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RESEARCH ARTICLE

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Predicting gully erosion susceptibility in South Africa by integrating literature directives with regional spatial data

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Abstract

Gully erosion has been identified as a severe land degradation process with environmental and socio-economic consequences. Identifying areas susceptible to gully erosion will aid in developing strategies to inhibit future degradation. Various approaches have been implemented to predict and map gully erosion susceptibility but are mostly restricted to small geographical extents because of process limitations. Here, we introduce a novel method that predicts gully erosion susceptibility on a regional/national scale (1.22 million km^2) by synthesising literature directives with a statistical approach. Findings from a literature review were used to extract physiographic properties associated with gully erosion that was conditioned to characterise susceptibility by using the Frequency Ratio model. The conditioned physiographic properties were aggregated by a weighted overlay procedure using an aggregation of controlling factors derived from the literature review as a weighting system. The gully susceptibility index (GSI) model was validated against a published gully inventory map ($n = 163\,019$) and randomly generated 1-km^2 tessellation zones from which primary validation data were derived. Although uncertainties within the modelling procedure exist (e.g., gully site distribution, the spatial resolution of input data and determination of gully points), the validation shows that the GSI model is generally robust, identifying areas of contrasting susceptibilities. Furthermore, findings converge with other susceptibility metrics, which have been derived by different methodologies. Because empirical gully erosion research has been conducted worldwide, this model could be applied to regional-scale gully susceptibility modelling assessments (as a solitary method or combined with primary data) in other parts of the world. Additionally, the GSI model can be adopted to model environmental change scenarios.

KEYWORDS
climate change, frequency ratio, GIS, gully erosion, modelling, South Africa, susceptibility, weighted overlay

1 | INTRODUCTION

Gully erosion is a form of channelised water erosion, which range in size from small drainage patterns on agricultural land that can easily be filled with conventional tillage methods (e.g., Wells et al., 2016; Zhang et al., 2007), to dramatic landscape scars several meters in depth and width (e.g., Hudec et al., 2005; Vanmaercke et al., 2021) - (Figure 1). Irrespective of their appearance, gullying has been shown to be the dominant erosive form when active in a catchment (Shellberg & Brooks, 2012; Wu et al., 2008), comprising up to 94% of total soil loss when considering world data (Bennett et al., 2000; Poesen et al., 2003). Soil loss incurred from gully erosion affects land

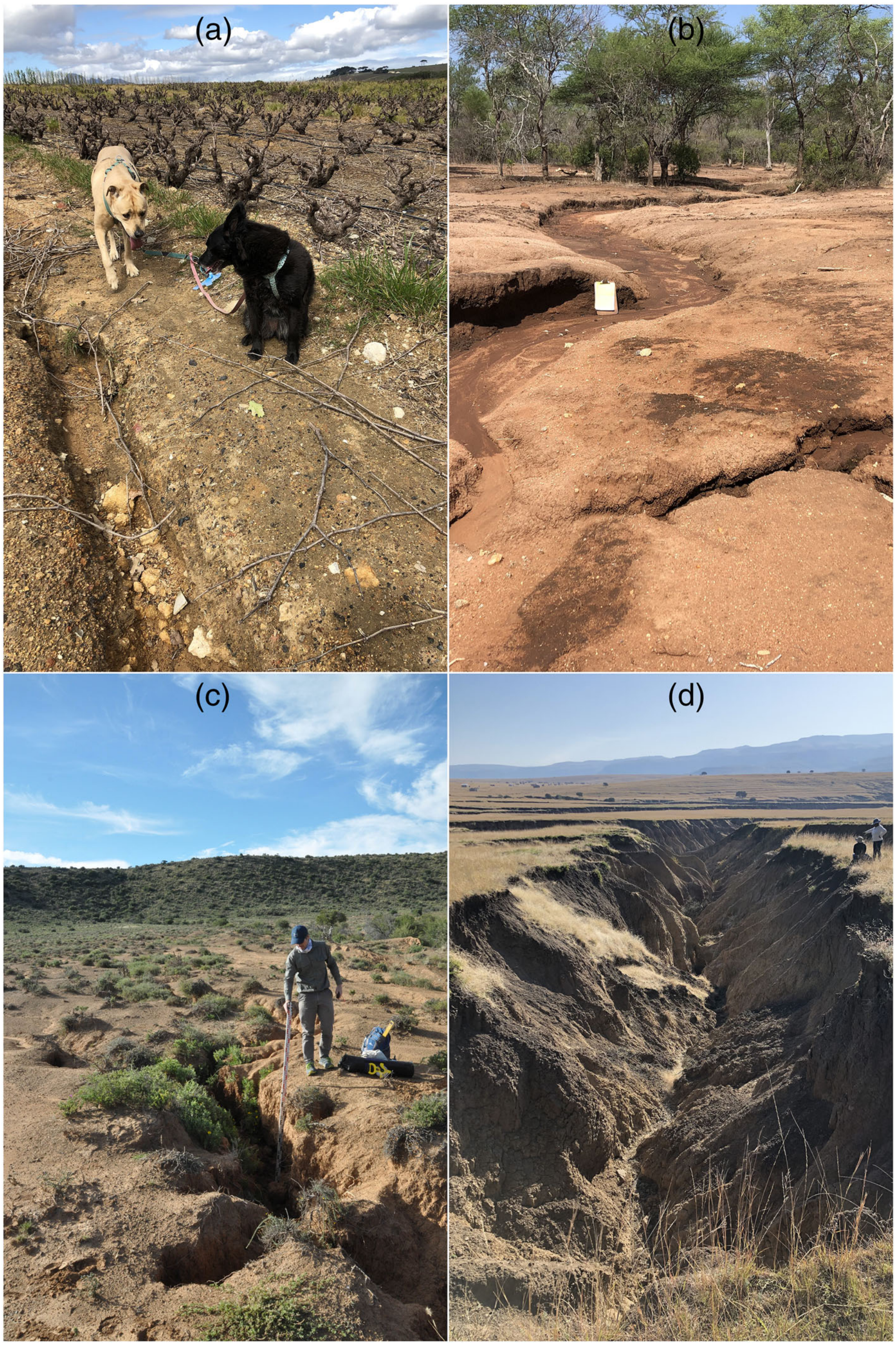

FIGURE 1 Examples of gullies found in different land-uses and varying levels of magnitude in South Africa: (a) a gully in proximity to a bush vine vineyard in the Cape Winelands, Stellenbosch; (b) a sinuous gully on a private game reserve in the Savanna biome in the Lowveld, close to Ofcolaco; (c) a deep narrow gully found on rangeland in the Karoo, close to Graaff Reinet; (d) a mother gully found in the Grasslands biome where communal tenure is practiced, close to Nqanqrhu (photographs by George Olivier [a,b,d] and Marco Van De Wiel [c]). [Color figure can be viewed at wileyonlinelibrary.com]

and water resources resulting in environmental and socio-economic pressures.

Mapping gully features can show the distribution thereof and be used to indicate vulnerability to gullying (Vanmaercke et al., 2021). Creating large gully inventories from manual mapping is, however, scarce because of the labour-intensive workflow (Mararakanye & Le Roux, 2012), whereas results are influenced by image resolution and interpretation of the cartographer. Mapping gully susceptibility can overcome the limitations associated with manual mapping, conserving the outcome to identify gully-prone areas where mitigation and rehabilitation works can be focused (Le Roux & Van der Waal, 2020).

Gully susceptibility mapping makes use of conditioned factor maps as input. Determining the input factors is critical as it needs to represent the factors, which can work independently or synergistically, to control gullying. Lithology, soil, rainfall, topography and anthropogenic influences should be considered as they are the main factors exerting a control over gully processes (Castillo & Gómez, 2016; Poesen et al., 2003; Valentin et al., 2005) because of their capacity to increase soil erodibility and/or concentrated surface or sub-surface water flow (Bocco, 1991; Nordström, 1988; Patton & Schumm, 1975). The rock type of parent material can exert an influence on the physical and chemical properties of a soil, controlling erodibility (Laker, 2004) that affects gully susceptibility (Rienks et al., 2000), morphology (Imeson & Kwaad, 1980; Shellberg & Brooks, 2012) and the dominant erosive process (Bernatek-Jakiel & Poesen, 2018). Rainfall characteristics exert a control over gullying (Vanmaercke et al., 2016) because of its impact on concentrated surface and sub-surface water flow, and the distribution of rainfall also impacts antecedent soil moisture affecting the erodibility of a soil (Anderson et al., 2021). Topography directs water flow from rainfall, therefore, regulating the volume and velocity of concentrated flow, affecting gully susceptibility (Gómez-Gutiérrez et al., 2015; Parkner et al., 2006; Rossi et al., 2015). Overwhelming evidence suggests that anthropogenic activities are accelerating gully erosion (Castillo & Gómez, 2016; Olivier et al., 2023). Human influences that expose gully-prone pre-conditions and/or increase concentrated include land-use change to farming (Boardman et al., 2003; Zucca et al., 2006), commercial farming intensification (cultivated and rangelands) (Shellberg & Brooks, 2012; Talbot, 1947), population pressure in communal areas resulting in deforestation and overgrazing (Grellier et al., 2012; Le Roux & Sumner, 2012) and abandonment of cultivated fields (Kakembo & Rowntree, 2003; Lesschen et al., 2008). Infrastructure and movement corridors have also led to gullying, for example, roads including road culverts (Moeyersons et al., 2015; Seutloali et al., 2016) and footpaths (both from animal and humans) (Le Roux & Sumner, 2012; Nir et al., 2021).

Lithology (Azedou et al., 2021; Dewitte et al., 2015; Saha et al., 2020) and soil (Domazetović et al., 2019; Rahmati et al., 2016; Shit et al., 2015) classification maps are frequently used as input factor maps. Topographical factors are generally used as multiple inputs consisting of first- (slope and aspect) and second-order terrain derivatives (curvature). Additionally, terrain-derived hydrological parameters such as stream density, distance to stream, contributing drainage area, Stream Power Index (SPI) and Total Wetness Index (TWI) (see Azedou et al., 2021; Dewitte et al., 2015; Domazetović et al., 2019; Garosi et al., 2018; Gómez-Gutiérrez et al., 2015; Lucà et al., 2011; Rahmati et al., 2016; Rahmati et al., 2017; Saha et al., 2020). Anthropogenic activities are mostly represented by land-use/land-cover maps (Azedou et al., 2021; Lucà et al., 2011; Rahmati et al., 2017). Rainfall and climate inputs are rarely used as inputs (Arabameri et al., 2019; Nhu et al., 2020) because there is generally not enough climatic variability within the geographical extent in which gully susceptibility mapping is applied to justify inclusion.

