many of the hypothesis, it is common that sharp elevation change, probably far more than the angle of internal friction, is responsible for ravine formation. Placement of most of the ravine along the concave bank where the sharp slope is seen indicates that damage would have started from riverbank at many places preferably from the concave bank where stream bank erosion is prominent (Kumar et al. 2018). About 83% of ravine patches about River Mahi was found associated with the concave bank. Elevation profile of this concave bank reveals a sharp elevation rise along the bank (Fig. 1.4). Slope failure under wet as well as dry conditions and removal of fallen loose materials during the wet season either by runoff or by rainfall seem to be the most plausible consideration for headward progress of instability. Multiple factors can be attached to landward extension of the gully. When slope/bank instability coincided with the drainage line, ravine ingression would have progressed very fast. Unlike gullies in high-slope area which is an advanced form of rill erosion and initiates over the land, these gullies have probably started from the riverbank. Headward progress is common to both categories of the ravine. Once inside the land, instability propagates in different direction resulting in new branches that often crisscross each other and form a network of the gully. Concave bank stream is always at the risk of gully initiation and subsequent ravine formation.

1.3.3 Other Mechanisms of Gully Head Extension

Discontinuous gullies which are features of ravine begin as an abrupt head cut, as usually associated with the concentration of flow in soil pipes. Gully extension also takes place by means of tension cracks and tunnelling.

1.3.3.1 Tension Cracks

Tensional cracks decrease the stability of the gully head and gully wall by reducing cohesion. Tension cracks developed around 20–60 cm upslope from the gully head under the combined influence of desiccation and tension stress, which is often observed in lateritic soils of eastern India. The pore water pressure increases multifold when these cracks get filled with runoff water, which results in failure or toppling (Collison 2001; Bull and Kirkby 2002). The presence of tension cracks, therefore, indicates that gully is active.

Tension cracks development is also influenced by the undercutting of gully walls and gully heads.

1.3.3.2 Tunnelling

Tunnelling is an important mechanism for headword and lateral gully expansion. Tunnelling is more frequently observed in dispersible soils. It is also observed in black soils where enlarged cracks develop into tunnels which carry a suspension of soil and water. Tunnel collapse causes a rapid extension of the gully (Fig. 1.5). Tunnel usually develops below the course of surface flow. In dispersible or loose soil materials, it may develop below flatter runoff course or on a gentle slope as it provides greater opportunities for infiltration and subsurface flow. Grain size distribution plays a very important role in tunnelling. Failure of burrow pits created by animals also promotes tunnelling and gully extension.

1.3.3.3 Suffusion/Internal Erosion/Internal Instability

Fine grains and soluble materials can pass through coarse soil matrix due to seepage flow. This process is called suffusion or, internal erosion or, internal instability. When surface water moves into the soil along cracks or channels or through burrows pits, the cavity of tree roots or through natural pore system and moves along the subsurface, it carries finer materials. Dispersive clays are the first to be removed. With enlargement, more water enters and erodes the soil. Sinkholes are formed due to the partial collapse of the tunnel roof. Water seepage at foot of a slope and fine sediment fans at outlet of tunnels are the indication of the tunnelling. Tunnelling is mainly observed in non-cohesive and dispersive soils in which fine particles are in abundance. The geometric criterion is though considered to avoid suffusion in embankment and bunds, and the same holds good regarding tunnelling. Kenney and Lau (1985) proposed *F*–*H* diagram by transforming the ordinary grain size distribution curve. *F* is the mass percentage of grains with diameters less than a particular grain diameter *d* and *H* is the mass percentage of grains with diameters between *d* and 4*d*. For poorly graded soils $H/F \geq 1.0$ for $F \leq 0.3$ and for well-graded soils $H/F \geq 1.0$ for $F \leq 0.2$ are considered stable (Kenney and Lau 1986). Kezdi (1979) proposed splitting up the grain size distribution of a soil into two distributions of the fine and coarse parts, and assessing the stability by Terzaghi's well-known filter criterion applied to the two distributions: $d_{c,15} \leq 4\ d_{85,f}$ with $d_{c,15}$ = grain diameter for which 15% of the grains by weight of the coarse soil are smaller and $d_{85,f}$ = grain diameter for which 85% of the grains by weight of the fine soil are smaller. Recent earth fill over compact materials is prone to quick tunnelling and collapse.

In some places, tunnels are visible and may be of 10–50 cm equivalent diameter before it collapses, but often may not be visible until collapse because as a result of suffusion, it is made up of many micro tunnels with the intact matrix. The non-visible suffusion and collapse are mainly observed in the coarse and relatively graded materials. For

Fig. 1.5 Tunnelling as observed on adjacent tableland near ravine and on bank slope

poorly graded (in terms of particle size) soil, suffusion is not an issue; however, hydraulic failure may occur under upward seepage flow. In fine-textured soil, widening of cracks may serve as a channel.

