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Gullies and badlands of India: Genesis, geomorphology and land management

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Abstract

Gully erosion is a formidable land degradation process globally. It is omnipresent across India, wherein two of the largest badlands regions in the world also exist. However, despite being affected by widespread gullying, gully erosion research in India has been rather limited, with key aspects of gully formation, morphologies and dynamics remaining unknown. Through this comprehensive systematic review, we synthesise previous studies on gully erosion in India and in turn highlight pivotal knowledge gaps. The review starts with a discussion of the causal factors of gullying in India, which underlines how gully initiation in several regions was an aftermath of deforestation and overgrazing. Contrastingly, the badlands of Central and Western India have mainly developed in response to natural triggers like neotectonics and Holocene climate change. The section on mapping highlights how mapping methodologies have not only been dictated by the availability of imagery and/or means of data processing, but also the mapping purpose—that is, individual gully channels or entire badlands. Although a few studies applying concepts of fractal geometry to characterise badlands' geomorphology are innovative and unique, the most striking research gaps we have identified also pertain to understanding and quantification of gully geomorphology and erosion dynamics in different regions of India. Our review reveals that gullies of peninsular India have been the least studied, followed by those of the Himalayan and Sub-Himalayan region. Although the literature provides interesting examples of linkages between badlands development and the wider geomorphic evolution of the landscape, better chronological understanding is required to disentangle the relative importance of natural and anthropogenic drivers of landscape change in India's badlands. Large-scale mapping of gully characteristics, quantification of gully morphologies, gully erosion rates and its share in catchment sediment budget across various physiographic regions or river basins of the country also constitute important areas for future research.

KEYWORDS
Badlands, Gully dynamics, Gully erosion, Gully formation, Gully morphology, India

1 | INTRODUCTION

Gullies are products of deeply channelised soil erosion that have been studied for over a century (Castillo & Gómez, 2016). Termed differently in different parts of the world (Castillo & Gómez, 2016; Thwaites et al., 2022; Wells, 2004), gullies have been classified with respect to their landscape position (i.e., valley-bottom, valley-side and bank gullies) (Begin & Schumm, 1979; Morgan & Mngomezulu, 2003; Poesen et al., 2002) and their permanence (i.e., ephemeral and permanent gullies) (Castillo & Gómez, 2016; Poesen et al., 2003). Recently, however, a generic gully classification system has been proposed that considers landscape surroundings, local soil characteristics, hydrology

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and erosion processes, modes of formation and morphology (cf. Thwaites et al., 2022).

Incipient gullying is always associated with landscape instability and resultant exceedance of a geomorphic threshold (Begin & Schumm, 1979; Patton & Schumm, 1975), the most important factors dictating which are runoff, soil properties, topography and land cover/use (Poesen et al., 2003; Valentin et al., 2005; Wells, 2004). Conceivably, these factors vary widely across geographic regions and interact with each other in many different ways, making gully initiation a very complex phenomenon that is notoriously difficult to understand and predict (Wells, 2004). Once formed, gullies are extremely troublesome to mitigate and, as such, preventing gully initiation is easier (Kirkby & Bracken, 2009; Wells, 2004).

Gullies are ubiquitous in India (Figure 1). A first estimate on the spatial extents of gullies in the country was provided by the Planning Commission as part of the Third Five-Year Plan in 1961, when 41,900 km^2 of Indian lands were gullied (Ahmad, 1973, p. 82). Fifteen years later, in 1976, the National Commission of Agriculture estimated that gullies and ravines covered 36,700 km^2, which was ~1% of the country's total geographical area (Haigh, 1984). As per the latest land degradation assessment (2015–16), gullies and/or ravines are found in 23 states and the national capital territory of Delhi, with the areal extent being just over 25,000 km^2 (NRSC, 2019). The earlier figures of gully erosion extents in India as reported by the concerned government agencies were based on broad observations and not ground surveys (Deshmukh et al., 2011; Kumar, Adhikary, & Dash, 2020). As such, the reduction in gullied area over the last 60 years could also be due to the precise measurements obtained nowadays through remote sensing, besides actual land reclamation (cf. Kumar, Adhikary, & Dash, 2020; Marzolff & Pani, 2018; Ranga et al., 2016).

It is worth noting that the term 'ravine', which is the French synonym of the English word 'gully', is used in India to refer to landscapes with an intricate network of gullies (Haigh, 1984; Kumar, Adhikary, & Dash, 2020; Sharma, 1980). Such landscapes characterised by an extremely high drainage density are commonly denoted as 'badlands' (Bryan & Yair, 1982; Harvey, 2004; Howard, 1994; Schumm, 1956), and 'ravine' is a term that is normally used to refer to river gorges (Tinkler, 2004). In fact, some Indian regional geography books (e.g., Singh, 1971; Spate & Learmonth, 1967) use the term 'ravine' to refer to gullies, badlands and river gorges interchangeably. As this

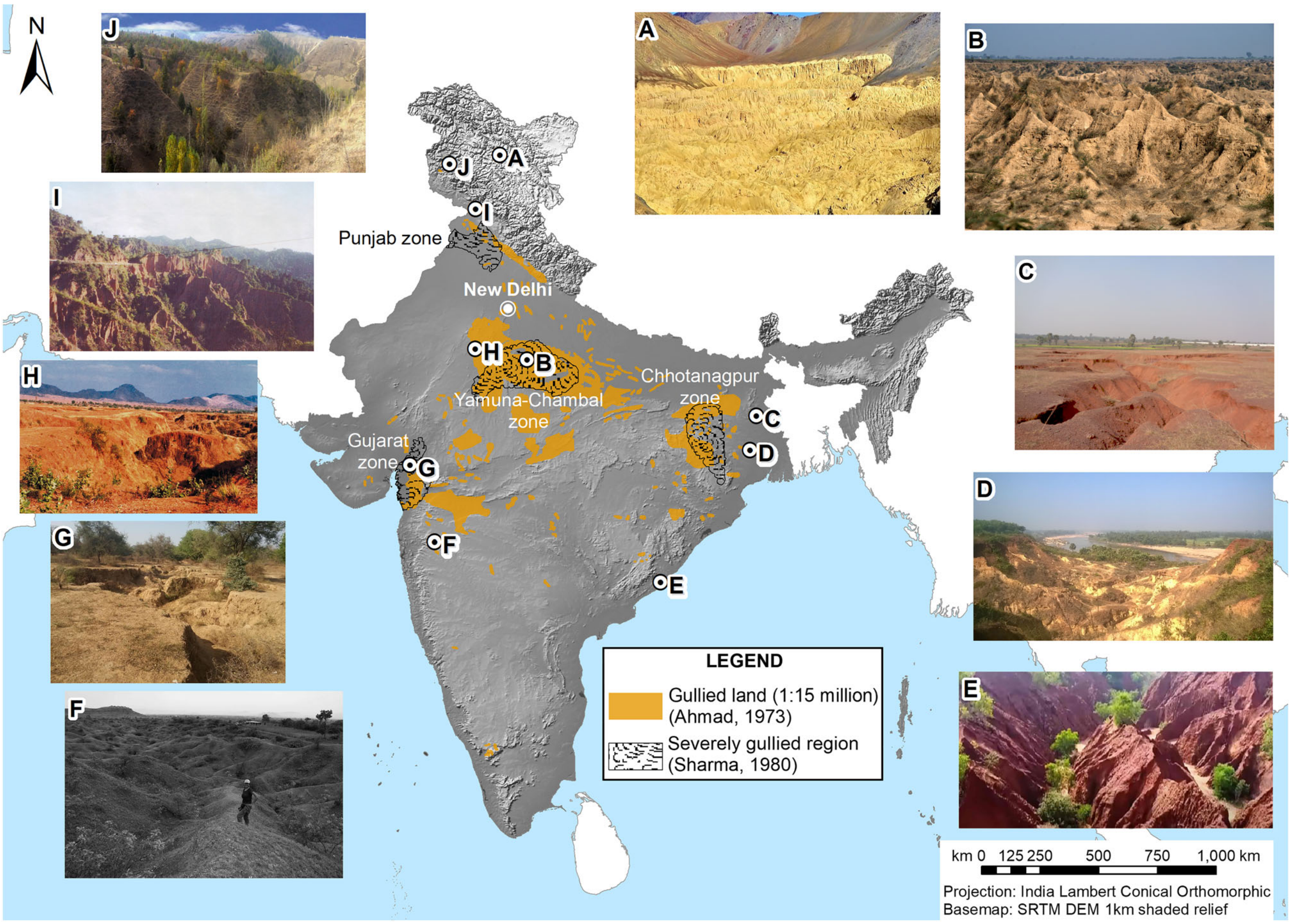


FIGURE 1 Spatial extent of gully erosion in India as mapped by Ahmad (1973) and zones of severe gully erosion as delineated by Sharma et al. (1980). The latter author pointed out that the most severe gully erosion occurs in the Yamuna–Chambal zone, followed by the Gujarat, Chhotanagpur and Punjab zones. Gully erosion occurs in a wide range of substrates in India, including, but not limited to, (A) lacustrine sediments (Lamayuru Moonland) ©P. Seth (Flickr); (B) alluvium (Chambal badlands) ©V. Hegde (Flickr); (C) primary laterites (Dwarka-Brahmani interfluve) ©A. Majhi; (D) secondary laterites (*Ganganir Danga*) ©Wikimedia commons; (E) polygenetic coastal sands (*Erra Matti Dibbalu*) ©S. Patnaik (*The Hindu*); (F) valley colluvium (Adula–Mahalungi badlands) ©Joshi and Nagare (2013); (G) loessal deposits (Vasad) ©Kumar, Chavan, et al. (2020); (H) arid palaeodunes (Rajasthan *Bagar*) ©Kar (2014); (I) hillslope colluvium (Siwaliks) ©P. P. Patel (pers. comm.); (J) fluvio-glacio-lacustrine sediments (*Karewas*) ©Ganjoo (2014).

ambiguous terminology can cause confusion, we use the word 'badlands' when referring to extensively gullied regions and recommend its usage in the Indian context.

The badlands of Central and Western India are exemplar erosional geomorphic features covering an area of ~17,000 km^2 (NRSC, 2019) with gullies up to 80 m deep (Sharma, 1980, pp. 20–21; Haigh, 1984). They occur along the alluvial river reaches across five of India's largest states, viz. Rajasthan, Madhya Pradesh, Uttar Pradesh, Gujarat and Maharashtra. The Yamuna–Chambal zone (YCZ) badlands in Central India pre-date the Mughal empire, which was founded in 1526 (Habib, 1963). Peter Mundy, the British explorer, observed these badlands during his travels in India ca. 1631–32 (Temple, 1914). Badlands of the Gujarat zone are found along the middle and lower reaches of the rivers Tapi, Narmada, Sabarmati and Mahi in Western India (Ahmad, 1973, pp. 56–57; Haigh, 1984). Other regions severely affected by gully erosion include the foothills of the Lesser Himalayas (Siwaliks) in the northwest and the Chhotanagpur Plateau and surroundings in Eastern India (Ahmad, 1973, p. 44; Haigh, 1984) (Figure 1).

Gullies and badlands occur in a multitude of soilscapes in India (Figure 1 insets). The YCZ badlands have developed in alluvium (Ahmad, 1973, pp. 50–51; Joshi, 2014b), while those in Gujarat have formed through erosion of loessal sediments overlain on alluvium (Chamyal et al., 2002; Raj et al., 1999). Gullies in the Rajasthan *Bagar* (meaning 'dry country') have gouged into stabilised dune surfaces and sandy plains (Kar, 2014) and in the Western Himalayas they have incised into lacustrine and fluvio-glacial sediments (Ganjoo, 2014; Móga et al., 2019). There are a number of locations where gullies have formed in hillslope or valley colluvial deposits (Gargani et al., 2016; Joshi & Kale, 1997; Sinha et al., 2019). In Eastern India, one can find gullies in both primary (in situ) (Ghosh et al., 2021) and secondary (ex situ) (Majhi et al., 2021) laterites as well as in polygenetic coastal sands (Rao et al., 2006).