Several methods exist to aggregate the conditioned factor maps to produce gully susceptibility maps. These mapping procedures can be divided into three broad categories (Arabameri et al., 2020): (1) multi-criteria decision-making (MCDM), (2) statistical methods and (3) machine learning. MCDM includes analytical hierarchy procedure (AHP) (Arabameri et al., 2019; Domazetović et al., 2019; Makaya et al., 2019). Statistical methods include approaches such as the certainty factor, linear or logistic regression, frequency ratio, weight of evidence and index of entropy (Conoscenti et al., 2014; Dewitte et al., 2015; Dube et al., 2014; Garosi et al., 2018; Lucà et al., 2011; Rahmati et al., 2016; Zabihi et al., 2018). Machine learning algorithms include procedures such as support vector machine, random forest, Naïve Bayes, artificial neural networks, maximum entropy, classification and regression trees (Eustace et al., 2011; Garosi et al., 2019; Hosseinalizadeh et al., 2019; Phinzi et al., 2020; Pourghasemi et al., 2020; Saha et al., 2020; Taruvinga, 2008). Despite an increase in global gully erosion research, and thus an increase in associated sites where gullying is investigated (Castillo & Gómez, 2016), using existing literature as a directive to predict gully susceptibility has not been tested to the authors' knowledge. Gully erosion research sites from literature can be used to train data and compile a factorial database from expert analysis of the main causes of gullying, which can be used as a standardised weighing scale. Furthermore, findings regarding the severity of activity can be implemented as an additional scalable weight. Gully susceptibility modelling from literature directives has the potential to be used as standalone input on a regional scale, depending on the distribution of gully erosion sites in the research area of interest. The impact of climate and rainfall becomes significant at such scales (Vanmaercke et al., 2016) and warrants inclusion, which may also benefit modelling efforts to test gully susceptibility to climate change. Additionally, data mined from literature can be supplementary and used as additional data points, when conducting a high-resolution analysis on a smaller geographical extent. Data from literature can be readily combined with existing approaches, namely, MCDM, statistical approaches, or machine learning.

In this study, we test the applicability of using data mined from gully erosion research sites in published literature as training data points to map gully susceptibility on a national scale in South Africa (SA).

Our research aims to (1) capture local physiographic properties associated with gullying from published case studies (land-use/land-cover, geology, soil and topography) and combine it with global factors (climate) to predict gully susceptibility on a national scale and (2) to validate these findings with an existing gully inventory map for SA (Mararakanye & Le Roux, 2012), in addition to 15 randomly selected zones, each consisting of a singular susceptibility class, 1 km^2 in extent. If successful, this gully susceptibility mapping procedure should be transferrable to other countries even if different geomorphic and physiographic conditions exhibit and geographic extents vary, provided gully case studies have been conducted there previously.

2 | METHODOLOGY

2.1 | Study area

SA is located on the southern-most tip of Africa between 22°S and 35°S and 15°E and 33°E and is approximately 1.22 million km^2 in extent. Erosion in SA is not a recent phenomenon, with King (1963) remarking that gullies are prominent landscape features in SA. Mararakanye and Le Roux (2012) mapped gully features larger than 10 m in dimension from SPOT-5 imagery, finding gullies to be widespread (Figure 2). They found gullies to be prevalent in the Karoo (northern Eastern Cape and south-eastern Northern Cape), former homelands areas (eastern Eastern Cape, central North West, northern and south-western KwaZulu Natal, south-eastern and north-eastern Limpopo and along the provincial border of the Free State with the Eastern Cape and KwaZulu Natal) and in the Grasslands biome in the Free State along the Lesotho border (see Figure 2 for mapped gullies, Figure 3a for the geographical extent of the Karoo and former homelands and Figure 3d for the biome classification map). Scattered gullying also occurs in the Western Cape (Fynbos and Karoo biomes), Mpumalanga (Grasslands biome; Figure 3d) and the rest of the Northern Cape (Karoo biome) (see Figures 2 and 3d).

Many of the gullies can be considered 'old'. In the Swartland region, Talbot (1947) investigated severe erosion and gullying due to the intensification of cultivation in the 1930s. Gully networks in the Karoo have mainly been attributed to ox wagon trackways that were developed in the late 19th century (Neville et al., 1994), a change to European farming systems and intensification on rangelands leading to overgrazing in the late 19th and early 20th century (Keay-Bright &

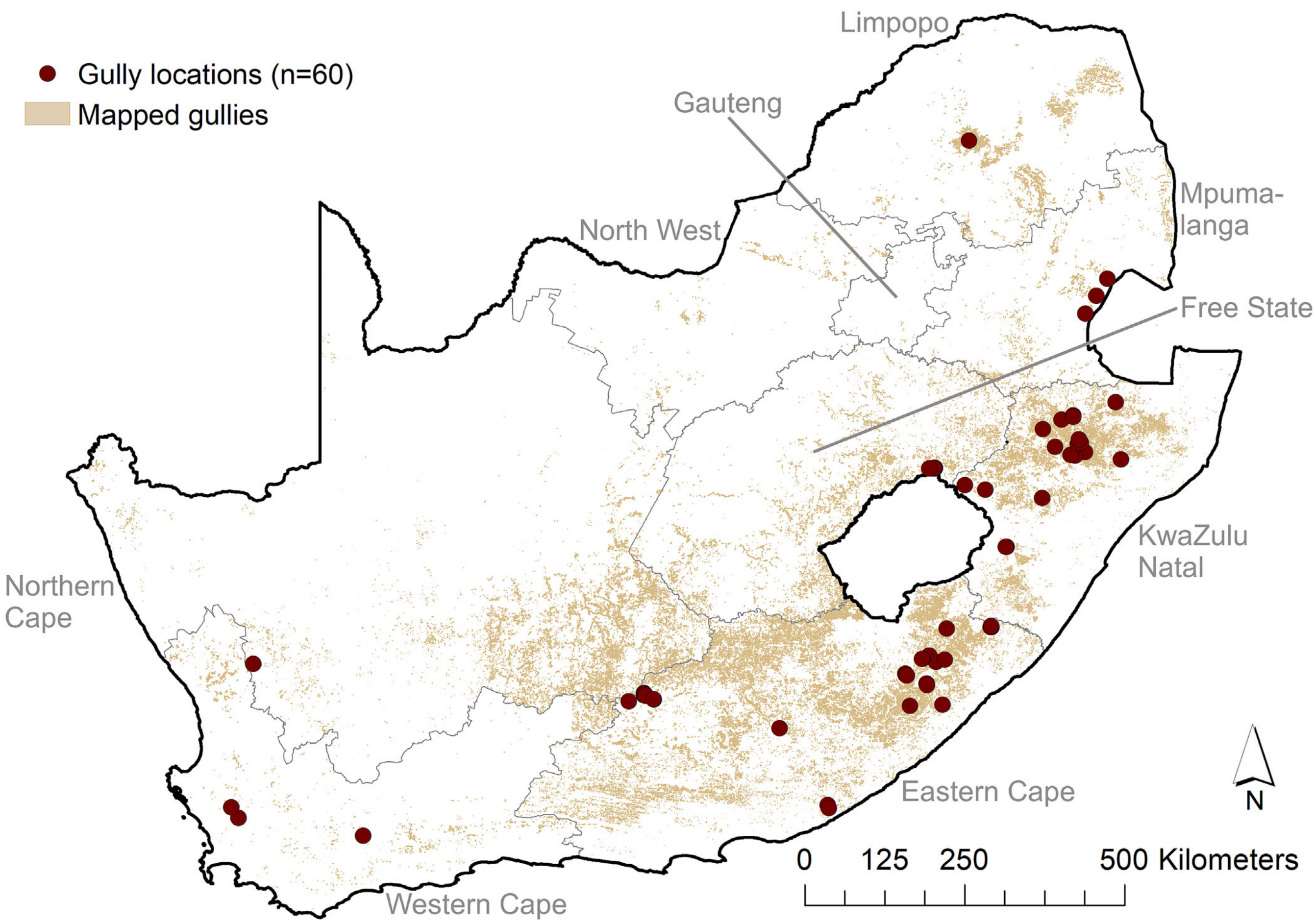

FIGURE 2 Mapped gully features in South Africa from SPOT-5 imagery by Mararakanye & Le Roux (2012), overlaid with gully research sites. [Color figure can be viewed at wileyonlinelibrary.com]

Boardman, 2007; Rowntree, 2013). In the former homelands, which were established in the 1960s, severe land degradation, including gullying, occurred from population pressures in an environment susceptible to erosion (Hoffman & Ashwell, 2001). Gully erosion, mostly in the north-east of SA, has been argued to have an even earlier origin, emerging from climatic disturbances (Lyons et al., 2013; Temme et al., 2008).

A recent review by Olivier et al. (2023) showed contemporary gullying to be a continued concern in SA. Gully erosion rates of up to 25.7 t ha^{-1} year^{-1} (Grellier et al., 2012) are documented, which increases to up to 123.7 t ha^{-1} year^{-1} (Favis-Mortlock et al., 2018) when badlands are included. These contemporary erosion rates exceed the upper limits of the SA baseline (0.64 t ha^{-1} year^{-1} by Reinwarth et al., 2019) and sustainable threshold (10 t ha^{-1} year^{-1} by McPhee & Smithen, 1984) rates established for SA. Currently, contemporary gullying in SA, as in the rest of the world, is driven by a complex synergistic relationship between human and natural controls (Castillo & Gómez, 2016; Olivier et al., 2023).