1.4 Gully Reclaimability Classification System

Realizing the potential of gully and ravine reclamation and use for the productive purpose to address the socio-economic and environmental concern, the Government of India took several initiatives in these parts. This includes the setting of the ravine research centres at Vasad (Gujarat), Kota (Rajasthan) and Agra (Uttar Pradesh) and during the 1950s, establishing the Ravine Reclamation Board and National Ravine Reclamation Policy during 1967–1970, and launching of several centrally and externally funded ravine reclamation programmes during 1970–1995. Development and dissemination of technologies for reclamation and productive utilization of ravine lands through field demonstration and capacity-building programmes conducted by ICAR-IISWC regional centres located at Kota (Rajasthan), Vasad (Gujarat) and Agra (Uttar Pradesh) has helped reclamation of about 1.7 million ha of ravine land in four major ravine states of UP, MP, Rajasthan and Gujarat as indicated by nearly 62.5% reduction in ravine land since 1976 in a recent estimate by Kumar et al. (2018). In a recent remote sensing-based survey, ravine area (rugged land) in Gujarat, Rajasthan, Madhya Pradesh and Uttar Pradesh has been estimated to be 1.036 million ha. The treatable area including peripheral land is likely to be as high as 1.5 times the actual ravine. The ravine reclamation packages developed and recommended by the ICAR-IISWC can transform these wastelands into productive land by encouraging sediment entrapment and water harvesting.

Extensive areas under medium-deep and deep ravines continue to remain unattended despite exorbitantly escalated land value and available economically viable and ecologically sustainable ravine reclamation technology developed and demonstrated by ICAR-IISWC over a period of about 60 years. Understanding the problem is prerequisite for selecting proper invention and approach. As alluvial ravines are made of network of gullies, the treatment plan is generally gully centric. Several gully classifications have been used in the past.

As per the gully classification scheme developed at ICAR-IISWC, classes 1–6 lands indicate progressively increased terrain deformation with corresponding increase in erosion hazards and land-use restrictions. The target of ravine reclamation is to arrest the degradation process, promote ecological restoration, positive on-site and off-site hydrological influences and to establish socio-economic balance with a defined benefit-sharing mechanism.

Ravine restoration starts with protection of peripheral land of ravine. Safe disposal of runoff from marginal/peripheral land by means of peripheral bund and spillways is crucial to check gully head extension into marginal land. Contour bund and field bunds in adjoining arable land for in situ water harvesting also help reduce runoff load, and thus help to protect gully extension. Land levelling and periodic slope smoothening promote in situ soil and water conservation, ease of cultivation operation, higher water and nutrient-use efficiency. Contour tillage, deep summer ploughing, vegetative barriers, intercropping, mulching, etc. are helpful to promote in situ water conservation.

For narrow ravine systems with depth up to 3 m deep, land shaping, levelling and bench terracing along with riser stabilization are important measures for reclamation and productive utilization. Marginal bund of 1.5 m^2 cross section (bottom width, 2.5 m; top width, 0.5 m; height 1.0 m) with 0.1–0.2% grades is recommended; lesser section (0.6 m^2) may be used towards ridge. For ravine with gullies deeper than 3 m, it is difficult to reclaim through levelling. Reclamation process for deeper gully involves stabilization of gully heads, gully bed and side slopes, establishment of protective vegetation with economic importance and encouraging socio-ecological harmony for sustenance of protective measures.

A comprehensive gully classification scheme evolved at ICAR-IISWC (Table 1.3) classifies the gully network into size categories based on gully dimensions, soil characteristics, water availability and climate (Kumar et al. 2018). With progressively increased terrain deformation from class 1 to class 6, there is a corresponding increase in erosion hazards and land-use restrictions.

Marginal lands at the periphery of ravine system with occasional presence of shallow gullies are classified as Gully Reclaimability Class I (GRC-I). These lands require minor levelling work on gently sloping sides and bed for reclamation. Favourable soil texture and deep soil depth facilitate cultivation of most crops possible and also alleviate levelling and maintenance cost of these lands. Narrower and deeper gullies make the reclamation process expensive and challenging. Accordingly, land-use restrictions are imposed as land degrades from GRC-I to GRC-VI. Generally, GRC-I to -IV are recommended for cultivation with increased level of management and restriction. GRC-V has similar topographic feature as of GRC-I to -IV, but this cannot be reclaimed for agriculture or horticulture as the gully is prone to seasonal backflows from a nearby river or it has developed water logging, salinity due to irrigation or any other adverse factor like arid climate. Such lands may be put under perennial vegetation like suitable fuel and fodder