Bank gullies are the most common in India. Bank gullies form wherever concentrated runoff crosses an earth bank (e.g., river bank, terrace bank, sunken lane bank, lynchet or quarry bank). Once formed, they rapidly develop by headward retreat in erodible hillslopes owing to almost vertical slope gradient of the soil surface at the bank edge (Poesen et al., 2002, 2003). The badlands of Central (e.g., Figure 1B) and Western India (e.g., Figure 1F) have developed along rivers and there are many other riverside gullied sites (e.g., Figure 1D) across the country. Hillslope or valley-side gullying is observed in the Himalayas (Datt, 1991; Rao & Pant, 2001; Sinha et al., 2019) (e.g., Figure 1J), its foothills (Gargani et al., 2016; Singh, 2008) (e.g., Figure 1I), the Deccan (Joshi & Kale, 1997; Joshi et al., 2013) and the Chhotanagpur Plateaux (Ahmad, 1973, pp. 58–59; Satpathi, 1981, pp. 277–279) (e.g., Figure 1C). Valley-bottom gullying or ephemeral gully erosion in croplands is yet to be reported from anywhere in India.

Despite being a country whose lands are lost to acute and extensive gullying, research on gully erosion in India has been sporadic rather than systematic, which becomes especially clear on consulting seminal global review articles. For instance, there were no papers from India referred to in the global meta-analysis of Torri and Poesen (2014) on topographic thresholds of gully erosion or that of Vanmaercke et al. (2016) on gully head retreat rates, and only two papers featured in two recent reviews (one in each) on gully rehabilitation and prevention (cf. Bartley et al., 2020; Frankl et al., 2021). This paper therefore constitutes an attempt to take a stock of the state of research on gully erosion in India vis-à-vis that of other countries, to discern knowledge gaps and outline potential future research directions.

To this end, a literature search was conducted in December 2021 in the SCOPUS and Web of Science databases (title, abstract and keywords query) using the phrase 'gully OR gullies OR ravine OR ravines OR badland OR badlands AND India'. Querying in both repositories proved to be logical, as unequal numbers of results were returned (216 in Web of Science and 280 in SCOPUS), and each search yielded several papers that were not present in the other database. Additionally, papers that were published in journals not indexed in either of these databases but were known to the first author were considered, as were books, reports and other unpublished works. Following the literature collation, publications that focused on gully and badlands formation, their mapping, morphological or morphometric analyses, erosion dynamics, gully erosion effects and gully control or reclamation were identified and grouped separately. Papers investigating palaeontological (e.g., Brosse et al., 2017; Singh, Pandita, et al., 2015; Tewari et al., 2015), geochronological (e.g., Brookfield et al., 2020; Mir et al., 2016; Sial et al., 2021) or biological aspects (e.g., Joshi, 1983; Joshi & Chauhan, 1982; Mukhopadhyay et al., 2021) and mineral exploration potential (e.g., Asnani et al., 2020; Laxmi et al., 2012; Mishra et al., 2019) of badlands were naturally excluded. Our final bibliography comprised 185 entries.

We start this review by discussing the causes of gully erosion in various parts of the country, followed by a treatise on development of badlands in Central and Western India. A brief discussion on gully and badlands mapping ensues, following which papers on gully geomorphology and dynamics are reviewed. Subsequent sections highlight various environmental, social and economic impacts gully erosion have had in India and critically examine several land management techniques implemented to rehabilitate gullies and badlands. The discussion and conclusion sections respectively synthesise the review's findings and outline directions for further research on gully erosion in India.

2 | GULLY FORMATION IN INDIA: THE CAUSAL FACTORS

Patton and Schumm (1975) advanced the concept of geomorphic thresholds to explain the occurrence of discontinuous valley-bottom gullies in the western USA. The concept essentially refers to the critical condition at which a landform undergoes abrupt changes (i.e., a gully starts to form), either engendered by some external variable that upsets the stability of a landform through transgression of an extrinsic threshold (e.g., rainfall, runoff hydraulics, land use and land cover), or due to an intrinsic change in the landform itself (e.g., weathering, tectonics) (Schumm, 1979, 2004).

Work on the causes of gully erosion worldwide, as well as landmark review articles (e.g., Castillo & Gómez, 2016; Frankl et al., 2021; Poesen, 2018; Poesen et al., 2003; Valentin et al., 2005), reveal that in an overwhelming majority of the cases, land cover/use change and consequently augmented runoff volume and increased erosivity have been cited as the primary cause of gully formation—so much so that 'land use change is expected to have a greater impact on gully erosion

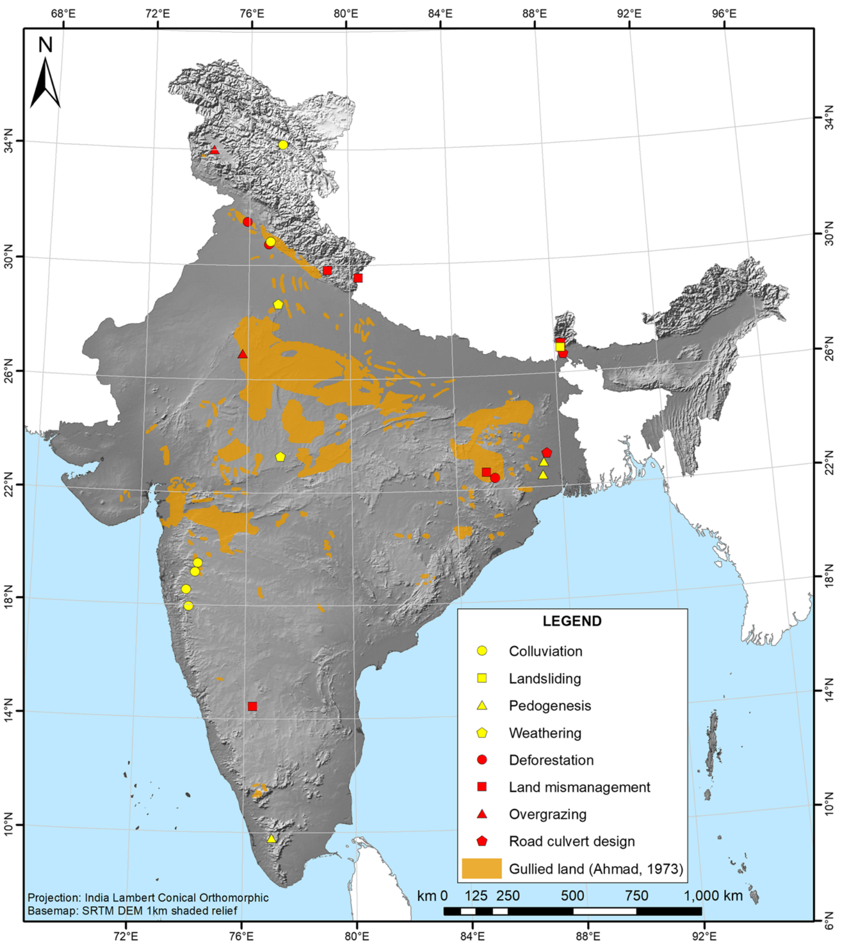


FIGURE 2 Approximate locations of studies reporting gully formation due to anthropogenic causes (marked in red) and natural factors (marked in yellow).

than climate change' (Valentin et al., 2005). However, we find several cases in India where gullies have formed naturally due to exceedance of the intrinsic geomorphic threshold (Figure 2). Formation of weak slip planes due to weathering (Das et al., 2020; Tripathi & Rajamani, 2003), natural susceptibility of soils owing to pedogenesis (Lalitha et al., 2021; Shit & Adhikary, 2020), mass wasting or colluviation (Gargani et al., 2016; Joshi & Kale, 1997; Sinha et al., 2019; Spate & Learmonth, 1967, p. 690) and landslides (Froehlich et al., 1991) have all caused natural gully formation across India (Figure 2). Neotectonics has also played a pivotal role in initiating badlands formation over extensive parts of Central and Western India (see Section 3). Despite being caused by natural drivers in various regions, gully erosion in India is largely anthropogenically induced (Figure 2), with the principal causes being deforestation and poor land management.

2.1 | Gullying due to deforestation

Gully formation due to deforestation has been reported from the Himalayan foothills and the Eastern plateaux (Mandal & Giri, 2021; Roy Mukherjee, 1995; Singh, 1971; Spate & Learmonth, 1967). The piedmont plains of the Himalayas, formed through coalescence of alluvial fans, are naturally prone to gully erosion because of the poor aggregate stability or shear strength of its soils and due to this region's break of slope (Ahmad, 1973, p. 48; Spate & Learmonth, 1967, p. 535). Profligate lumbering in such an erosion-susceptible region has, unsurprisingly, led to widespread gullying (Singh, 2008; Spate & Learmonth, 1967, p. 93), particularly in the *Chos* (meaning 'torrents') area in the state of Punjab (Singh, 1971, p. 122; Spate & Learmonth, 1967, p. 535). The severity of erosion (both gully and surface erosion) here becomes conspicuous from the fact that the Chos, which covered only 194 km^2 in 1852, expanded to 380 km^2 in 1897 and 1680 km^2 by 1939 (Singh, 1971, p. 122) and has continued to grow ever since (Mandal & Giri, 2021).

Chhotanagpur Plateau and its surroundings in Eastern India is another area where the main precursor to gullying is deforestation (Sharma, 1980, p. 28). Until ca. 1850–1870, this region was covered by almost pristine vegetation, after which deforestation started in accessible areas for timber production, to promote agriculture and to build transport lines (Pattnaik & Dutta, 1997; Roy Mukherjee, 1995). As these activities were only possible in areas with relatively low relief, gullies in this region are only found in the undulating peneplains and gentler scarp slopes, while the steeper scarp faces remain densely forested and free from gully erosion (Ahmad, 1973, pp. 58–59). The newly created agricultural lands were subsequently found to be unsuitable for crop production and were thus abandoned by the early 1900s and left as wastelands, thereby promoting soil erosion in general (Pattnaik & Dutta, 1997) and gullying in particular (Bradbury & Ghosh, 1988; Satpathi, 1981, p. 277).

2.2 | Gullying due to land mismanagement

Poor land management has also contributed to gully formation in India, although not as extensively or seriously as deforestation.

Overgrazing and the deliberate burning of forests to prepare land for agriculture are the main types of land mismanagement that have resulted in gully formation. The glacio-lacustrine sediments of the *Karewas* (famous for being the saffron-producing region) in the Kashmir Himalayas (Ganjoo, 2014) and eastern fringes of the Great Indian Sand Desert (Kar, 2014) are regions of India that have both been heavily and extensively gullied, owing mainly to overgrazing (Spate & Learmonth, 1967, pp. 111, 434). Overgrazing, together with deforestation by the resident tribes, is also a cause of gully erosion in the Sub-Himalayan belt and the Chhotanagpur plateau (Roy Mukherjee, 1995; Satpathi, 1981, pp. 277–279; Singh, 1971, p. 780; Spate & Learmonth, 1967, p. 93). The deliberate burning of forests in order to prepare land for agriculture, known as *Jhuming*, has resulted in localised gully erosion in parts of the Himalayan foothills and Chhotanagpur plateau (Roy Mukherjee, 1995; Satpathi, 1981, pp. 277–279; Singh, 1971, p. 780; Spate & Learmonth, 1967, p. 93). Jhuming is a widespread practice in shifting cultivation systems in tribal regions of the country, which has had a particularly detrimental effect in the Sub-Himalayan zone, where obliteration of the forest cover has exacerbated the inherent instability of soils in this region and has, in turn, made gully erosion inevitable (cf. Saha et al., 2011).

Although not as widely reported, mismanagement of croplands has also resulted in gully formation in India. Graded terraces built to drain excess water have been observed to induce valley-side gullying in the Western Himalayas when the slope gradient exceeds 7–10°. Bank gullies start to form on the steeper terrace risers and grow into the terraces (Datt, 1991; Rao & Pant, 2001). Tea gardens in the Eastern Himalayas are all situated on well-draining slopes, as stagnant water is detrimental to the plants. Thus, gullies form wherever runoff is poorly or not attenuated along convergent concave slope sections (Starkel & Sarkar, 2014). Poor maintenance of contour bunds has also been reported to cause gully erosion in the Deccan (Fujiwara & Nakayama, 1985) and the Chhotanagpur Plateaux (Satpathi, 1981, p. 279) (Figure 2).