SA exhibits a diversity of natural controls. SA has marked rainfall regions, which are dominated by a large summer rainfall region, apart from a winter rainfall region in the west and an all-year winter rainfall region in the SW Cape (Schulze & Maharaj, 2006). Mean annual rainfall exhibits a W-E climate gradient (De Wit & Stankiewicz, 2006), generally increasing from west to east (Figure 2c). Arid regions with a mean annual rainfall below 200 mm are found in the west, becoming sub-humid to humid in the east where mean annual rainfall can exceed 1000 mm (Schulze et al., 2006). The natural vegetation is reflected by the E-W rainfall gradient, consisting of nine broadly classified biomes (Mucina & Rutherford, 2006) (Figure 2b). To the west, the unique Fynbos biome, which consists of small shrubs and succulents, is situated within the winter rainfall region, extending partially into the all-year rainfall region. The succulent Karoo and Nama-Karoo biomes cover much of the arid interior of SA, which transitions to the Albany Thicket biome that gives way to Grasslands in the east. To the north-east, the Karoo biomes change to Savanna. The forest biome is interspersed in the all-year rainfall region and the humid east, with the Indian Ocean Coastal Belt biome found on the eastern coastal area.

The natural vegetation in SA has been extensively disturbed to make room for agriculture. The agricultural regions closely follow the biomes (Hoffman & Ashwell, 2001; Waldner et al., 2017) (Figure 2c). Grains and fruit are found in the west, which transitions to sheep farming in the arid to semi-arid interior. Cattle farming and subsistence farming are found in the southern and south-western Grasslands and Savanna in the north. The Grasslands biome in central SA is used for grains, and forestry and sugar plantations are found in the humid east. Vegetables are found interspersed between these agricultural regions in the south and north-east (Hoffman & Todd, 2000).

SA has a narrow coastal region, separated from a vast plateau by the Great Escarpment (Moore et al., 2009), which is at its highest in the western Drakensberg range (Figure 2a). The inland plateau gradually slopes downwards from 1500 m in the east to 1000 m in the west (Hoffman & Ashwell, 2001) and comprises a sedimentary basin (Moore et al., 2009), with scattered mafic intrusions. The Bushveld Complex is

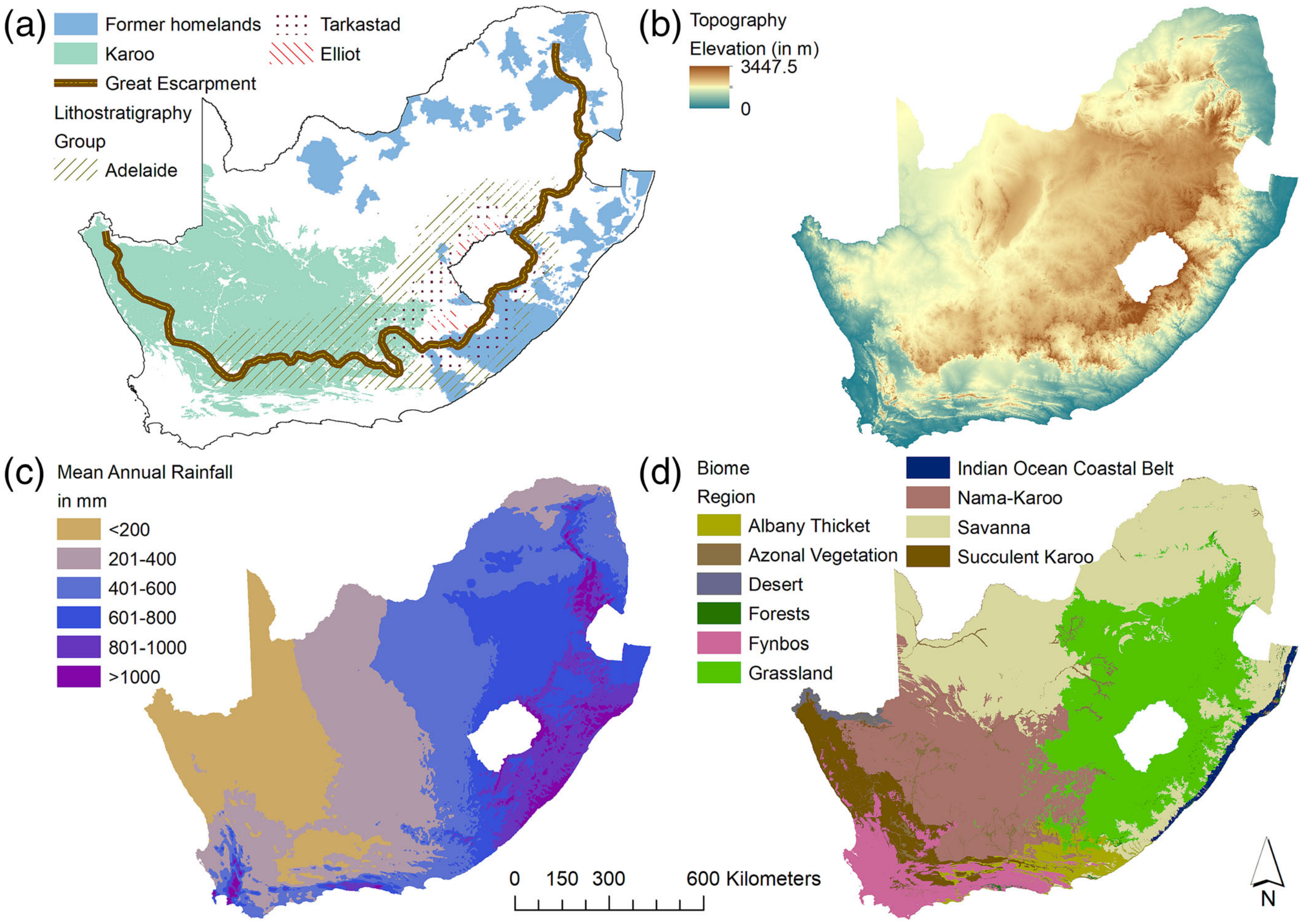

FIGURE 3 Study area map: (a) introductory map showing areas and lithology locations commonly referred to in text; (b) topography; (c) mean annual rainfall; and (d) biomes found in South Africa. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Broad South African soil classes with a short description of soil concept from Fey (2010a) and Fey (2010b).

South African soil class	Soil concept	Comparison to world reference base
Red-yellow apedal soils	Mostly freely drained, iron enrichment (residual); uniform colour with structured B	Ferralsols and Latosols
Plinthic soils (soft B)	Soft B, iron enrichment, mottling or some cementation	Plinthosols
Glenrosa and Mispah (Inseptic lithic soils)	Young soil on weathered rock	Cambisols and Leptosols
Duplex dominant	Permeable topsoil with marked clay enrichment resulting in contrast texture in subsoil	Stagnosols, Solonchaks and Luvisols
Undifferentiated soils	Variable soil associations	More than one soil form occurs
Ferrihumic horizon (Podzolic soil)	Diagnostic podzol B, metal humate enrichment	Podzols
Grey regic sands (Cumulic soil)	Freely drained, young soil formed on recently deposited colluvial, alluvial or aeolian sediment	Cambisols Arenosols Fluvisols Luvisols Acrisols Lixisols
Rocky, with little soil	N/A	N/A

situated in the north-east and comprises the world's largest mafic intrusion (Maier et al., 2013). Felsic intrusions are also common in the north-east and form part of the roof structure of the Bushveld Complex (Van Tongeren & Mathez, 2015). Carbonate-rich rocks are less common, although a large sequence is found in the central north of SA.

Soils in SA contain a wide range of properties resulting in 73 defined soil forms. These soils are broadly classified into eight categories (Fey, 2010a, 2010b) (see Table 1 for soil concept and World Reference Base classification system comparison). Duplex soil, often derived from mudrocks in the Karoo basin, has a marked texture contrast in the soil profile. The texture contrast of duplex soil results in permeability differences, which have been demonstrated to be susceptible to erosion (Parwada & Van Tol, 2016; Podwojewski et al., 2020). Glenrosa and Mispah soils are abundant in SA. These soils are lithic with distinguishable parent material visible in the B horizon. Lithic-type soils have been associated with erosion in SA, not because of their common occurrence but because of their position on convex crests and mid-slopes (Fey, 2010a). Structureless red-yellow apedal soil is largely found in the arid north.

2.2 | Literature directives

Google Scholar and Scopus were used to build a database of gully erosion research in SA. The textbook 'Geomorphology of Southern Africa' (Moon & Dardis, 1988) was used as the landmark text from which the search started. The keywords used in the search included 'gully', 'donga', 'sluit' (a term occasionally used for gullies in SA) and 'sloot' (Afrikaans terminology used for gullies). The abovementioned terms were searched individually and combined with the word 'erosion'. The keyword search was applied to all search fields, but the search was limited to SA, excluding other southern African countries. The search was limited to English and Afrikaans texts and was completed on 10 March 2023.

After applying the above search criteria, publications featuring gully erosion as part of their research aim (based on the title and information attained from abstracts) were incorporated into a database. Hereafter, the database was expanded by a backward and forward reference search, adding relevant works missed during the keyword search, including published research with a broader scope that addressed gully erosion. During the backward reference search, the reference lists of publications in the database were examined. Scopus was used to conduct a forward reference search to identify studies that cited research works from the database.

The database was used to compile factors indicated to have led to gully formation and controlling factors that played a role in contemporary gullying processes. Several published papers investigated the same area of interest. In cases where one or more of the same researchers were involved in the authorship, gully origin and controlling factors were captured once and edited only if additional factors were identified in the subsequent work. If different researchers investigated the same area of interest, it was considered a new appraisal, and all gully origin and controlling factors were captured.

The location of each gully erosion site was identified from coordinates, maps and place names provided in the study location descriptions of the papers in the database. A single (*x*, *y*) coordinate point, placed at the main gully headcut, was assigned to represent each gully site. The placement of the point at the main gully headcut was derived semi-automatically from a manually digitised polygon of the gully feature. Semi-automated mapping methods of gullies are rarely tested outside the area where they are developed. Therefore, the challenges to upscale and transfer semi-automated mapping methods remain poorly understood. We thus opted to manually digitise gullies to achieve high data accuracy. A single user digitised the gully features on a scale of 1:2000 in QGIS 3.16.16 using Google Earth images imported as XYZ tiles.

In studies investigating a plot or singular gully network, the whole gully network was digitised. The gully with the largest planimetric area was selected as the representative gully and digitised in study areas consisting of catchment scale extents. The main gully headcut point was derived from the digitised gully network. The mapped polygon was converted to points, spaced at 1-m intervals. The furthest point from the gully outlet, digitised as the line perpendicular to flow where the gully expires, was deemed the main gully headcut location. A sensitivity analysis was conducted by digitising two gullies driven by contrasting processes (sub-surface vs. surface) five times to assess planimetric areal and gully headcut position changes.

The level of activity at each gully research site was discerned and classified as stable, partially active, or active. The publications were used to extract activity severity information, but where the text refrained from reporting it, the level of activity was determined from Google Earth imagery. The most recent clear image available from Google Earth was compared with a clear historical image acquired 10 years prior (or as close to 10 years as possible). Gullies were labelled as stable when no extent changes were evident. A gully was classified as partially active when no gully headcut changes were evident and changes to gully wall expansion were limited to 5% of gully length, or depositional features within the confines of the gully were discernable. Gullies with more extensive lateral and linear growth were classed as active.

2.3 | Susceptibility modelling

Based on the database and a recent literature review of gully erosion in SA (Olivier et al., 2023), five broad categories were identified to include in the susceptibility model, namely, topography, soil, geology, climate and anthropogenic activities. Seven control factor datasets were selected to represent these five broad categories, all of which were limited to national extents (where spatial resolution is not indicated, the dataset consisted of vector data) (Table 2).

TABLE 2 Specific control factor datasets used per broad category, including its native spatial resolution and source, in addition to the weights derived from the literature database that was used in a weighted overlay to produce the final gully susceptibility map.

Broad category	Local/global gully control factor dataset	Native spatial resolution	Source	Literature-derived weighting (in %)
Topography	Slope (in %)	20 m	GeoSmart Space, 2020a	15.7
Geology	General rock type	Vector	Burger, 2013	14.5
Soil	Broad soil classification	Vector	Land Type Survey Staff, 1972–2006	16.9
Climate	Rainy Day Normal	10′	Calculated from New et al., 2002	7.85
	Aridity	0.01′	Council for Scientific and Industrial Research, 2021	7.85
Anthropogenic	Land-use/-cover	30 m	Department of Environment, Forestry, and Fisheries, 2016	18.6
	Agricultural regions (1978)	Vector	Khuthadzo, 2019	18.6

Human activities were indicated as a critical driver of gully erosion worldwide (Castillo & Gómez, 2016). In SA, the political past has significantly impacted erosion distribution (Hoffman & Ashwell, 2001; Olivier et al., 2023). To spatially accommodate the historical narrative of gullying, a regional agricultural zonal map derived from 1978 data (Khuthadzo, 2019) was implemented as a factor map (Figure 4b). Furthermore, a generalised land-use/land-cover class map with a spatial resolution of 30 m (Department of Environment, Forestry, and Fisheries, 2016) was used to represent contemporary anthropogenic coverage (Figure 4a).

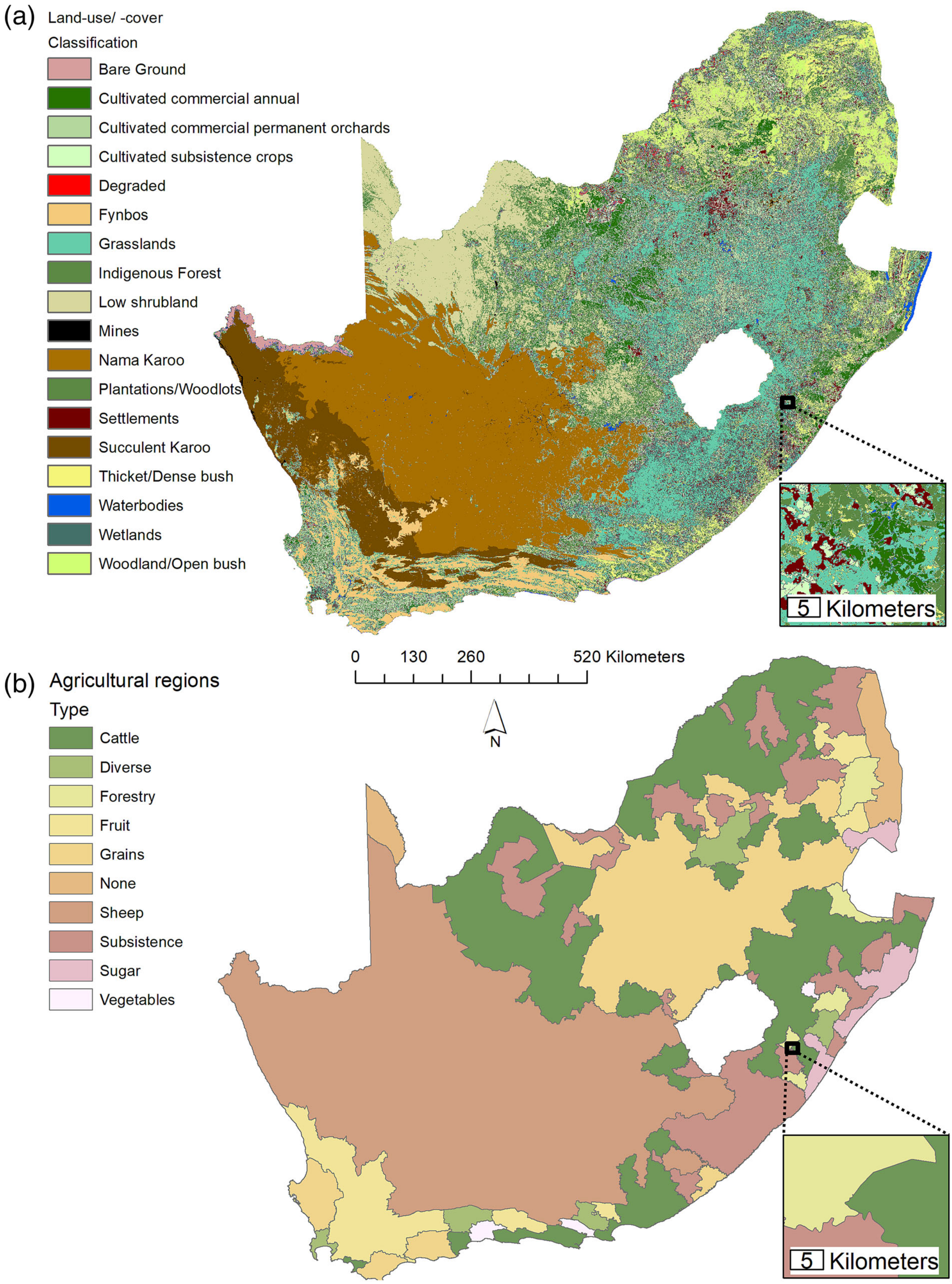

FIGURE 4 Factor maps representing anthropogenic factors used in the weighted overlay procedure: (a) land-use/-cover map from 2014 (Department of Environment, Forestry, and Fisheries, 2016); (b) an agricultural zonal map derived from 1978 data (Khuthadzo, 2019). [Color figure can be viewed at wileyonlinelibrary.com]

Climate is represented through two datasets. Firstly, an aridity index was used (spatial resolution of 0.01′; Council for Scientific and Industrial Research, 2021) as a local climatic factor, calculated from annual rainfall and mean annual temperature. Aridity has been associated with gully erosion because of its impact on protective vegetative cover and rainfall variability (Kakembo & Rowntree, 2003). Secondly, Rainy Day Normal (RDN) was used as a rainfall intensity proxy. Using a global dataset, Vanmaercke et al. (2016) demonstrated a significant correlation between RDN and gully headcut retreat. RDN was calculated from a 10′ resolution long-term (1961–1990) climate data from New et al. (2002), according to Equation (1) (Figure 5).

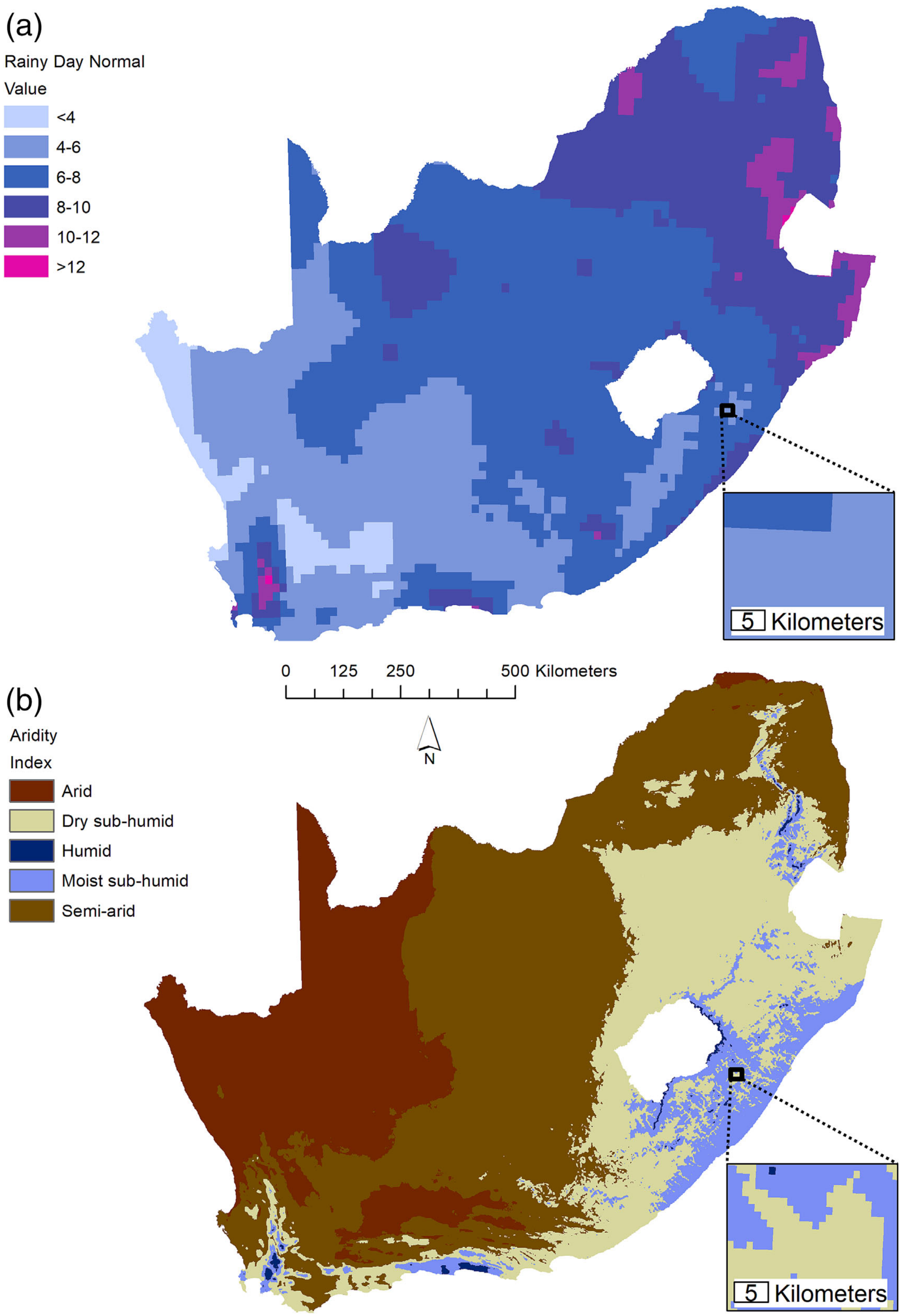

FIGURE 5 Climate input for the weighted overlay procedure: (a) Rainy Day Normal, which can be used as a proxy for rainfall intensity; (b) an aridity index (Council for Scientific and Industrial Research, 2021). [Color figure can be viewed at wileyonlinelibrary.com]

$$RDN = \frac{\text{MAR}}{\text{ARD}} \quad (1)$$

where MAR is the mean annual rainfall and ARD is the number of annual rain days.