Road building can trigger or accelerate gully erosion in more ways than one. Roads induce concentration of surface runoff and reduce the critical catchment area required for incipient gullying, as well as diverting runoff towards adjacent catchments, thereby increasing the area under risk of gully erosion (Nyssen et al., 2002; Seutloali et al., 2016). Moreover, gullies have also been observed to form at road drain outlets or culverts (Crouch, 1977; Takken et al., 2008). Instalment of improper and/or undersized cross-drainage structures results in poor drainage of water and has been observed to cause roadside gully formation in the Himalayas (D. C. Das, 1977), Eastern Himalayan foothills (Roy, 2020) and the Bengal Basin (Majhi, 2020).

While we have highlighted several precursors of gullying in different regions of India, notably the Himalayan foothills and Chhotanagpur Plateau, there are many regions of the country where the causes of gully erosion remain unknown. Understanding the causal factors of gullying as well as establishing timelines of gully formation across India are of paramount importance in understanding their evolutionary dynamics.

3 | BADLANDS GENESIS IN WESTERN AND CENTRAL INDIA

Neotectonics (Ahmad, 1973; Sharma, 1980), Quaternary climate oscillations (Gibling et al., 2005; Roy et al., 2012), large-scale land cover changes (Gupta & Prajapati, 1983; Prajapati et al., 1982) or a combination of these factors (Haigh, 1984; Joshi, 2014b; Sharma, 1980) are often mentioned as causes of badlands development in Central and Western India (Figure 1). However, the exact reasons behind their formation and evolution are not yet fully understood. Although the drivers of badlands formation in both these regions are the same, they have interacted and manifested themselves differently, causing marked differences in badlands' extents and geomorphology. Therefore, the badlands of Central and Western India are discussed separately. However, the similarity lies in that neotectonics has influenced badlands genesis both in Central and Western India. Tectonic uplift and consequential fluvial incision can provide the necessary impetus for bank gullying (Begin et al., 1981). Badlands of Central and Western India have formed as a result of extensive bank gully erosion (Joshi et al., 2009; Kale, 2014).

3.1 | Badlands of Western India

The badlands in Gujarat (Figure 1) developed following cessation of Late Pleistocene aeolian sedimentation (Chamyal et al., 2003; Maurya et al., 2000; Prizomwala, 2018). These badlands occur between the (Late Pleistocene) alluvial plain and Mid–Late Holocene river terrace, both of which are ungullied surfaces (Chamyal et al., 2002; Raj et al., 1999). Such a geomorphic configuration (Figure 3) is observed along the rivers Mahi (Raj et al., 1999), Sabarmati (Bhatt & Shah, 2017) and Narmada (Chamyal et al., 2002) in mainland Gujarat as well as in the Kachchh peninsula (Maurya et al., 2003), which allows us to indirectly date the erosional period between 10 and 6 ka.

In the Lower Mahi valley, badlands up to 25 m deep and between 50 m and 5 km long are observed (Raj et al., 1999). The erosion, as evidenced by gully sizes, is more pronounced on the left bank compared to the right bank of the Mahi river, suggesting a differential uplift. Furthermore, the extent and orientation of the badlands on the left bank are controlled by a major lineament, making the structural/tectonic control obvious (Raj et al., 1999). Bhatt and Shah (2017) found similar evidence in the Central Sabarmati basin, about 130 km north of the Lower Mahi valley: badlands in upthrown blocks with their orientation aligning with the structural trends. However, the incision of badlands in this region is considerably deeper (up to 80 m), which could be due to the relative dominance of the highly erodible aeolian loess in the soilscape. The work of Maurya et al. (2003) in the Kachchh Peninsula confirmed the tectonic control on the formation of badlands in Gujarat. They discuss how the depth, extent and intensity of badlands and fluvial incision gradually decrease towards the south (the downstream direction), and then disappear altogether much before the coastline, controlled by the form of the tiltblock structure of the region.

Through their work in the Lower Narmada Valley, Chamyal et al. (2002) firmly established that tectonic uplift resulted in badlands formation along rivers of Gujarat. They constrained the period of fluvial incision and badlands development by dating the alluvial plain (ca. 10 ka) and river terraces (ca. 6 ka), between which the badlands occur. This time period in the Early Holocene (10–6 ka) witnessed rapid sea-level rise (Chappel & Shackleton, 1986; Hashimi et al., 1995), thereby suggesting that formation of incised river valleys was not related to the lowering of sea level, and thus confirms the

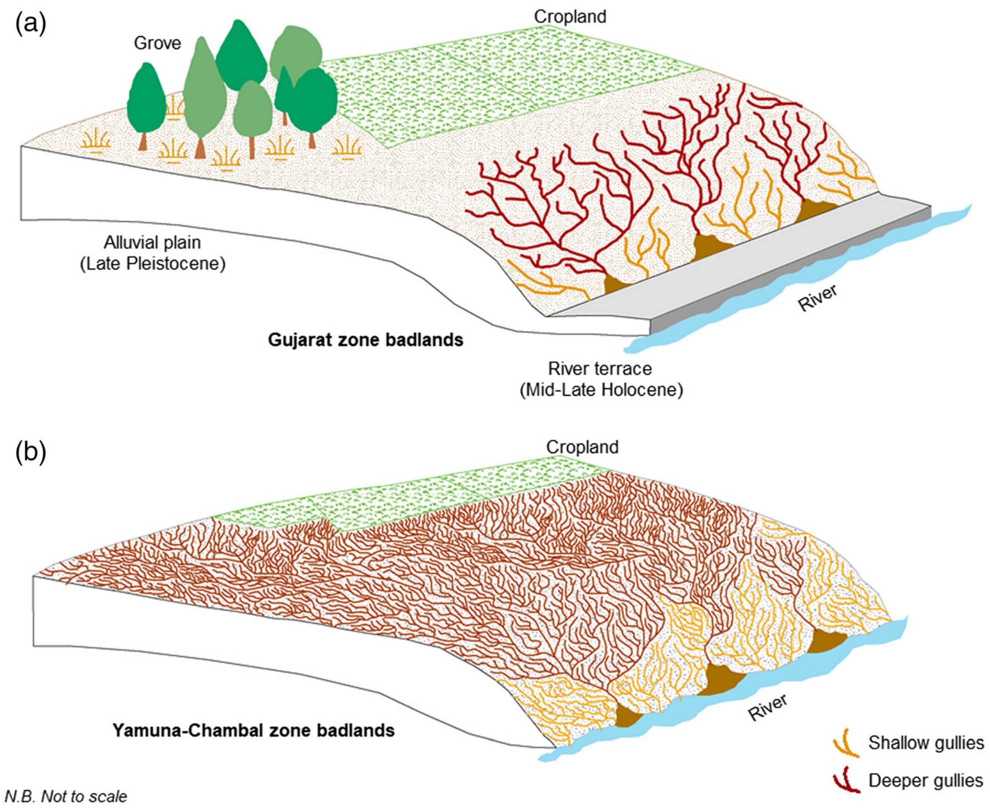


FIGURE 3 (a) Badlands of Gujarat are found between the Late Pleistocene alluvial plain and Mid–Late Holocene river terrace, whereas badlands in the Yamuna–Chambal zone (b) occur right alongside the river. Note the greater erosional intensity (lateral extent and drainage density) of the latter, which is possibly due to the prevalence of shrinking–swelling clays and calcite in the soilscape, likely exacerbated by large-scale deforestation.

role of Early Holocene tectonic upheaval in badlands genesis. Although the Early Holocene was also a period of monsoon strengthening in India (Misra et al., 2021; Sanyal & Sinha, 2010), which is a conceivable factor in gully erosion and badlands genesis, Chamyal et al. (2002) primarily ascribe the formation of badlands to tectonics, as the coastline morphology indicates, to an uplift of about 40 m, and geomorphic markers of the same, such as raised terraces, entrenched meanders and tiltblocks, abound.

The neotectonic argument has also been pertinently applied to account for the formation of the famous badlands site *Erra Matti Dibbalu* (meaning 'red sand mounds') (Figure 1E) in the polygenetic coastal sands on the East Coast (Rao et al., 2006), Adula–Mahalungi badlands (Figure 1F) along the Pravara River in the Northwestern Deccan Plateau (Joshi & Nagare, 2013) as well as in the Luni–Jawai plains in the Rajasthan Bagar (Kar, 1988), albeit these are not as extensive as those found in Gujarat. All three studies inferred that lineament-controlled block uplift resulted in local base-level fall and in turn prompted bank gullying and badlands development. Neotectonics also contributed to the formation of the Lamayuru palaeolake badlands (popularly known as Lamayuru Moonland; Figure 1A) in the Ladakh Himalayas. The Lamayuru Moonland developed at the site of a former lake, which was drained due to a tectonic event about 1000 years ago (Móga et al., 2019). At an altitude of 3600 m above sea level, it is the highest badlands landscape in India and possibly the world.

3.2 | Badlands of Central India

The YCZ badlands in Central India are observed along extensive reaches of several tributaries of the Ganga, most notably the Yamuna and Chambal (Ahmad, 1973, p. 50; Haigh, 1984; Sinha et al., 2002). Their existence has been explained in relation to the general erosion and deposition characteristics of the Ganga basin (Sinha et al., 2005), but their genetic factors are more difficult to ascertain. This is partly because stratigraphic records from the region indicate multiple episodes of gully erosion and infilling corresponding to floodplain aggradation and degradation cycles controlled by monsoonal oscillations between ca. 40–30 and 15–5 ka (Gibling et al., 2005; Roy et al., 2012). It is obvious that the last such episode (ca. 15–5 ka) during the phase of Early Holocene monsoon strengthening contributed to the evolution of the badlands to their present state (Sanyal & Sinha, 2010) but, akin to Gujarat, tectonics is touted as the major trigger to badlands development in the YCZ too (Ahmad, 1973, pp. 53–55; Ghosh et al., 2018).

Unlike the badlands of Gujarat, the regional geomorphic setting of the YCZ badlands prevents constraining the period of badlands evolution (Figure 3). Ghosh et al. (2018) categorically investigated the tectonic control on the formation of these badlands, and suspected that the erosion commenced after 14 ka, which was the youngest of four OSL dates they obtained for surficial strata. This is evidently somewhat arbitrary, even though the date is close to the phase of monsoon strengthening in the Early Holocene—that is, 11.5–8.2 cal ka (Bhushan et al., 2018; Misra et al., 2021), which likely facilitated badlands development all over India. In line with evidence from Gujarat, Ghosh et al. (2018) found that gully channels in the badlands strike in the same direction as that of the conjugate calcite-filled fractures, suggesting preferential erosion and making the structural/tectonic influence explicit. They, however, adjudged base-level fall to be of insignificant effect in the formation of the YCZ badlands, as no linear relationship was found between river incision depth and length of the badlands. This conclusion, albeit intuitive, does not align with our understanding of gully erosion mechanism. Two topographic variables that dictate formation and growth of gullies are upslope catchment area and slope (Poesen et al., 2003; Wells, 2004; Valentin et al., 2005), with the effect of the former probably more important than that of the latter in gully evolution (cf. Vanmaercke et al., 2021), implying that any straightforward relationship between bank height (river incision) and gully/badlands length is inconceivable. Although the extent of fluvial incision in both Central and Western India indicates similar degrees of upheaval, the lateral expanse of the YCZ badlands is far greater (Ahmad, 1973, p. 44; Haigh, 1984) (Figure 3), underlining that areal dimension of badlands is not necessarily a function of the extent of river incision.

Being 3–13 km wide (Singh, 1971, pp. 524, 615; Spate & Learmonth, 1967, pp. 112, 547), the YCZ badlands stand out in terms of its scale within India and beyond (Ahmad, 1973, p. 44; Haigh, 1984; Joshi, 2014b; Singh, 1971, p. 131). The geomorphological contrast of the YCZ badlands to the Gujarat zone badlands is quite enigmatic, given their formation was primarily triggered by neotectonics, possibly aided by a wetter climate. There are also no stark differences between the YCZ and the Gujarat zone in terms of the general slope gradient, relative relief or soil texture (NATMO, 1963). While larger catchment areas in the YCZ may have contributed to the badlands' growth, evidence from the literature indicates that the severe gully erosion and widespread badlands development in this region is due to the combination of several conducive environmental factors, possibly accentuated by large-scale land cover changes (Gadgil & Guha, 1992; Ghosh et al., 2018; Joshi, 2014b; Singh, 1971, pp. 15, 524).

The soilscape of the YCZ is particularly susceptible to gully erosion. Presence of shrinking–swelling clays (smectite) is a diagnostic feature of badlands worldwide (Bryan & Yair, 1982; Harvey, 2004; Nadal-Romero et al., 2018) and the YCZ badlands are no exception (Ghosh et al., 2018; Joshi, 2014b). Not only do soils rich in smectites develop cracks in the dry season, allowing runoff to channelise and erode, but they also disperse rapidly in a sodic environment (Kasanin-Grubin, 2013; Levy et al., 1993). The cratonic rivers like Chambal and Betwa transport smectite-rich sediments from the Deccan traps to this region, where they have been intermixed over time with sediments of Himalayan origin rich in mica and illite by flooding and reworking (Sinha et al., 2009). Joshi (2014b) opined that the spatial distribution of smectites dictates the badlands' morphology as they are more erodible than the other constituents of the clay suite of this region, namely mica, illite, kaolinite or chlorite. Contrarily, Ghosh et al. (2018) deemed preferential erosion along the conjugate calcite-filled fractures to have had greater bearing on badlands development in the YCZ. Calcareous nodules, which are locally called *kankar*, are so plentiful that they are commonly exposed on the gully walls and floors (Singh, 1971, p. 604; Spate & Learmonth, 1967, p. 112). In fact, soils of the badlands have significantly higher calcium carbonate ($CaCO_3$) content than that of the nearby croplands (Ranga, Mohapatra, & Pani, 2015). Presence or absence of $CaCO_3$ has profound implications for erosion response of a landscape as it dissolves in the presence of water and carbon dioxide to form the more soluble and readily transportable calcium bicarbonate ($Ca(HCO_3)_2$) (Williams, 2004). The relative importance of swelling clays against occurrence of $CaCO_3$ in contributing to gullying in the YCZ is uncertain but both these factors point to a strong influence of subsurface erosion (i.e., piping) on badlands genesis in the YCZ, as observed in badlands elsewhere (Bryan & Yair, 1982; Faulkner, 2006, 2013; Harvey, 2004). Furthermore, there is field evidence from a part of the YCZ (Lower Chambal Valley) of palaeochannels abetting gully formation and quickening their growth, contributing further to badlands development. These palaeochannels, likely formed as branches of an anastomosing river system, became disconnected due to tectonic uplift. At present, they exist as elongated depressions that are preferred areas of gully head growth (Ranga, Mohapatra, & Pani, 2015).

Our literature review reveals that the effect that land cover changes might have had in badlands genesis in the YCZ is largely unexplored. The vegetal cover of the Ganga plain has been periodically modified since ca. 5000 years BP to make way for agriculture (Gadgil & Guha, 1992; Singh, 1971, p. 15). Occasional groves and scrubs lend evidence of greater vegetation cover in the not too distant past (Singh, 1971, pp. 15, 524; Spate & Learmonth, 1967, p. 93). For instance, Singh and Agnihotri (1987) reported that the region around the city of Prayagraj (erstwhile Allahabad) was densely forested at the start of the 20th century, and that tree cover thinning was rapidly followed by incipient gullying. In light of conspicuous archaeological evidence, such as ruins of villages, castles, forts and temples within the badlands and relicts of an old Mughal Imperial Road broken by fringing gullies, Singh (1971, p. 524) inferred that most of the erosion occurred in the last four centuries. Even though the timeline is speculative, it is obvious that the badlands evolved most rapidly in the recent past and that sweeping land cover change played an important role, in addition to the tectonic, pedogenic and geomorphic agents. The relative role of land cover change in the formation of the YCZ badlands and its timing is an important subject for future investigations.

4 | MAPPING BADLANDS AND GULLIES

Accurate spatial information is crucial in remediating any environmental problem. Although gully erosion constitutes a dire land degradation issue, it is easily mappable, unlike other soil erosion processes such as sheet, rill or piping erosion. For a country so extensively affected by gullying, the importance of mapping gullies and badlands cannot therefore be overstated. Forty studies in our review's bibliography focused on mapping gullies and badlands. The initial focus was on mapping the badlands, as their management was deemed to be of high priority by the authorities. Gully mapping is a relatively recent undertaking.

4.1 | Badlands mapping

As India formulated her first badlands reclamation policy in the 1970s (Kumar, Adhikary, & Dash, 2020), precision mapping of the extent of the badlands and gully character (depth and width) was necessitated. The timing of this policy formulation coincided with the data launch of the Landsat-I mission (Lillesand et al., 2015, p. 295), and naturally the earliest efforts at badlands delineation made use of Landsat-I imagery (e.g., Singh, 1977, 1984). However, the horizontal resolution of Landsat-I imagery (80 m) was not suitable for discerning different reclamative groups (Singh, 1984). Therefore, aerial photographs were initially used for this purpose (Sharma et al., 1980; Singh, 1984). As improved Earth observation data products as well as means to analyse them became available, manual badlands delineation gave way to semi-automatic approaches.

While supervised classification of seasonal Landsat-5 TM imagery has proved to be useful for semi-automatic delineation of badlands using the contrast in vegetation activity relative to the adjacent croplands (Ranga, van Rompaey, et al., 2015), radar remote sensing products (ERS-1/2 and ENVISAT SAR) lend further insights into the badlands' characteristics, such as relief, density and surface cover (Chatterjee et al., 2009). However, badlands are best distinguishable from fused optical and radar imagery, compared to that of just optical or radar data (Khan et al., 2020). Nonetheless, some studies have solely used optical imagery for badlands mapping. Using LISS IV (5.6 m) and Google Earth imagery, Kumar et al. (2018) prepared the first high-resolution map showing the badlands' spatial extent in the state of Gujarat. Kandrika and Dwivedi (2013) extracted a digital elevation model from the high-resolution (2.5 m) Cartosat-I PAN stereo images for reclamative grouping of badlands in respect of gully depth and width in the Mahoba district in Uttar Pradesh. Pani (2012) and Tagore et al. (2021) classified LISS III (23.5 m) scenes of the Morena district of Madhya Pradesh in conjunction with visual assessment of Survey of India topographical maps (1:50,000 scale) for badlands delineation. In the Bhind district in Madhya Pradesh, Dwivedi and Ramana (2003) used the same data, but emphasized on the extraction of relief information from the topographical maps in order to obtain badlands' depth classes.

4.2 | Gully mapping

Localised gully systems have been mapped as part of regional land degradation or geomorphological mapping endeavours through a combination of remote sensing, field surveys and topographical map interpretation (Das Sarma, 1990; Raina et al., 1992; Rao & Reddy, 2004). However, the mapping of actual gully channels or systems as opposed to delineating areas of badlands topography was not as actively pursued until recently. This may be because badlands can be delineated from various freely available moderate-resolution imagery as discussed above, but mapping gullies is only possible from high-resolution images, procuring which in most cases become prohibitively expensive, especially so in a large country like India. However, since 2018, a plethora of studies have been published that uses mapped locations of gully heads and spatial data on several gully erosion-conditioning factors or proxies to generate 'gully erosion susceptibility maps' through spatialised applications of bivariate statistical methods (e.g., Chakrabortty et al., 2020; Hembram et al., 2020; Shit, Bhunia, & Pourghasemi, 2020), multivariate statistical methods (e.g., Debanshi & Pal, 2020; Ghosh & Maiti, 2021; Roy & Saha, 2019), multicriteria decision making (e.g., Dandapat et al., 2020; Shit et al., 2015) or machine learning (e.g., Chowdhuri et al., 2020; Gayen et al., 2019; Pal et al., 2021; Roy et al., 2020). Such data-driven mapping entails creating an inventory of gully (head) locations, the majority (70–80%) of which are used for model calibration and the rest are left for validation. Data on topographic variables, soils, geology, land cover and rainfall are then fed into the model, which essentially tries to find unmapped gullied locations that are characterised by similar environmental conditions to the mapped locations. Finally, the accuracy of the map is ascertained with respect to the validating dataset. As these analyses are primarily driven by and ultimately evaluated using locations of existing permanent gullies, the resultant maps simply show gully occurrence and not susceptibility of the landscape to emergent gullying. Twenty-eight of the 40 studies reviewed in this section were based on data-driven mapping, which has exclusively been conducted in Eastern India (11 in the state of Jharkhand and 17 in West Bengal).

Although such data-driven mapping is relevant in countries that have a dearth of data on the spatial extents of gullies and/or badlands, such as Iran (e.g., Arabameri et al., 2020; Rahmati et al., 2017), Ethiopia (e.g., Busch et al., 2021) or Namibia (e.g., Orti et al., 2021), it is difficult to find the value of such gully occurrence mapping studies in India, as state-wise land degradation datasets are already available, with gullies and badlands delineated at a scale of 1:50,000 (NRSC, 2007, 2019). Therefore, mapping geomorphic characteristics of gully systems/badlands, such as gully head density (cf. Vanmaercke et al., 2020), using similar methods or approaches would be more pertinent.

5 | GEOMORPHOLOGY AND DYNAMICS OF GULLIES AND BADLANDS

Geomorphic characterisation of gullies and their (evolutionary) dynamics is instrumental in the formulation of successful mitigative strategies. Information on topographic thresholds of gully initiation, morphometry, morphological characteristics and gully growth rates are vital in this regard (Figure 4).

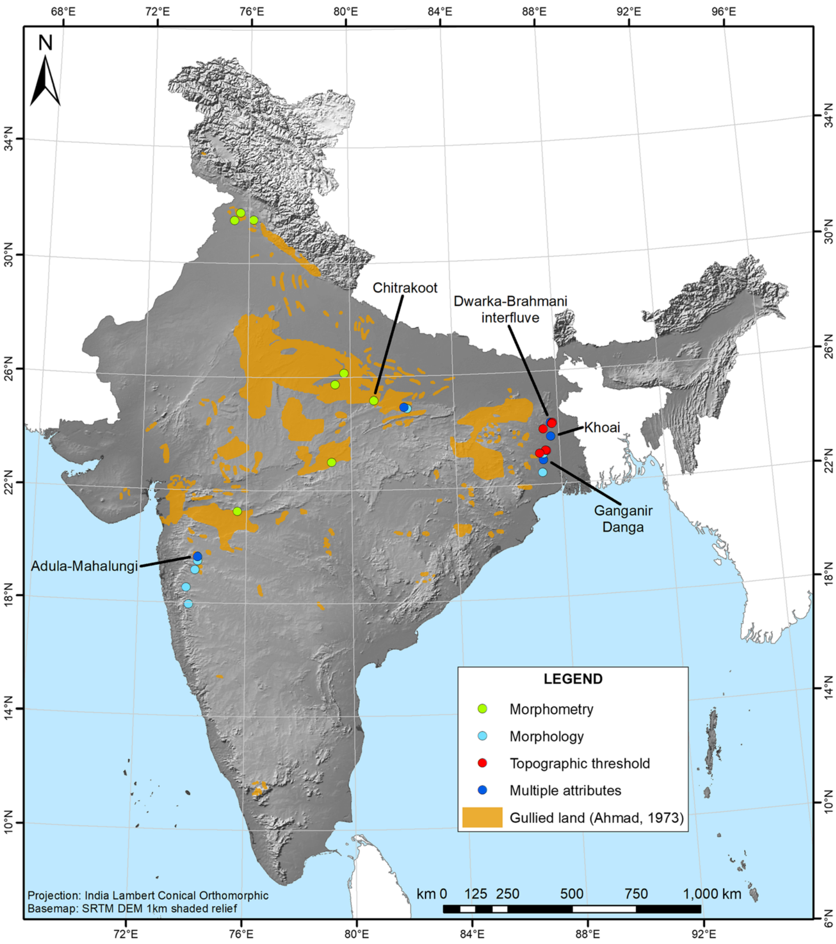
The geomorphology and evolutionary history of the amphitheatre-like landform created by bank gullies in the Pleistocene ex situ laterites at *Ganganir Danga* (meaning 'land of fire') (Figure 4) in Eastern India have been the subject of multiple studies. These have ranged from geomorphic mapping and description of the landscape (Bandyopadhyay, 1988), deciphering its morphogenesis (Kar & Bandyopadhyay, 1974; Shit et al., 2014), estimating gully initiation thresholds (Majhi et al., 2021), assessing cross-sectional (Islam et al., 2020) and longitudinal gully morphology (Patel et al., 2021), fine-scale rill modelling in 3D (Patel et al., 2020) to quantifying gully growth rates (Sen et al., 2004; Shit & Maiti, 2012; Shit et al., 2013).