In SA, the relationship between parent material and soil characteristics has been demonstrated as a significant impact to gully susceptibility (Laker, 2004). Highly dispersive and duplex soils have a propensity towards gullying and are often formed from the shales and mudstones of the sedimentary Ecca (early to mid-Permian period) and Beaufort (mid-Permian to early Triassic period) groups of the Karoo Supergroup. Parent material was incorporated by generally reclassifying the geology (Burger, 2013) to the most prominent rock type (classification scheme shown in Table A1 in Supporting Information). A broad soil classification from Land Type Survey Staff (1972–2006) was used to represent the soil factor. Although slope and contributing area are commonly used to identify gully headcut location (Torri & Poesen, 2014), the slope-area concept is strongly related to local environmental conditions, therefore not optimal for regional scale studies (Poesen et al., 2003; Vanmaercke et al., 2021). Additionally, De Geeter et al. (2023) demonstrated that coarser spatial resolution digital elevation models (DEMs) inflate upslope area resulting in poor gully susceptibility modelling performance. We therefore opted for slope as the topographical control factor, because a preferential topographic zone of gully development has been demonstrated on gentler footslopes, often with unconsolidated deposits or erosion-prone soils (Kakembo et al., 2009; Le Roux & Sumner, 2012). The percentage slope was derived in ArcGIS 10.6.1 from a 20-m spatial resolution DEM (GeoSmart Space, 2020a) (Figure 6).

The (x, y) point locations that were semi-automatically determined for each gully site were overlayed onto the local and global factor maps (Figures 4, 5 and 6) to extract the physiographic properties of each gully site. The Frequency Ratio (FR) was used to correlate the gully sites (x, y coordinates) with the local and global factors by

$$FR_i = \frac{\left(G_i/G_{tot}\right) \times 100}{\left(F_i/F_{tot}\right) \times 100} \times Act_i \quad (2)$$

where FR_i is the FR of the ith class of a factor; G_i is the number of gully sites distributed within the ith class; G_{tot} is the total gully sites; F_i is the pixel count in case of raster data or area in case of vector data of the ith class of a factor; F_{tot} is the total pixel count or area of a factor, dependant of data model; and Act_i is the average activity of gullies in the ith class quantified according to severity: Stable gullies were scaled as 1, partially active gullies as 1.5 and active gullies as 2.

The FR_i was normalised to a value of one, using

$$FR^{i\wedge\wedge} = \left(\frac{FR_i - FR_{min}}{FR_{max} - FR_{min}}\right) \quad (3)$$

where $FR^{i\wedge\wedge}$ is the normalised FR value of the ith class of a factor, FR_{min} is the minimum FR_i class score of a factor and FR_{max} is the maximum FR_i class value of a factor. The closer the $FR^{i\wedge\wedge}$ value is to one, the larger the association with gullying.

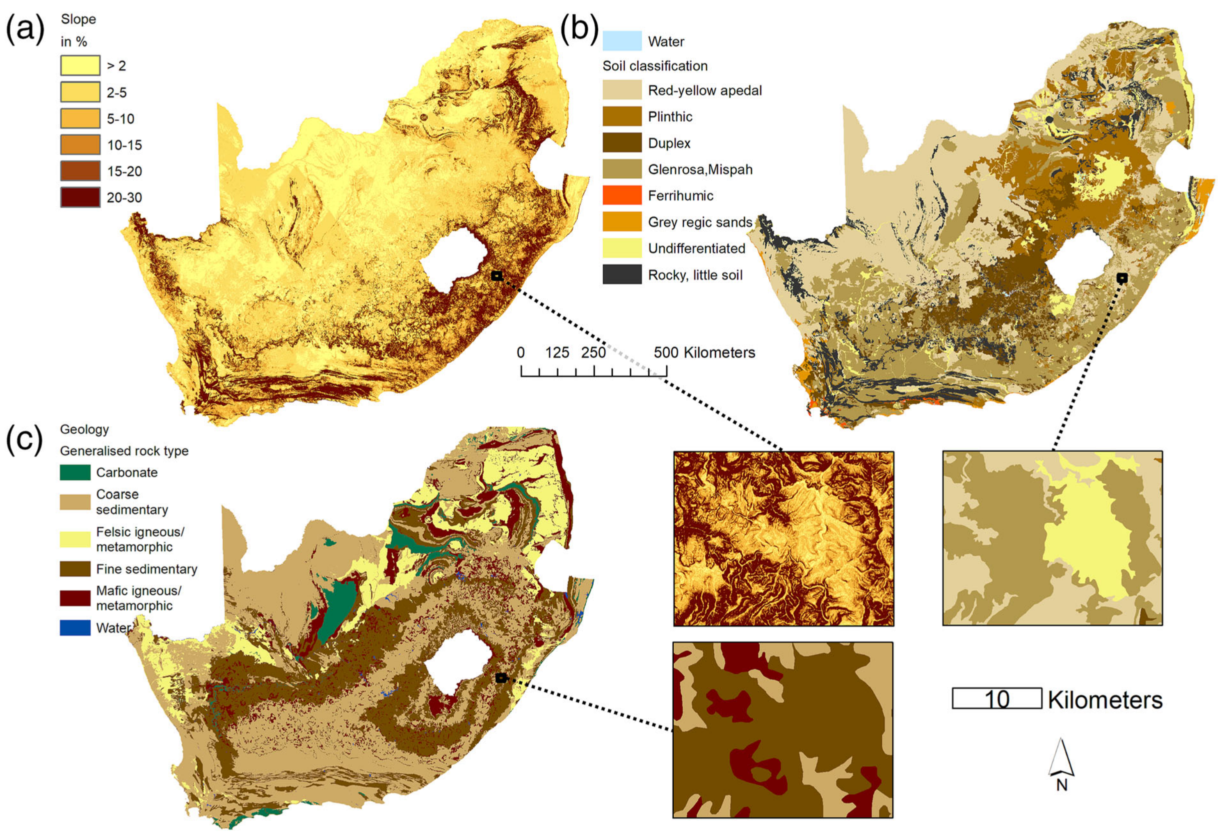

FIGURE 6 Physical precondition factor maps used as input to the weighted overlay model: (a) slope (derived from a Digital Elevation Model from GeoSmart Space, 2020a); (b) broad soil classification (Land Type Survey Staff, 1972–2006); (c) generalised rock type (see Table A1 in Supporting Information). [Color figure can be viewed at wileyonlinelibrary.com]

The local and global factor maps were prepared for weighted overlay by reclassifying the raster datasets. The reclassification procedure replaced the original factor-class pixel value with the $FR^{i\wedge\wedge}$ value. Once reclassified, the factor maps were resampled to a 10-m spatial resolution by the nearest neighbour technique to ensure alignment of pixels; moreover, no data values were created from resampling (Figure 7). For vector datasets, the $FR^{i\wedge\wedge}$ values were added to the attribute table and rasterised to a pixel size of 10 m.

Once the factor maps were conditioned, namely, rasterised or reclassified and resampled, the gully susceptibility was calculated by a weighted overlay sum from

$$GSI = \sum_{i=1}^{n} (nGDF_i \times W_i) \tag{4}$$

where *GSI* is the gully susceptibility value, *i* is the local and global factors selected for the *GSI*, *n* is the number of global and local factors, *nGDF* is the conditioned factor map for *i* and *W* is the weight assigned to *i*. The weights applied in the final aggregation step correlated to the compilation of control factors from literature (Table 2). The GSI output was classified according to the classes derived in De Geeter et al. (2023): very low (<0.1), low (0.1–0.3), moderate (0.3–0.5), high (0.5–0.7) and very high (>0.7).

2.4 | Validation

The GSI model was validated using two datasets. Firstly, the GSI model was compared with a published gully inventory map of SA (Mararakanye & Le Roux, 2012) produced by digitising gully features from SPOT-5 imagery at a scale of 1:10000 (smallest detectable feature equals 10 m), and secondly, the GSI model was validated against 15 randomly selected 1-km^2 zones in which primary validation data were captured.