Approximately 100 km north of Ganganir Danga lies another notable site near the city of Bolpur called *Khoai* (meaning 'eroded') (Figure 4). Gullies here have also been well researched, with papers published on their formation, evolution, and morphological and morphometric characteristics (Bandyopadhyay, 1987; Das & Bandyopadhyay, 1996; Hembram et al., 2020; Majhi et al., 2021). Other noteworthy hotspots of research on geomorphological aspects of gullies (locations studied at least twice as evidenced by the number of papers) include the Dwarka–Brahmani interfluve in Eastern India (Ghosh & Guchhait, 2017; Ghosh et al., 2021), the Adula–Mahalungi badlands in the Northwestern Deccan Plateau (Joshi et al., 2009; Joshi, 2014a) and the badlands near the city of Chitrakoot in the YCZ (Singh, Jha, et al., 2020, 2021) (Figure 4).

5.1 | Gully morphometry

A total of 14 studies in our review's bibliography have assessed morphometric characteristics of gully systems through computation of a wide range of indices, which, on the whole, are used to ascertain the

FIGURE 4 Approximate locations of the reviewed studies on gully geomorphology and dynamics. Hotspots (locations studied at least twice, as evidenced by number of papers) are labelled.



relative erosion susceptibility of a landscape. However, two indices are especially pertinent to assess extent or severity of gully erosion—that is, drainage density and stream frequency—which also happen to be the most frequently computed morphometric indices in our examined studies. Drainage or gully density is calculated as the total length of channels per unit area, whereas gully (stream) frequency in our examined studies refers to the total number of gullies or gully heads per unit area. Both these indices can be computed in a grid-based configuration or for an entire catchment, though the latter scheme was followed in all the reviewed studies.

Although a full meta-analysis could not be conducted due to inadequate standardisable data on morphometric characteristics of gullies in India, we have obtained gully density and frequency values from seven studies that computed both parameters and compared them by means of a scatter plot (Figure 5). The Adula–Mahalungi badlands in the Northwestern Deccan plateau (Joshi et al., 2009) is at a senile stage and is largely stabilised, which explains the remarkably high gully density value. Singh and Dubey (2000) studied the actively eroding badlands near Deoghat in the YCZ and reported gully frequency values quite similar to that of Joshi et al. (2009), although the gully density is much lower, as is to be expected for a nascent gully system. The severity of gully erosion in the Chos region at the foothills of the Western Himalayas, which has already been thoroughly discussed, is further confirmed by Figure 5 (e.g., Bhatt & Kukal, 2015; Kukal & Bhatt, 2014; Rasool et al., 2011). Gully systems investigated by Deshmukh et al. (2011) and Singh, Jha, et al. (2020) are relatively localised, with much lesser erosional intensity.

Figure 5 sheds some light on gully system evolution in India. As gullies form and grow in a landscape, there comes a time when new gully head development ceases, likely due to inadequacy of runoff volume from the progressively smaller upslope contributing areas. However, total length of gully channels seems to keep on increasing, possibly because of bifurcation and stream capture. This explains why the badlands studied by Singh and Dubey (2000) and Joshi et al. (2009) possess extraordinarily high gully frequency and density values. The gully systems of the Chos region (Bhatt & Kukal, 2015; Kukal & Bhatt, 2014; Rasool et al., 2011) unsurprisingly form a cluster, while those investigated by Deshmukh et al. (2011) and Singh, Jha, et al. (2020) plot near the origin. It should be noted that gullies at all these locations have gouged into alluvial soils, implying that soil erodibility differences are minimal and that this relationship may not hold true for all gullied areas in India.

Works that have classified fractal dimensions of badlands (Joshi, 2021; Joshi et al., 2009) deserve special mention, being quite rare in gully erosion or badlands research worldwide. A fractal is defined as a fragmented geometric shape that, when subdivided, yields parts that are approximately reduced-size (self-similar) copies of the whole (Joshi et al., 2009; Xu et al., 1993). When applied in geomorphological research, it is essentially a relief-based morphometric index that can be computed to ascertain whether parts of a landscape or sub-catchments of a larger basin have similar relief or not (i.e., they are self-similar or self-affine, in fractal terminology). Joshi et al. (2009) and Joshi (2021) implemented this technique at the Adula–Mahalungi badlands in the Pravara river basin and Bhaunak–Sur badlands in the Tapi river basin, respectively, in the Northwest Deccan Plateau. Both

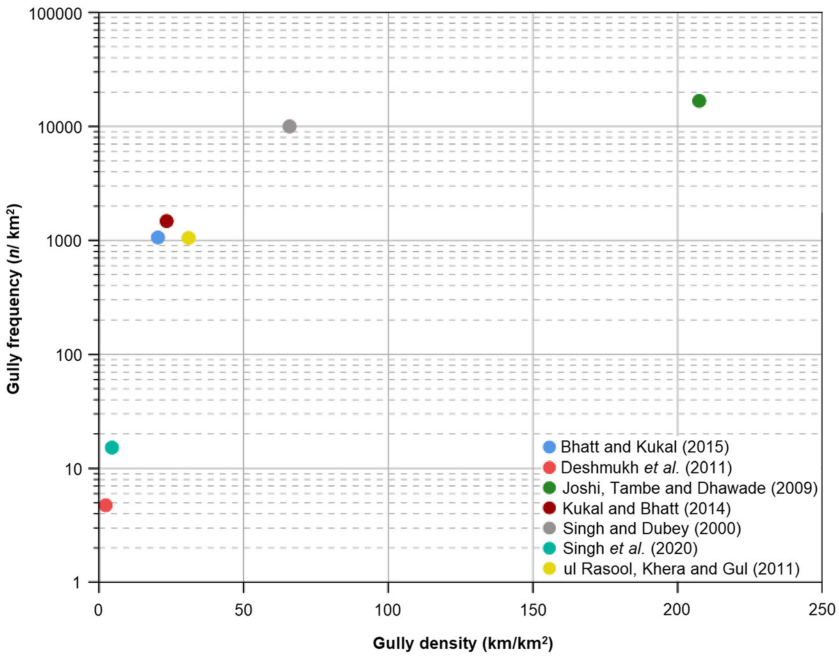


FIGURE 5 Comparison of gully frequency and density between gully systems/badlands developed in alluvial soilscapes

these studies classified the linear, areal and surficial (topographical) fractal dimensions of their respective study areas to first delineate the badlands and consequently conducted variogram modelling of the elicited fractal surface to discern self-similarity or self-affinity. Both areas were found to have a multifractal or self-affine topography, which is suggestive of contrasts in lithology and/or process regimes (Joshi, 2021; Joshi et al., 2009).

5.2 | Gully initiation thresholds, morphology and dynamics

Compared to catchment-wide morphometric applications, considerably fewer number of studies have sought to assess the morphology of gully channels. Among these, most have looked at longitudinal profiles of gullies (Joshi et al., 2013; Patel et al., 2021; Saha et al., 2020; Singh & Dubey, 2000), while only two studies inspected cross-sectional morphology (Ghosh et al., 2021; Islam et al., 2020). Nevertheless, none of these studies have enumerated the standard gully morphological ratios or quantified their volume–length relations (cf. Frankl et al., 2013; Yibeltal et al., 2019). Even fewer studies have computed (linear) gully head retreat rates, which are hereby compared (Figure 6). Apart from one account of gully dynamics from the YCZ (Singh & Agnihotri, 1987), the rest pertain to gully systems of the Chhotanagpur Plateau and adjacent Rarh Plain in Eastern India. The obvious difference between the gullies and badlands of the YCZ and that of Eastern India is that the latter have developed in (in-situ and ex-situ) lateritic soilscapes, whereas the former are found in alluvial plains. This soil erodibility differential explains the stark contrast in gully head retreat rates (Figure 6), as other factors of gully erosion are mostly indistinguishable across the regions.

Only two studies have so far attempted to estimate gully initiation thresholds and both were undertaken in Eastern India. Ghosh and Guchhait (2017) investigated topographic thresholds of 118 gullies in the in-situ primary laterites of the Chhotanagpur plateau, while Majhi et al. (2021) analysed the same at 110 gully heads across 10 sites in the ex-situ secondary laterites of the Rarh Plain. The latter authors discerned that the primary laterites offer considerably more resistance to gully head development and have one of the highest gully initiation thresholds in the world. Gully erosion process regimes differ across these soilscapes too; overland flow is the main agent of gully development in primary laterites (Ghosh & Guchhait, 2017), whereas that in the secondary laterites of the Rarh Plain is mostly driven by subsurface processes and resulting mass failures (Majhi et al., 2021).

There remain several knowledge gaps on gully morphology, dynamics and erosion rates in India. For example, although the variability in the scale of the gullies visualised as insets of Figure 1 raises the question, there is no quantitative information on their morphological characteristics, and factors controlling the morphological variability of gullies across India are yet unknown. There is also a complete lack of accounts of areal or volumetric gully growth rates from anywhere in the country, which is crucial to gauge the contribution of gully erosion in catchment sediment yield. Topographic thresholds estimation, which represents the most fundamental investigation of a gullied landscape, has only been locally conducted in Eastern India. As information on these aspects is pivotal for planning and implementing gully rehabilitation strategies, systematic research efforts concomitantly studying catchment-wide morphometry, topographic thresholds of gully erosion, gully channel morphology and gully dynamics are necessary.

6 | ENVIRONMENTAL AND SOCIO-ECONOMIC EFFECTS OF GULLIES AND BADLANDS

Gully erosion is at the root of serious land degradation issues. It not only causes soil (quality) loss, consequential yield declines and sediment production, but also induces other repercussions such as deterioration of water quality (Valentin et al., 2005; Verstraeten

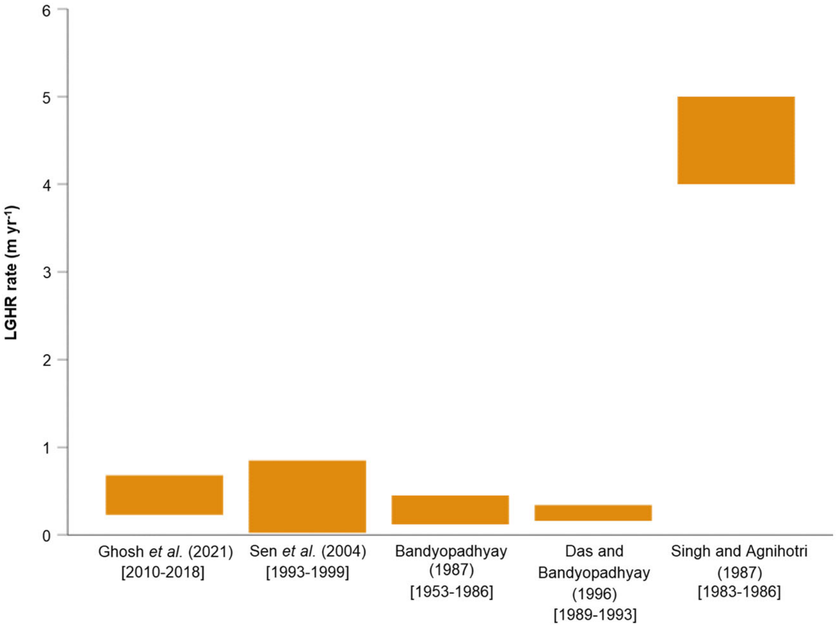


FIGURE 6 Linear gully head retreat (LGHR) rates in the Dwarka–Brahmani interfluve (Ghosh et al., 2021), Ganganir Danga (Sen et al., 2004) and Khoai (Bandyopadhyay, 1987; Das & Bandyopadhyay, 1996) in eastern India and Tons river basin in the YCZ (Singh & Agnihotri, 1987). Note: LGHR rates computed in Ganganir Danga by Shit and Maiti (2012) and Shit et al. (2013) have not been compared here, in view of their short (1-year) records.

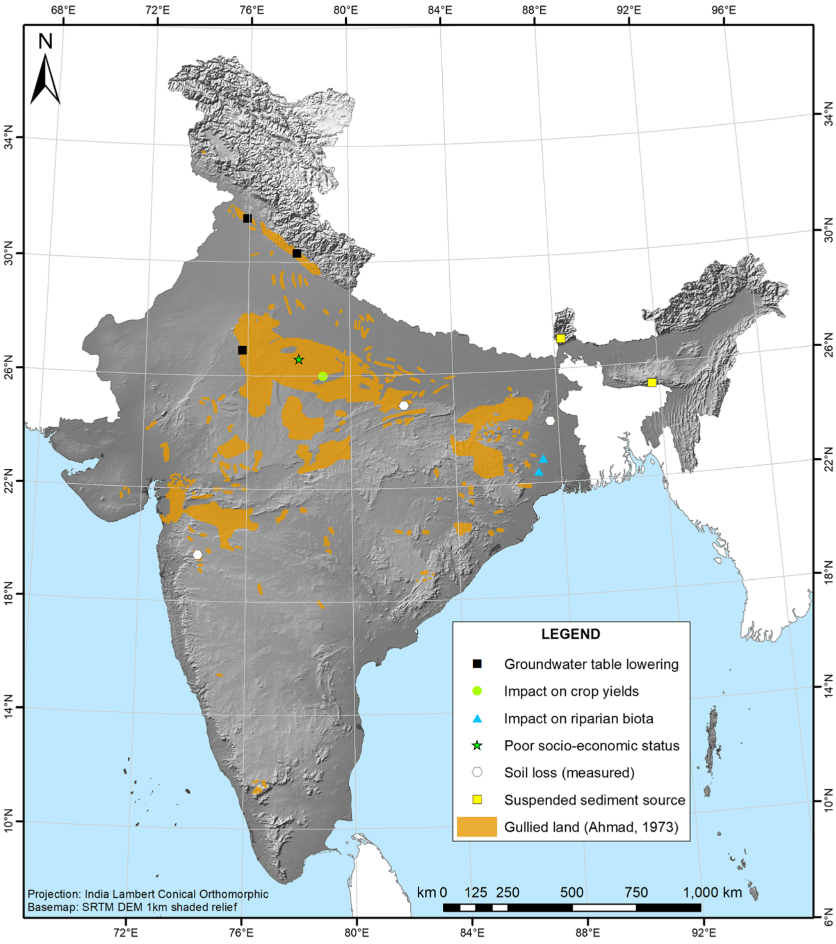


FIGURE 7 Approximate locations of studies reporting various effects of gully erosion in India.

et al., 2006; UNCCD, 2017), infrastructure damage (Imwangana et al., 2015; Nyssen et al., 2002), groundwater table lowering, reduced baseflow and amplified stormflow (Costa & Bacellar, 2007; UNCCD, 2017) and, in extreme cases, desertification and formation of badlands (Avni, 2005; Cánovas et al., 2017; Joshi, 2014b; UNCCD, 2017). Although impacts of gully erosion have not been studied widely in India, similar effects as noted above have been reported from across the country (Figure 7).

6.1 | Effects of gullies

The most obvious effect of gully erosion is soil loss, which a few studies have quantified. After a 2-year monitoring period (2007–2009) using repeated microprofilometer and erosion pin measurements at the quasi-stabilised and partially reclaimed Adula–Mahalungi badlands, Joshi (2014a) calculated gully erosion rate to be 7.6–17.9 t ha^{-1} yr^{-1}. Using the same techniques to measure soil erosion rates over 3 years (1991–1994) at an active badlands area near Deoghat in Uttar Pradesh (YCZ), Singh and Dubey (2002) found gully erosion rates to be one order of magnitude higher: 116.68–176.04 t ha^{-1} yr^{-1}. These figures, which are one of the highest rates of soil loss to gully erosion worldwide, serve to underline the severity of gully erosion in the badlands of Central India. The stark difference in the erosion rates between these two regions can be ascribed to the stages of gully evolution at the respective locales, as both areas have alluvial soils of similar nature and largely identical land use practices.

In Gujarat, Pande et al. (2013) detected the effect of gully erosion in dwindling yields through economic scenario analyses. They further highlighted how the affected farmers tend to fight yield reduction through application of higher doses of fertilisers, which increases their farming costs progressively, while their income decreases. Apart from loss of land and declining yields, another notable on-site impact of gully erosion is lowering of the groundwater table. In India, this has been reported from the Rajasthan Bagar (Spate & Learmonth, 1967, p. 111), Doon valley (Spate & Learmonth, 1967, p. 459) and the Hoshiarpur Chos (Singh, 1971, pp. 115, 155) (Figure 7). Among the off-site effects, Froehlich & Walling (2006) and Froehlich (2004) found through cosmogenic radionuclide analysis that gully erosion constitutes an important source of suspended sediment in streams in the Eastern Himalayas and Meghalaya Plateau respectively, and Kar et al. (2020) highlighted the adverse effects of gully erosion on the biota and fish resources of the Kangsabati and Silai rivers in Eastern India (Figure 7).

6.2 | Effects of badlands

The badlands of the YCZ in Central India have had a host of detrimental effects on the society and environment of the region, to a degree which is rare, if not unprecedented globally. The landscape is so intensively gullied and fragmented that the distribution of villages is governed by the spatial extent of the badlands (Singh, 1971, p. 143). In fact, the growth of large cities such as Agra has also, to some extent, been dictated by the badlands (Singh, 1971, p. 155), and many roads in the region have been built to avoid the badlands belt (Singh, 1971, p. 555). Badlands encroachment has also forced abandonment and relocation of numerous villages in Central India (Pani, 2018; Singh, 1971, p. 524; Tomar & Verma, 2018; Verma et al., 2018), besides crippling agricultural productivity (Kumar & Pani, 2013), causing water scarcity and droughts due to dwindling groundwater level (Sharma & Pani, 2017) and being the reason for the poor socio-economic status of the region (Pani, 2018; Pani & Carling, 2013). All these factors had contributed to a total breakdown of law and order, with gangs gaining a strong foothold in the region in the 1970s (Mudgal, 2005; Sharma & Pani, 2017). The vast badlands provided perfect hideouts for such outlaws and the fact that the region lies at the intersection of three states (namely, Madhya Pradesh, Rajasthan and Uttar Pradesh) made it a safe haven for them (Mudgal, 2005; Sharma & Pani, 2017). Although this threat has now been eliminated, the socio-economic problems related to the badlands persist to this day (Kumar & Pani, 2013; Mudgal, 2005; Pani, 2018; Pani & Carling, 2013). For a thorough, field-based perspective on how the Central Indian badlands have shaped the socio-economic–cultural attributes of the region, the interested reader is referred to the book *Land Degradation and Socio-Economic Development: A Field-based Perspective* authored by Pani (2020).

Similar to the causes of gully erosion, nothing is known about how gullying affects parts of peninsular India. Another major area for further research, especially with climate change looming large, would be to quantify the contribution of gully erosion in catchment sediment yield and assess its spatio-temporal dynamics in different river basins of the country. The role of gully erosion in groundwater table lowering also deserves special attention.

7 | BADLANDS MANAGEMENT: SYSTEM, STRATEGIES, PROBLEMS AND PROSPECTS

7.1 | System and strategies

Post 1950, the Government of India has taken several initiatives to alleviate land degradation problems and thus improve the socio-economic status in and around the badlands of Central and Western India. Soil conservation research institutes were set up at Vasad (Gujarat), Kota (Rajasthan) and Agra (Uttar Pradesh) to specifically study the badlands dynamics, resultant soil erosion and factors aggravating or lessening badlands growth so as to arrive at sound conclusions on efficient land management and reclamation techniques. The first badlands rehabilitation policy was formulated in the early 1970s and several nationally and internationally funded projects were launched subsequently (Haigh, 1984; Kumar, Adhikary, & Dash, 2020; Verma et al., 2018).

Although badlands occur extensively across the states of Uttar Pradesh, Madhya Pradesh, Rajasthan and Gujarat, the lateral expanse or gully morphologies are not similar throughout. Therefore, applying the same categorisation criteria (relative to gully depth and width) was deemed inappropriate and initially a state/region-wise classification system was followed (cf. Haigh, 1984). Bali and Karale (1977) coined the first comprehensive badlands classification system for their management, considering the local climate, soilscape and hydrogeology, besides gully morphologies, and Gupta and Prajapati (1983) subsequently recommended appropriate land management measures for the various reclamative groups. As more insight was gained through experimental works at the Vasad, Kota and Agra badlands research centres (BRC) of the Indian Institute of Soil and Water Conservation (IISWC) during the 1990s and 2000s, the badlands management system and strategies were continually updated. The most recent guidelines published by the IISWC elaborate on pertinent land treatment measures (both hard engineering and soft bio-engineering), along with strategies to maximise ecosystem services and possibilities to improve productivity (crop, fuel, fodder) in order to enhance income generation for the local communities (cf. ICAR-CSWCRTI, 2014; Kumar, Adhikary, & Dash, 2020).

Rudimentary rehabilitation measures include prevention of gully head retreat into the marginal (reclaimed) croplands, runoff attenuation and minimisation of rill and interrill erosion therein. Gully heads are usually stabilised by diverting runoff away and through regulation of runoff ingress into the badlands by construction of earthen marginal bunds and spillways (ICAR-CSWCRTI, 2014; Kumar, Adhikary, & Dash, 2020; Yadav & Bhushan, 1994). Hydro-geomorphologically optimal land holding sizes and appropriate soil conservation measures such as contour bunding and graded terracing in the adjacent arable lands enhance infiltration, facilitate rainwater harvesting and reduce runoff, thereby limiting surface erosion (Bhan & Arora, 2018; Sikka et al., 2018; Soni et al., 2018; Yadav et al., 2003).

The shallow lower-order gullies (≤5 m depth) are then infilled through a combination of (concrete) check damming, erecting vegetative barriers and mechanical levelling (ICAR-CSWCRTI, 2014; Marzolff & Pani, 2018; Pani, 2016; Sikka et al., 2018). Wider higher-order gullies that are deeper than 5 m and cannot be reclaimed by infilling or levelling are under cultivation wherever possible upon stabilisation of the sidewalls and reshaping of the floor. Bench terracing, contour trenching and gully plugging (locally called *Bori bandhan*) are the most frequently implemented soil conservation measures in such gullies (ICAR-CSWCRTI, 2014; Singh & Verma, 2018; Soni et al., 2018).

In tracts unsuitable for agriculture, ecologically beneficial, economically viable and commercially rewarding afforestation is undertaken as part of government-incentivised projects. The potential of various agroforestry systems to arrest the growth of the badlands, improve the soilscape, enhance productivity through provisioning of food crops, timber, fuelwood, fodder etc., thereby ensuring livelihood security and also facilitating income generation, has been thoroughly discussed (Chaturvedi et al., 2018; Ghosh & Mahanta, 2018; Parandiyal et al., 2018). Besides agroforestry, the soil conservation suitability and cost effectiveness of bamboo-based afforestation has also been exhaustively evaluated (Kala et al., 2020; Krishna Rao et al., 2018; Pande et al., 2012, 2017; Singh, Kala, et al., 2015). It is highlighted that bamboo (*Dendrocalamus strictus*) is appropriate to effectively manage about 10,000 km^2 of deep badlands. The dense, deeply penetrating and extensive fibrous root system of bamboo aids in stabilising the gully surfaces and their concentrated foliage suitably acts as rainfall interceptor, thereby considerably reducing splash erosion. It also inhibits (inter)rill erosion through production of sufficient amounts of leaf litter. Unsurprisingly, it is considered to be the most hydrologically favourable plantation in the badlands of India (Sikka et al., 2018). Moreover, bamboo wood can be used for bio-engineering-based gully management practices (e.g., gully plugs, barrier and filter strips) (Kumar, Adhikary, & Dash, 2020), and is commercially viable once fully matured (after 7 years since planting), in addition to the intangible socio-ecological benefits such as retention of soil nutrients and carbon sequestration (Pande et al., 2012; Singh, Kala, et al., 2015). It must, however, be noted that another species of bamboo, *Bambusa bambos*, also widely found in India, is much less resilient to the harsh pedoclimatic conditions of the badlands.