In the first instance, these manually mapped gullies (Mararakanye & Le Roux, 2012; $n = 163\ 019$) were draped over the GSI modelled raster to calculate the mean GSI value for each gully. The relative gully occurrence was used as an additional accuracy measure by correlating the areal extent of each GSI class with the gullies modelled to have the same mean GSI value by

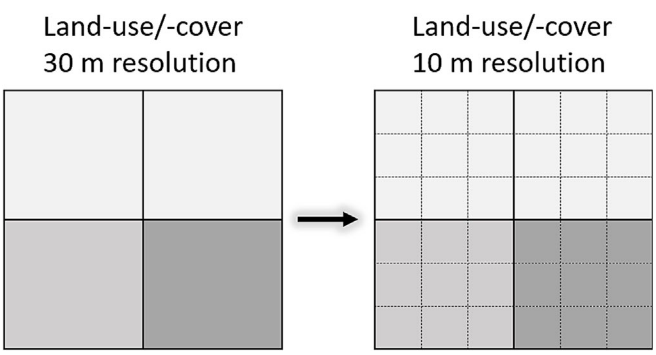

FIGURE 7 Example of resampling raster datasets to a common spatial resolution of 10 m avoiding creating artificial values and ensuring overlay; the shades of grey represent different raster values. [Color figure can be viewed at wileyonlinelibrary.com]

$$G_{Ri} = \frac{GSI^{Gi\%}}{GSI^{Ai\%}} \tag{5}$$

where G_{Ri} is the relative gully occurrence of the *i*th GSI class, $GSI^{Gi\%}$ is the percentage of gullies in the *i*th GSI class and $GSI^{Ai\%}$ is the percentage areal coverage of the *i*th GSI class. The calculation was compared with a random probability of gully occurrence.

In the second instance, a 1-km^2 hexagon tessellation grid was created for SA and overlaid with the GSI model raster. Hexagons with 90% coverage of a particular GSI class were extracted, and three hexagon sites were randomly selected for each GSI class. Gully features within each site were manually digitised at a scale of 1:2000 from Google Earth imagery (smallest detectable feature equals 2 m) imported as XYZ tiles in QGIS 3.16.16 to produce a higher accuracy validation dataset compared with the national inventory map. Gully density in terms of planimetric area was calculated for each site.

3 | RESULTS

3.1 | Mapped gullies

A total of 60 gully locations are mapped as points (see Table A2 in Supporting Information). Several papers present continued findings from the same sites and as such mapped only once (see Table A2 in Supporting Information). The Eastern Cape and KwaZulu Natal have the most gully locations, 27 and 19, respectively (Figure 2). No papers were found that presented gully erosion research in the Gauteng and North West provinces.

The sensitivity of gully headcut placement was tested on a gully in the Tsitsa catchment (31° 11' 28.62" S; 28° 27' 59.64" E), where sub-surface processes are dominant, and the Sandspruit catchment (33° 25' 55.09" S; 18° 51' 33.78" E), where surface processes dominate. The Tsitsa gully is an order of magnitude larger than the Sandspruit gully, with a mean planimetric area of 13 653.8 m^2 and 5584.1 m^2, respectively. The standard deviation varies between 122.4 m^2 and 125.8 m^2, indicating a percentage difference of less than 1% than the mean for the Tsitsa catchment gully, and 2.3% lower than the mean for the Sandspruit catchment gully. The distance between the furthest gully headcut points for the Tsitsa gully is 5.1 m, with a minimum bounding geometry of 2.4 m^2. A shorter length of 3.1 m is found between the furthest gully headcut points for the Sandspruit gully, although there is a more extensive lateral spread resulting in a minimum bounding geometry of 3.8 m^2. At both gully locations, the gully headcut positions are well within the spatial resolution of the 10-m datasets. Hence, the model results are not sensitive to the manual headcut placement.

3.2 | Control factors associated with gully erosion susceptibility

Gullies are strongly associated with vegetable farming (*FR*^^: 1.00) and subsistence areas (*FR*^^: 0.80) in the agricultural zones, which are used to represent the historical land-use of SA (Table 3). The small geographic extent of vegetable farming, in addition to the high activity

TABLE 3 Distribution of gully sites according to key physiographic characteristics and the calculated Frequency Ratio (FR) and Normalised *FR^^* values.

Factor classification	Class area %	No. of study sites	Study sites %	Frequency ratio, FR	Activity	Normalised value, *FR^^*
Land-use/-cover						
Indigenous forest	0.3	0	0	0.00	0.0	0.00
Thicket/dense bush	5.7	1	1.7	0.44	1.5	0.04
Woodland/open bush	8.7	3	5.0	0.74	1.3	0.07
Low shrubland	14.4	1	1.7	0.23	2.0	0.02
Plantations/woodlots	1.5	1	1.7	2.22	2.0	0.20
Cultivated commercial annual crops	9.1	0	0	0.00	0.0	0.00
Cultivated commercial orchards	0.4	0	0	0.00	0.0	0.00
Cultivated subsistence	1.6	0		0.00	0.0	0.00
Settlements	2.3	2	3.3	2.15	1.5	0.19
Wetlands	0.8	0	0	0.00	0.0	0.00
Grasslands	19.0	35	58.3	5.52	1.8	0.49
Fynbos	5.6	3	5.0	1.35	1.5	0.12
Nama Karoo	20.5	8	13.3	1.24	1.9	0.11
Succulent Karoo	6.1	1	1.70	0.55	2.0	0.05
Mines	0.3	0	0	0.00	0.0	0.00
Water	1.7	0	0	0.00	0.0	0.00
Bare ground	1.2	2	3.3	5.56	2.0	0.50
Degraded	0.8	3	5.0	11.18	1.7	1.00
Agricultural zones						
Cattle	22.9	15	25.0	1.75	1.7	0.22
Diverse	1.8	0	0	0.00	0.0	0.00
Forestry	1.5	0	0	0.00	0.0	0.00
Fruit	4.9	1	1.6	0.68	2.0	0.09
Grains	15.8	10	16.7	1.90	1.8	0.24
None	2.3	0	0	0.00	0.0	0.00
Sheep	37.7	9	15.0	0.76	1.9	0.10
Subsistence	10.9	23	38.3	6.31	1.8	0.80
Sugar	1.8	1	1.7	1.92	2.0	0.24
Vegetables	0.4	1	1.7	7.94	2.0	1.00
Rainy Day Normal						
<4	4.3	0	0.0	0.00	0.0	0.00
4–6	25.1	16	26.6	1.91	1.8	0. 69
6–8	44.3	22	36.7	1.49	1.8	0. 54
8–10	23.2	19	31.7	2.32	1.7	0.84
10–12	3.1	3	5.0	2.77	1.7	1.00
>12	0.1	0	0.0	0.00	0.0	0.00
Aridity index						
Arid	22.7	2	3.3	0.29	2.0	0.04
Semi-arid	44.5	11	18.3	0.70	1.7	0.10
Dry sub-humid	24.9	30	50.0	3.42	1.7	0.47
Moist sub-humid	7.3	17	28.4	7.32	1.9	1.00
Humid	0.6	0	0	0.00	0.0	0.00
Slope (in %)						
<2	29.4	0	0.0	0.00	0.0	0.00
2–5	34.9	3	5.0	0.14	1.0	0.02
5–10	14.6	14	23.3	2.72	1.7	0.34
10–15	6.1	13	21.7	6.39	1.8	0.81

(Continues)

TABLE 3 (Continued)

Factor classification	Class area %	No. of study sites	Study sites %	Frequency ratio, FR	Activity	Normalised value, FR^^
15–20	3.8	10	16.7	7.89	1.8	1.00
20–30	4.8	11	18.3	6.88	1.8	0.87
>30	6.4	9	15	4.45	1.9	0.56
Soil						
Red-yellow apedal	33.8	6	10.0	0.53	1.8	0.12
Plinthic	11.5	4	6.6	0.87	1.5	0.20
Duplex dominant	9.8	3	5.0	0.87	1,7	0.19
Undifferentiated	5.8	1	1.7	0.29	1.0	0.06
Glenrosa and/or Mispah	28.9	43	71.7	4.46	1.8	1.00
Ferrihumic horizon	0.2	0	0	0.00	0.0	0.00
Grey regic sands	1.3	0	0	0.00	0.0	0.00
Rocky with undifferentiated or little soil	8.5	3	5.0	1.00	1.7	0.22
Water	0.2	0	0	0.00	0.0	0.00
Rock type						
Fine sedimentary	25.7	17	28.3	1.99	1.8	0.92
Coarse sedimentary	46.0	35	58.3	2.15	1.7	1.00
Mafic igneous/metamorphic	11.9	4	6.7	0.90	1.6	0.42
Felsic igneous/metamorphic	12.7	4	6.7	0.52	1.0	0.24
Carbonate	3.4	0	0	0.00	0.0	0.00
Water	0.3	0	0	0.00	0.0	0.00

rating, results in vegetable farming having the highest *FR^^*, even though only one gully is located within it. Most gullies are in the subsistence areas, but because of the larger coverage and lower activity rating, it had a lower *FR^^* than vegetable farming. Although a large proportion of gullies are in cattle (25%), sheep (15.0%) and grain (16.7%) farming zones, the prominent geographical extent of those areas reduces the *FR^^* to 0.2390 or lower. In the land-use/-cover dataset, used to relate gullying to a more contemporary anthropogenic setting, gullies are related to degraded areas (*FR^^*: 1.00) and bare ground (*FR^^*: 0.50). Grasslands had a comparable *FR^^* to that of bare ground because most gully sites are located within this land-use/-cover class. Although 20% of gully research sites are located in the Karoo, its *FR^^* were between 0.01 and 0.12 because of its extensive geographic coverage.

The strongest correlation between gully occurrence at the 60 sites and rainfall intensity, as represented by RDN, is within an RDN range of eight to 12. A lower yet still significant correlation is found in lower RDN values between four and eight. Most gullies are mapped in the dry sub-humid and moist sub-humid climate zones, and the strongest *FR^^* correlation is found here with values of 0.47 and 1.00, respectively.

In our 60 sites, 80% of gullies are found in sloping areas from 5% to 30% and are also highly active (activity ratings of 1.7–1.8). The strongest correlation is found in the 15%–20% slope class (*FR^^*: 1.00). In the broad soil class, 43 gullies formed in Glenrosa and/or Mispah soils. Because of the large proportion of gullies located within the Glenrosa and/or Mispah soil class, other soil types had a low correlation with gully erosion (up to 0.22). Sedimentary rock is abundant in SA (71.7% coverage), and most gully sites ($n = 42$) are found within these lithologies. Gullies are strongly correlated to coarse (*FR^^*: 1.00) and fine sedimentary rock (*FR^^*: 0.92), although a significant correlation is also evident with mafic igneous/metamorphic rock types (*FR^^*: 0.42).