As this review does not aim to expound the various types of gully prevention and rehabilitation measures or the integrated watershed development projects that are implemented in the badlands, we direct the interested reader to consult the guidelines of the IISWC (ICAR-CSWCRTI, 2014; Singh, Kurothe, et al., 2021) as well as recent reviews on badlands rehabilitation techniques and their effects (Bhan & Arora, 2018; Kumar, Adhikary, & Dash, 2020; Sikka et al., 2018; Soni et al., 2018; Tomar & Verma, 2018; Verma et al., 2018), essays on nutrient management approaches for soil health improvement (Dey et al., 2018; Verma & Singh, 2018) and discourses on economic viability, public perception, policy dimensions and ground-level applicability of the badlands management strategies (Balooni, 2003; Dagar & Singh, 2018; Mishra et al., 2018; Pande, Bhatnagar, et al., 2018; Pande, Kurothe, et al., 2018) specific to India.

7.2 | Prospects and problems

The many experimental studies conducted at the three BRCs of the IISWC and beyond have provided valuable land management insights to halt gully growth, reduce the severity of overall land degradation and enhance the productivity of the landscape, in terms of livelihood generation, economic returns and ecosystem services provisioning. Although such investigations are undertaken in a rather localised manner, they highlight efficient management practices for wider adoption (see Table 1). In particular, the value of such landscapes in trapping carbon and protecting biodiversity has been stressed multiple times in the literature (Dagar, 2018; Lal, 2018; Somasundaram et al., 2018; Uthappa et al., 2018). Effectively managed and/or stabilised badlands could also act as geoheritage sites and provide many opportunities for promoting geotourism. Albeit this is quite normal in Europe, the geotourism potential of Indian badlands, like other tropical countries, remain largely untapped (Mandal & Chakrabarty, 2021; Zgłobicki et al., 2021). Ganganir Danga and Erra Matti Dibbalu deserve special mention in this regard, by virtue of being the only two gullied sites in India designated as geomorphosites that are frequented by tourists. However, despite their geomorphosite status, there are currently no laws or guidelines governing geoheritage conservation, and these locations are consequently perceived as mere 'picnic spots' (Patel et al., 2021; Zgłobicki et al., 2021).

Badlands being successfully reclaimed for agriculture in India is a real success story, even though it may not always have happened as per governmental plans. The focus has been on reclaiming the Central Indian badlands (Marzolff & Pani, 2018; Pani, 2016, 2017; Ranga et al., 2016), but similar operations are undertaken in Western India as well (Joshi & Nagare, 2009; Singh, Kumar, et al., 2020). Consequently, the total badlands area has been reduced from 27,650 km^2 in 1976 to 10,370 km^2 in 2014 in the states of Uttar Pradesh, Madhya Pradesh, Rajasthan and Gujarat (Kumar, Adhikary, & Dash, 2020; Singh, Kumar, et al., 2020). Although this is a staggering 62.5% decrement, mostly the shallow and broad U-shaped gullies have been reclaimed due to their accessibility and ease of levelling (Marzolff & Pani, 2018; Kumar, Adhikary, & Dash, 2020; Singh, Kumar, et al., 2020) and vast tracts with deeper gullies remain untreated. Ranga et al. (2016) and Marzolff and Pani (2018) discerned the extents and spatio-temporal patterns of badlands reclamation in the Chambal valley at decadal timescales using historical and recent high-resolution satellite imagery. It was found that in the last 40–45 years 20–23% of the badlands have been levelled, with the reclamation rate accelerating upon passage of time. It was further observed that badlands reclamation is primarily dictated by the gully morphology, distance to drainage lines, proximity to settlements and existing croplands as well as slope and contributing area.

Although badlands obliteration programmes elsewhere have had detrimental impacts on the soilscape, ranging from general deterioration of soil (hydrological) properties (Martínez-Casasnovas & Ramos, 2009; Phillips, 1998; Ramos & Martínez-Casasnovas, 2010) to inhibited infiltration, increased hillslope-channel coupling and consequently augmented erosion rates (Cerdà et al., 2009; Clarke & Rendell, 2000; Peter & Ries, 2013; Peter et al., 2014), similar effects

TABLE 1 Details of the reviewed experimental badlands management studies and pilot projects.

Authors	Location	Key findings
Agnihotri and Yadav (1995)	IISWC BRC Agra (27.167° N; 78.033° E)	Grazed parts of badlands and up-and-downslope tillage practice in marginal croplands inhibits infiltration and augments runoff. Terraced croplands have marginally better infiltration rates, while afforested areas are the most permeable.
Ali et al. (2017, 2020)	IISWC BRC Kota (25.725° N; 75.442° E)	To implement horti-pastoral system in the badlands, a staggered contour trenching density of 417 trenches ha^{-1} is the best. However, 375 trenches ha^{-1} is economically the most optimal.
Bhushan et al. (1992)	Sheetalpur catchment, Hamirpur district, Uttar Pradesh (25.467° N; 79.083° E)	Implementing contour bunding on lands with ≤3% slope gradient and bench terracing on steeper (3–10% slope gradient) sections results in manifold yield increase.
Jha et al. (2010)	IISWC BRC Agra (27.167° N; 78.033° E)	A 25-year-old afforestation in the badlands contributed to twofold increase in soil organic carbon, improvement in soil structure, significant reduction in bulk density and increase in infiltration rates, while reclamation for agriculture had the converse effects.
Joshi and Tambe (2010)	Adula–Mahalungi badlands, Ahmadnagar district, Maharashtra (19.633° N; 74.2° E)	Rainfall simulation experiments in runoff plots with variations in surface (cover) properties highlighted the effectiveness of grass cover in inducing infiltration and concomitantly reducing runoff and soil losses.
Kala et al. (2020), Singh, Kala, et al. (2015), Pande et al. (2012, 2017)	IISWC BRC's Agra (27.167° N; 78.033° E), Kota (25.725° N; 75.442° E) and Vasad (22.267° N; 72.967° E)	Bamboo-based soil conservation techniques stabilise gully sidewalls and floor and considerably reduces runoff and soil erosion rates, besides improving biomass and soil carbon stocks. Economic analysis revealed that when fully matured, i.e. from the seventh year onward, commercialisation fetches the stakeholders INR 30,500–48,000 per hectare.
Kumar et al. (2013)	Kulahri–Johranpur–Sansiwala watershed, Solan district, Himachal Pradesh (30.9° N; 76.85° E)	Loose boulder check dams are effective in controlling first- and second-order (narrow) gullies in the Himalayan foothills.
Kumar, Bhardwaj, Rao, Vishwakarma, Bhatnagar, et al. (2021), Kumar, Bhardwaj, Rao, Vishwakarma, Kakade, et al., (2021)	IISWC BRC Vasad (22.267° N; 72.967° E)	Trenched and terraced gully sidewalls have lower soil loss rates than untreated straight slopes, and are consequently more enriched in soil nutrients, have higher biomass, carbon stocks and fruit yields. Overall, bench terracing was observed to produce the best effects.
Kumar, Bhatnagar, et al. (2020)	IISWC BRC Vasad (22.267° N; 72.967° E)	In an experimental sapota (*Achras zapota*)-based horticultural system, it was observed that conservation measures such as trench and terrace augmented fruit yields during droughts, though uncultivated terraces had highest carbon sequestration. Overall, it highlights the combined potential of agroforestry and soil conservation measures to boost climate resilience of badlands.
Meshram et al. (2020)	Kharashalia watershed, Panchmahal district, Gujarat (22.694° N; 73.556° E)	Series of check dams are effective in stabilising gullies, reducing runoff and soil loss and harvesting water.
Pande, Kurothe, et al. (2018)	IISWC BRC Vasad (22.267° N; 72.967° E)	Agri-horticultural combination of drumstick (*Moringa oleifera*), amla (*Emblica officinalis*) trees and mung bean (*Phaseolus radiatus*) and fennel (*Foeniculum vulgare*) in the badlands of Gujarat is financially more viable than the existing practice of tobacco monocropping.
Prajapati (1998); Prajapati et al. (1989)	IISWC BRC Agra (27.167° N; 78.033° E)	A 10-year goat (*Capra hircus*) grazing experiment in a stabilised badlands site revealed no adverse effects on the soil and hydrological properties of the land. In fact, through droppings and urine, the goats added 22 kg N ha^{-1} year^{-1} to soil, besides fetching INR 2480 ha^{-1} yr^{-1}

TABLE 1 (Continued)

Authors	Location	Key findings
Prajapati et al. (1982)	IISWC BRC Kota (25.725° N; 75.442° E)	Contour furrows, contour trenches, half-slanting pits and saucer pits are useful water-harvesting measures for vegetation development in the badlands of Gujarat.
Rao et al. (1996)	Chinnatekur watershed, Kurnool district, Andhra Pradesh (15.7° N; 78° E)	A combination of contour trenches and runoff diversion waterways in a gully catchment, along with installation of loose rock check dams in the gully channel contributed to lessening of runoff volumes and rising groundwater table.
Rashmi et al. (2021)	IISWC BRC Kota (25.725° N; 75.442° E)	Soil amendments like gypsum, crop residue, farmyard manure reduced soil loss and runoff by 29% and 26% respectively relative to untreated plots, and significantly improved grain yields.
Shit, Pourghasemi, and Bhunia (2020)	Rangamati, Paschim Medinipur district, West Bengal (22.413° N; 87.299° E)	Grass buffer strips are useful for in-channel sediment entrapment in the lateritic gullied lands of Eastern India.
Singh et al. (2014)	Garhkundar–Dabar watershed, Tikamgarh district, Madhya Pradesh (25.45° N; 78.88° E)	Integrated Watershed Management interventions consisting of catchment-based measures like contour bunding and across-slope cropping and gully plugging reduced runoff, increased groundwater level/base flow and soil erosion by more than 50% with respect to the control catchment. A benefit–cost ratio of three and payback period of 4 years was estimated.
Singh et al. (2018)	Bindwa village, Morena District (26.75° N, 70.5° E) and Himmatpur village, Bhind District (25.9° N, 78.2° E), Madhya Pradesh	A combination of earthen check dams in gullies and afforestation of the sidewalls and intergully areas results in increased soil depth, improved soil fertility conditions and groundwater recharge, which in turn bettered crop yields and vegetation growth. High benefit–cost ratios (>5) indicate the investment's feasibility.
Sran et al. (2012)	Hoshiarpur Chos, Punjab (31.6° N, 76° E)	Loose rock check dams reinforced with grass on the upstream side can effectively stabilise first-order gullies, managing which should be a priority (instead of the higher-order, larger gullies where check dams often fail).
Yadav and Bhushan (1994)	IISWC BRC Agra (27.167° N; 78.033° E)	Prefabricated drop spillways are equally as effective as, but cheaper than in situ constructed structures for safe runoff diversion in badlands.
Yadav and Bhushan (2002)	Multiple locations in Uttar Pradesh, Madhya Pradesh, Rajasthan and Gujarat	Integrated watershed management strategies for rehabilitation of badlands reduce runoff and sediment yields, sustainably increases crop production and is well received by the local communities.
Yadav et al. (2003)	IISWC BRC Agra (27.167° N; 78.033° E)	Plot-based experiments indicated that plot dimensions of 18 m by 3.6 m and 0.9 m wide partitioning are best to amplify infiltration, reduce runoff and soil erosion in reclaimed croplands.

have not yet been reported from the reclaimed badlands in India. Gullies have, however, been observed to reappear in levelled areas (Pani, 2017; Ranga et al., 2016), meaning that persistent land management is necessitated after levelling operations.

Nevertheless, badlands rehabilitation in India has been plagued with many policy-related problems and marred by numerous setbacks pertaining to ground-level applications. This is in large part due to the abnormally ambitious nature of the various governmental projects, especially the earlier ones. For example, the central government aimed in 1971 to reclaim 550 km^2 of land for agriculture and 275 km^2 for forestry and pastureland but the plans were never realised. The state government of Madhya Pradesh once framed a plan to level the badlands mechanically using bulldozers and earth movers, which unsurprisingly failed. Later, they attempted badlands afforestation through aerial seeding of *Babool* (*Acacia nilotica*) and other hardy plant species. This scheme proved to be horribly wide of the mark as the seeds so dropped were washed off and ended up in the farmlands more often than not, germinating therein and severely hindering agriculture in turn. These plants further suppressed the indigenous vegetation and created a fodder shortage (Mudgal, 2005; Sebastian, 2001). Poor to non-existent coordination between the concerned state governments and absence of any kind of liaison across departments of the same government have also been notable bottlenecks in the way of badlands rehabilitation in India (Pani, 2016; Singh & Agnihotri, 1987).

Another long-standing drawback of the badlands management initiatives has been the poor integration of local communities. This has meant that in most cases the projects have not benefitted from the wealth of knowledge the villagers residing in proximity of the badlands possess about the surroundings (Pani, 2016; Venkatesh, 2016). Although known to be detrimental to any kind of land management interventions (Pawluk et al., 1992), this is not unexpected in a top-down policy formulation system (Pani, 2016; Yadav & Bhushan, 2002). Besides the government, local communities have long been fighting against the menace of the badlands (Tomar & Verma, 2018; Venkatesh, 2016) and trying to reclaim lost lands through manual labour (Pani, 2016). However, large-scale badlands reclamation is a costly enterprise that only a few affluent farmers can afford when it is not being supported governmentally. This means that, while small farmers are only ever able to reclaim meagre patches, the powerful ones acquire large areas through use of land-levelling machinery and paid labour. This creates land ownership disparities owing to rare amendments in land records and further marginalises the poorer households, leading to social conflicts in a region that is infamous for its history of lawlessness (Pani, 2016, 2017).

Although we have discussed the environmental and economic viability of badlands rehabilitation through agroforestry and bamboo afforestation, such projects are few and far between. As wealthy farmers are increasingly intent on filling in the deeper gullies, which used to serve as grazing lands and was a means of livelihood in general for the poor and landless villagers, many are forced to migrate to nearby urban areas in search of jobs. This is altering the demographic character of the region manifold. Besides, land levelling has had multiple effects on the ecology and biodiversity of the badlands, including disappearance of indigenous plant species and loss of habitat for wild animals, which are mostly overlooked (Pani, 2016, 2017).

Although it is understandable as to why the gully rehabilitation priorities in India have revolved around the badlands of Central and Western India, this has meant that other gullied regions have largely been neglected, most importantly the Chhotanagpur and Punjab zones, which also experience serious gully erosion problems (see Figure 1). In fact, we have found that, to date, only five papers have been published on gully management outside of the two badlands regions (e.g., Joshi & Tambe, 2010; Kumar et al., 2013; Rao et al., 1996; Shit, Pourghasemi, & Bhunia, 2020; Sran et al., 2012) (see Table 1). It is possible that other regions have received interventions that have not been written about, either as reports or scientific papers, but it appears that there exists a geographical imbalance as regards gully management in India, which is likely linked to governmental policies prioritising the management and reclamation of the badlands in Central and Western India.

8 | DISCUSSION

Gullies of India occur in a wide range of soil types, geomorphic regions and physiographic provinces. Mainly observed alongside rivers as bank gullies or on hillslopes (valley-side gullies), their genesis and geomorphology vary considerably across the country. Extensive gully erosion has resulted in the formation of badlands in Central and Western India, which are quite striking erosional features. Their scale (both individual gullies as well as the entire eroding landscape), the material they have dissected (alluvium), the process interactions that contributed to their formation, as well as the host of deleterious effects they have had on the environment and society, are not just rare but exceptional. Although the states where the badlands are located (viz. Uttar Pradesh, Madhya Pradesh, Rajasthan, Gujarat and Maharashtra) are faced with the severest problem, gully erosion in India is a countrywide issue that affects 23 of her 28 states (NRSC, 2019).

Case studies describing natural gully formation are not common in the global gully erosion literature, with the few studies that do report it mostly referring to intense rainstorm events (e.g., Nachtergaele et al., 2002; Parkner et al., 2006; Yang et al., 2019). However, we have found that gullies in many locations across India have formed due to the inherent properties of soils making them susceptible to gullying. Nevertheless, the most serious and extensive gully erosion in extra-peninsular India, notably the (Sub-)Himalayan region and the Eastern Plateaux, have been induced by anthropogenic drivers such as deforestation, overgrazing and shifting cultivation practices. Mismanagement of croplands and road building have also locally caused gully initiation in the said regions. Although the badlands of Central and Western India have largely developed in response to natural drivers, namely neotectonics and Holocene climate change, land cover changes have possibly had exacerbating effects. Although gullies and badlands of India may be unique in terms of their geomorphological characteristics and land degradation effects, the anthropogenic factors that have driven their formation are not (cf. Castillo & Gómez, 2016).

Badlands are observed along certain alluvial river reaches in India's heartland as well as in the western states of Gujarat and Maharashtra. Genesis of both Central and Western Indian badlands can be ascribed to the same factors (neotectonics and Early Holocene monsoon strengthening), but those in the west are relatively more localised (allowing to better understand the period of their formation and evolution, which is constrained to 10–6 ka), because of strong structural control of rifts and tiltblocks in the region limiting their expansion. In contrast, the lateral extent of the badlands of Central India are much greater, as is their drainage density. Such extensive badlands development is possibly due to the high erodibility of the soilscape caused by the prevalence of shrinking–swelling clays and calcite, likely worsened by large-scale deforestation in the last few centuries. Field evidence suggests that presence of palaeochannels has also abetted the growth of Central India's badlands.

Gully/badlands mapping has been undertaken in India since the 1970s, although the initial focus was exclusively on mapping the badlands as part of rehabilitation programmes. Gully mapping is a relatively recent endeavour and has almost exclusively been undertaken in Eastern India. Mapping methodologies have changed considerably over time, helped by the advances in remote sensing and availability of new means of data processing. What started with manual interpretation of aerial photographs is now being performed semi-automatically using various machine learning methods. However, the mapping focus and spatial extent (individual gully channels, gully systems or entire badlands) have remained a key consideration in selecting the type and resolution of imagery to be used. Using machine learning or similar data-driven methods to map gully occurrence has become a very popular subject of research worldwide (e.g., Arabameri et al., 2018; Conoscenti et al., 2013; Jiang et al., 2021; Rahmati et al., 2017), and India is no exception, with 70% of the mapping studies we have reviewed being of this kind.

Although the differences in gully morphologies across India as visualised in Figure 1 are obvious, there is no quantitative account of these spatial patterns. Studies on geomorphological aspects of gullies have been sporadic, with Eastern Indian sites receiving the greatest attention. Most papers on gully geomorphology have focused on enumeration of catchment-wide morphometric parameters, rather than examining the topographic threshold conditions of gully initiation, morphological characteristics of gullies and their temporal dynamics. For instance, India was an absentee in the global meta-analysis of Torri and Poesen (2014) on gully initiation thresholds that reviewed studies from other global south nations such as Uganda, Tanzania, Ethiopia, Brazil, China, Iran and Thailand. Unlike India, gully morphology and/or dynamics have been well studied in several Chinese regions affected by gully erosion (e.g., Cheng et al., 2007; Deng et al., 2015; Li et al., 2019; Wang et al., 2023; Wu et al., 2018) as well as in the Ethiopian highlands (e.g. Frankl et al., 2012, 2013; Nyssen et al., 2006; Yibeltal et al., 2019; Zegeye et al., 2016) or Nigeria (e.g., Adediji et al., 2013; Ehiorobo & Ogirigbo, 2013; Fashae et al., 2022; Osumgborogwu et al., 2022), to name a few. India really lags in these aspects of gully erosion research, which precludes analysis of the formation conditions, morphologies and growth rates of gullies across different regions of India as well as with those of other countries. Similar gaps exist in our understanding of the role of gully erosion in controlling catchment sediment yield in different physiographic regions or river basins of the country. We have, however, been able to analyse gully frequency and density values obtained from several morphometric studies conducted across extra-peninsular India (Figure 5), which has allowed us to understand formation and evolution of gullies in similar (alluvial) soilscapes. It appears that, even after new gully heads cease to form, gullies in badlands areas continue to grow in length, likely due to stream capturing and anabranching.

The Central Indian badlands are the root cause of the poor socio-economic status of the region. From forcing abandonment of entire villages, hampering agricultural productivity, causing water scarcity to providing refuge to criminal gangs, they have affected the communities of the region in more ways than one. Unsurprisingly, reclamation of the badlands was one of the policy priorities of independent India. Consequently, there has been steady research assessing the efficacy of various land management measures implemented therein, unlike that of other gullied regions of India. We highlight that badlands reclamation is a success story in India, but also note the several socio-economic, ecological and environmentally adverse effects that stem from it. The geoconservation argument premised on the notion that these landscapes should be viewed as geoheritage/geodiversity sites and protected also holds relevance.

9 | CONCLUSIONS

Gully erosion is observed across the length and breadth of India. It becomes especially acute in Central and Western India, wherein it has resulted in the formation of extensive badlands. The presence of gullies in many different soilscapes and physiographic provinces and the formation of vast badlands owing to natural factors such as neotectonics, Holocene climate change and high soil erodibility are unique aspects of gully erosion in India. However, despite its widespread occurrence and obvious land degradation effects, gully erosion has not been well studied in India. For instance, among other nations of the global south, characteristics of gully erosion are much better understood in China, Ethiopia or Nigeria, akin to countries of Mediterranean and Western Europe. As gully erosion is by far the most serious impediment in the way of India's mission to achieve land degradation neutrality by 2030 (cf. Mandal & Giri, 2021), systematic research efforts to investigate drivers, geomorphology and land degradation effects of gullies across India are necessary.

Castillo and Gómez (2016) discussed multicausal and non-coincidental gully initiation in their landmark review. Along the same lines, we have found that anthropogenic influence in the form of deforestation, overgrazing and shifting cultivation practices has caused gully formation in the (Sub-)Himalayan belt and Eastern Plateaux. However, there is little information on the causes of gully formation in other parts of the country and their evolutionary timeline can only be speculated upon. There is thus a real need for further research to establish the chronology of gully development in different parts of India. Approaches to develop the necessary understanding could range from conventional archival research methods to state-of-the-art sediment fingerprinting techniques, which would allow reconstructing the environmental history of the region being studied. Further work is also required to understand the effects of recent land cover changes on gully/badlands evolution, for example in the case of the Central Indian badlands.

In keeping with the global research thrust on large-scale data-driven mapping of gully occurrence (cf. Vanmaercke et al., 2021), many studies of this type have been undertaken in India. However, spatial information on the extent of gully systems and badlands of India are already available at a scale of 1:50,000 (23.5 m horizontal resolution). Therefore, gully occurrence studies are not very useful unless there is a considerable improvement in terms of resolution/scale, relative to the existing datasets, which we did not note of in any of the reviewed data-driven mapping studies. Spatially explicit modelling of gully system characteristics, such as gully head density (cf. Vanmaercke et al., 2020) using similar data-driven mapping methodologies are potentially more informative.

Generally speaking, while much work has been done to determine morphometric characteristics of gullied catchments in India, knowledge of gully processes is almost non-existent, as was also noted by Castillo and Gómez (2016) as a global research gap. Although short-term morphological measurements do not contribute to understanding the spatio-temporal variability of gully dynamics (Castillo & Gómez, 2016), they are useful in quantifying soil losses to gully erosion. Besides morphological accounts, quantification of critical slope–area thresholds is crucial in analysing the formation of gully heads in different regions (Torri & Poesen, 2014), and the importance of long-term gully monitoring with standardised survey or remote sensing techniques cannot be overstated in the analysis of gully erosion dynamics (Castillo & Gómez, 2016). Unfortunately, there remain glaring shortcomings on each of these aspects of gully erosion research across India. It is also vital to compute the share of gully erosion in the sediment budget of Indian river basins, as it is to better understand the effects of gully erosion, such as its possible role in inducing groundwater decline.

Our review also highlights a concentration of studies in only some parts of India with scant attention accorded to other regions. An overwhelming majority of our reviewed studies were conducted in the northern half of the country (i.e. extra-peninsular India), with just 9% of the studies undertaken in the states of peninsular India. Though gullies and badlands of Western, Central and Eastern India (i.e., the states of Rajasthan, Gujarat, Maharashtra, Madhya Pradesh, Uttar Pradesh, Jharkhand and West Bengal) have overall been well studied, the same cannot be said about that of the Himalayas and Sub-Himalayan tracts, which account for about 11% of the papers reviewed. However, it is worth noting that gullying affects more than half a million hectares of land in the peninsular, Himalayan and Sub-Himalayan states of India taken together (NRSC, 2019). There is thus an urgent need for increasing the spatial ambit of gully erosion research in India.

AUTHOR CONTRIBUTIONS

AM conceptualised this review, framed the review methodology, collated the literature, conducted the study and wrote the first draft of the paper. AH, ME and ES reviewed and revised several drafts of the paper.

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CONFLICT OF INTEREST STATEMENT

The authors declare that no new data has been created through this study. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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