3.3 | Gully susceptibility output

According to the GSI using literature directives, 1.8% of SA is classified with a very high susceptibility to gullying, and 12.0% is highly susceptible (Figure 8; Table 4). Overall, GSI increases from the western coast, eastwards to KwaZulu Natal. The Eastern Cape (43.3% of its area classifies as high to very high GSI) and KwaZulu Natal (92.1% classifies as moderate to very high GSI) exhibit the most heightened susceptibility to gully erosion. Although the Northern Cape has the lowest GSI (67.6% low to very low GSI), a considerable proportion of the Karoo region is moderately susceptible to gully erosion. The Northern Cape and North West are the provinces with the lowest GSI, with 67.6% and 60.5% of its extent classified as very low to low GSI.

3.4 | Gully susceptibility model validation

The mean GSI was calculated for each gully in SA ($n = 160\,952$; 2067 gullies were omitted because of size limitation and NoData values along the SA border and coastline), as mapped by Mararakanye and Le Roux (2012) (Table 4). Nationally, 79.8% of the mapped gullies have a mean GSI of moderate or higher. The Eastern Cape and KwaZulu

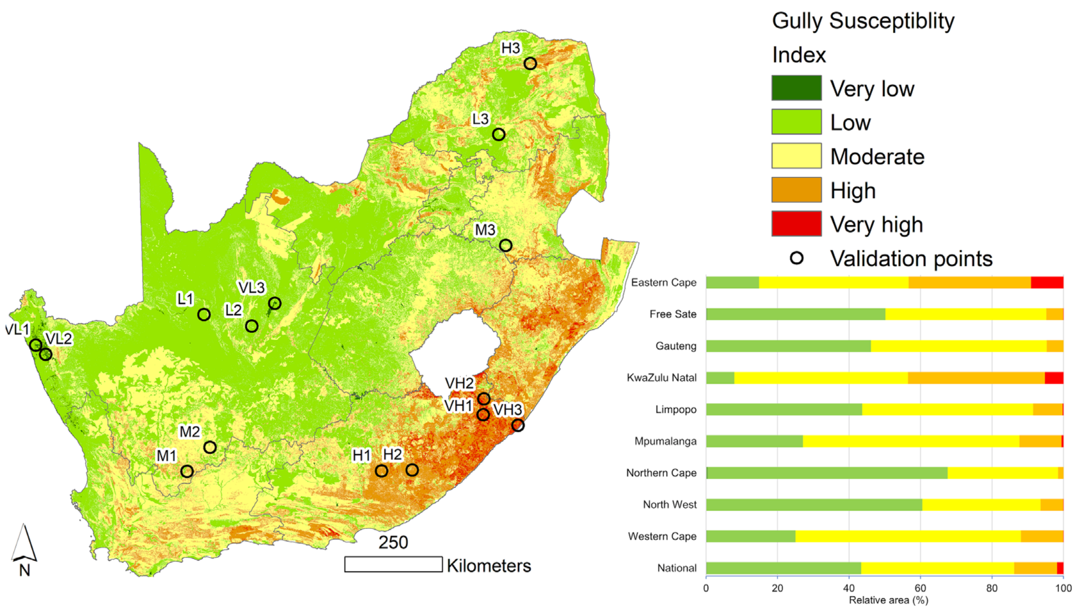

FIGURE 8 Gully susceptibility according to literature directives in South Africa (spatially mapped on the left and in graph format showing relative area on the right). The location of random validation sites is given on the map: VL signifies very low GSI validation sites, V shows low GSI validation areas, M for moderate GSI validation hexagons, H shows the high GSI validation sites, and VH represents the very high GSI validation hexagons. The numbers (1 to 3) following the GSI class show the order of the validation sites for a particular GSI class according to longitude. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Spatial distribution of the gully susceptibility index (GSI) aggregated for the nine provinces of South Africa, including a national outlook (area GSI denotes the areal coverage of each GSI class for the model respectively).

Province	Area (km^2)	Gullies (count)	Variable	Very low	Low	Moderate	High	Very high
Eastern Cape	168 215		Area GSI	0.2	14.6	41.9	34.2	9.1
		81 172	Gully GSI	0.0	19.8	33.8	28.3	18.1
Free State	129 806		Area GSI	0.3	49.9	45.0	4.7	0.1
		14 211	Gully GSI	0.0	17.0	75.5	7.4	0.1
Gauteng	18 015		Area GSI	0.1	46.0	49.2	4.7	0.0
		129	Gully GSI	0.0	30.2	69.0	0.8	0.0
KwaZulu Natal	92 702		Area GSI	0.1	7.8	48.6	38.3	5.2
		25 846	Gully GSI	0.0	0.7	42.9	46.6	9.8
Limpopo	125 384		Area GSI	0.0	43.7	47.8	8.2	0.3
		3732	Gully GSI	0.0	20.0	71.2	8.8	0.0
Mpumalanga	76 257		Area GSI	0.0	27.1	60.6	11.7	0.6
		2568	Gully GSI	0.0	23.9	63.1	12.8	0.2
Northern Cape	372 203		Area GSI	0.5	67.1	30.9	1.5	0.0
		18 278	Gully GSI	0.1	62.2	37.3	0.4	0.0
North West	104 730		Area GSI	0.1	60.4	33.1	6.3	0.1
		797	Gully GSI	0.0	27.9	58.3	13.8	0.0
Western Cape	128 708		Area GSI	0.2	24.8	63.1	11.8	0.1
		4219	Gully GSI	0.3	23.9	68.9	6.8	0.1
National	1 216 020		Area GSI	0.2	43.2	42.8	12.0	1.8
		160 952	Gully GSI	0.0	20.2	42.7	25.8	11.3

Note: The calculated mean GSI for each manually mapped gully by Mararakanye and Le Roux (2012) [$n = 160\ 952$ (2067 gullies were omitted because of size limitation and NoData values along the SA border and coastline)] is given for each province, including nationally, for each weighted model (denoted as gully GSI).

Natal have the most gullies, also the most mapped gully locations from the literature database. The GSI model performance is best in these two provinces, with 46.4%–56.4% of gullies predicted with a high to very high mean GSI, whereas 99.3% of gullies in KwaZulu Natal are predicted with a mean GSI of moderate or above. Although gullies in the high to very high classes are limited in the Free State and Limpopo

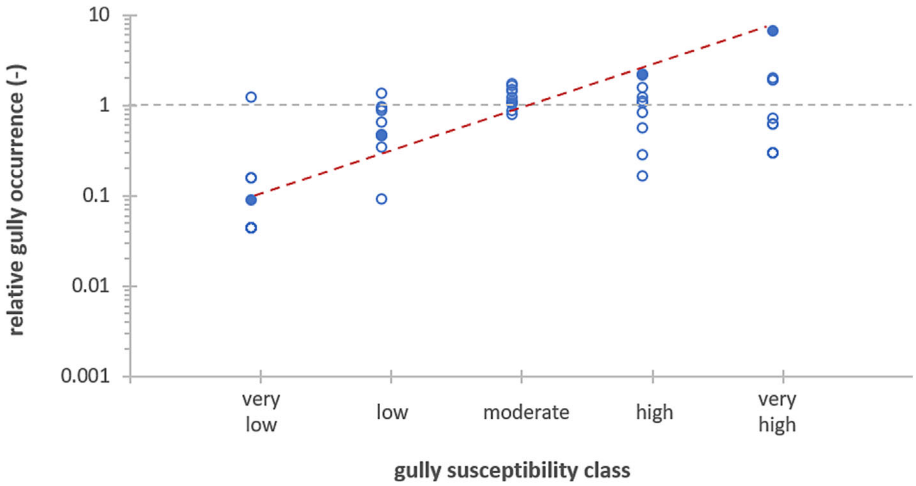

FIGURE 9 Relative gully occurrence per gully susceptibility for the gullies mapped in the national gully inventory map ($n = 163\,019$). Non-filled circles denote provincial data, while filled circles denote national data. The horizontal dashed line indicates expected gully occurrence under random distribution, while the red dashed line shows the general trend line. [Color figure can be viewed at wileyonlinelibrary.com]

(up to 8.8%), most gullies (80% and 83%) have a mean GSI classification of moderate or higher. The GSI prediction in the Northern Cape was poor, with 62.3% of gullies predicted in the low to very low GSI class.

The relationship between relative gully occurrence and GSI is compared with a random occurrence probability, of which the assumed value is 1 (Figure 9). Gullies with a moderate mean GSI converge to the random probability. A strong positive trend is observed nationally for relative gully occurrence and mean gully GSI severity. Low (0.5) to very low (0.09) GSI drops below the random probability of 1, whereas high (2.1) to very high (6.4) GSI increases above random probability. The positive correlation indicates that the GSI-modelled classifications perform better than a random baseline classification. Interprovincially, the correlation between relative gully occurrence and mean GSI gully severity becomes more spread, with the best performance in KwaZulu Natal. The GSI model performance was worst in the Western Cape, where very low, low and moderate GSI converge to a random probability, whereas the high and very high GSI have a classification score lower than a random classification. The low mean GSI classification for gullies in the Northern Cape translates into poor correlation with the higher GSI classes. Still, the large geographic extent of lower GSI prediction in the province improves prediction, with gullies with a low (0.9) to very low (0.2) mean GSI showing a stronger correlation and modelled below the random baseline.

Fifteen 1-km^2 hexagonal validation areas, three per GSI class, were randomly selected to test the predicted GSI with a high-resolution, manually digitised reference dataset (Figure 10). A general increasing trend in gully density is noticeable from the low to very high GSI. Gullies are absent in the very low validation zones and in two of the low GSI classification zones. In the high GSI validation zones, the gully density was comparable with the moderate GSI in two of the areas, whereas gullies were absent in the third. For the two zones where gully density is similar to the moderate areas (Figure 10j,k), the mitigation works in the form of dams and contours are evident. On one of the hillslopes in Figure 10k, gully erosion has broken through the contour banks, likely indicative of a higher susceptibility to gullying. At the third validation, aimed for the high GSI, gullies are absent. The GSI model most likely predicted a high GSI for this zone, because of the presence of Glenrosa and/or Mispah soils, RDN of 4–6, and the historical land-use of subsistence farming. The very high validation zones show the highest gully density, up to 171 783.5 m/km^2.

4 | DISCUSSION

4.1 | The spatial relationship between gully controlling factors and literature directives

Regarding the historical land-use dataset, subsistence farming was closely correlated to gully erosion (80%; Table 3). Subsistence farming in the historical land-use dataset corresponds to areas of communal land tenure, which has been demonstrated to have high gully incidence (Hoffman & Todd, 2000; Mararakanye & Le Roux, 2012). Although this impact can be considered historical, it remains an area of severe gully erosion (Olivier et al., 2023). Surprisingly, vegetable farming, a land-use not commonly associated with gully erosion in SA, had the highest correlation. The significant association of gullying with vegetable farming is likely due to the small geographical extent of gullying. However, ephemeral gully erosion research has been neglected in SA and could contribute to gully erosion from vegetable-farmed areas. As expected, bare ground and degraded regions correlated well with gully erosion, which conforms to other research findings that demonstrated the importance of vegetation as a controlling factor for gullying (Rey, 2003; Zhao et al., 2016). Grasslands also had a good correlation with gully erosion, which has been shown to be prone to gullying, especially where degraded and unimproved land occurs (Mararakanye & Le Roux, 2012). Bush encroachment in grasslands, which is a recent phenomenon (Hoffman & Ashwell, 2001), has also been demonstrated to impact gully erosion indirectly (Grellier et al., 2012).

Gully erosion is associated with higher rainfall intensities (Anderson et al., 2021; Vanmaercke et al., 2016), and a higher correlation was found with increasing RDN values for SA. There was a poor correlation with semi-arid regions, where research has shown a prevalence towards gullying, mostly because of the impact of rainfall variability on vegetation (Valentin et al., 2005). Although large proportions of the Karoo were modelled as moderate GSI, the low correlation significantly impacted the prediction in the Northern Cape, where GSI showed poor performance.

In the 60 study sites, 66.7% of gully headcuts were located on slopes <20%. A good correlation is also found between the slope range of 20%–30% (*FR*^^: 0.87). Although gullies occur in varied geo-environmental settings, including different slopes (DeWitte et al., 2015; Liggit & Fincham, 1989; Mararakanye & Sumner, 2017;

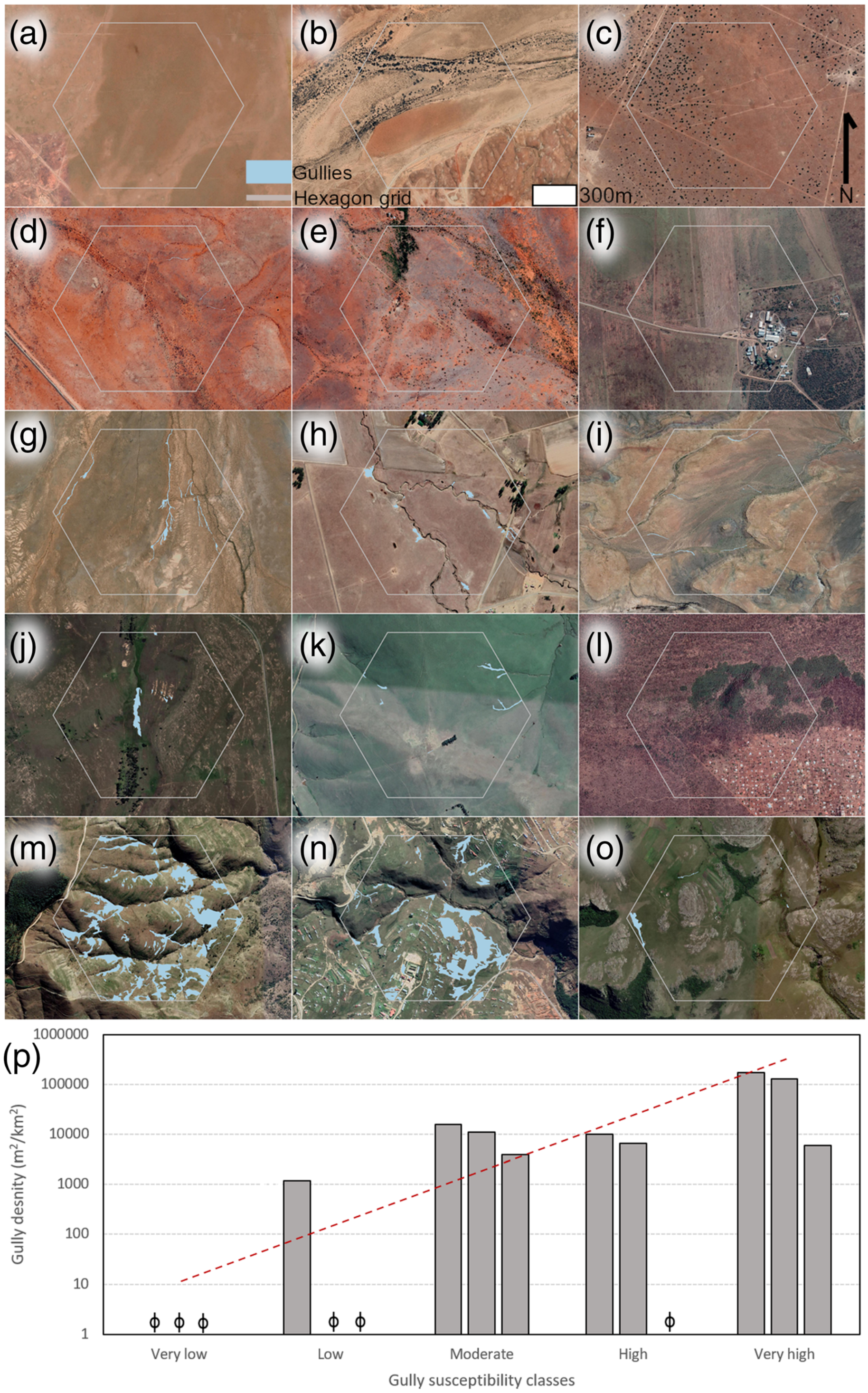

FIGURE 10 The randomly selected 1-km^2 hexagon sites used for validation of the GSI model. The first row consists of validation areas that had a 90% or higher very low GSI and is ordered according to longitude: (a) VL1 site, (b) VL2 site, (c) VL3 site; the second row shows validation areas that had a 90% or higher very low GSI and is ordered according to longitude: (d) V1 site, (e) V2 site, (f) V3 site; the third row represents the validation areas that had a 90% or higher moderate GSI and is ordered according to longitude: (g) M1 site, (h) M2 site, (i) M3 site; the fourth row represents areas of 90% or higher high GSI and is ordered according to longitude: (j) H1 site, (k) H2 site, (l) H3 site; the fifth row consists of the validation areas that had a 90% or higher very high GSI and is ordered according to longitude: (m) VH1 site, (n) VH2 site, (o) VH3 site (see Figure 8 for the geographic location); (p) shows gully density of the validation areas according to GSI. The red dashed line shows the general trend line, while ϕ denotes a zero value. Satellite images courtesy of Google Earth. [Color figure can be viewed at wileyonlinelibrary.com]

Valentin et al., 2005), our correlation is towards the higher spectrum of slope ranges when compared with other studies in SA (e.g., Kakembo et al., 2009; Le Roux & Sumner, 2012). Kakembo et al. (2009) and Le Roux and Sumner (2012) conducted a zonal approach investigating the effect of slope gradient on gullying, demonstrating gullying is prevalent in slopes ranging from 8% to 17.5%. The relationship between gullying and slope is complex and hinges upon several variables such as rainfall, upslope drainage, upslope drainage shape, vegetation, land-use and soil characteristics (Laker, 2004; Liggit & Fincham, 1989; Rossi et al., 2015; Summerfield, 2014; Torri & Poesen, 2014). In SA, the most prominent cause resulting in gullies being found in lower slopes can be attributed to the large upslope area that allows an erosive water mass to encounter deep, unstable, often duplex soils derived from mudrocks and shales (Laker, 2004). A plausible reason, however, for our higher slope ranges is caused by the methodology applied to extracting control factor data. An (x, y) point is placed at the gully headcut interface, where the surrounding hillslope is likely to be steeper than at lower elevations. This point-based methodology is unlike zonal (Kakembo et al., 2009; Le Roux & Sumner, 2012) or field-measurement (Cobban & Weaver, 1993) approaches that consider the entire gully channel.

The steeper slope position identified at the 60 study sites is also likely to have a strong influence on the correlation between gully erosion and soil form. Young soils on weathered rock (i.e., Glenrosa and/or Mispah), often found on steeper convex slopes (Fey, 2010a), show the best correlation with GSI (71.7%). These soils are predominantly shallow and lithic, with a sandy loam topsoil texture (Van Zijl, 2010), exhibiting a weak structure, resulting in an erodibility rating of medium to high (Crosby et al., 1981, in Kakembo & Rowntree, 2003). Although gully headcuts may have originated or retreated into the steeper young soils, the concentrated flow from the less permeable rocky soils can exacerbate gullying in the lower slopes (Laker, 2004; Rienks et al., 2000). This is especially significant in duplex-dominant soils, which show a weak correlation with gullying according to the GSI model. The low correlation contrasts other works, including on the African continent (Imeson & Kwaad, 1980; Van Zijl & Ellis, 2013; Parwada & Van Tol, 2016; Mararakanye & Sumner, 2017), Europe (Faulkner, 2013), the Americas (Wilson et al., 2018) and Australia (Sidle et al., 2019). The predominance of gullying on duplex soils is associated with the abrupt texture contrast between the surface and a sub-surface horizon, which typically exhibit dispersive properties (Parwada & Van Tol, 2016). Once the dispersive subsoil is exposed, gullying can become accelerated and more severe (Rienks et al., 2000). Therefore, the low correlation with duplex soil is likely erroneous, and GSI in these areas would have been underpredicted.

Sedimentary rock is abundant on the earth's surface, which could be the reason for the association with gullying in a worldwide review (Castillo & Gómez, 2016) and locally (Olivier et al., 2023). In SA, a strong influence of lithology on gullying has been detected. As parent material, the sedimentary Ecca and Beaufort groups have shown a predisposition towards gullying, primarily because of the formation of duplex and dispersive soils (Laker, 2004).

4.2 | Model performance and SA gully erosion narrative

The GSI model was validated in three ways using two different datasets. Firstly, the GSI model generally performed well when tested against a published national gully inventory for SA (Mararakanye & Le Roux, 2012), consisting of 160 952 gullies. Secondly, The GSI model showed a distinctly better performance than a random classification model when considering relative gully occurrence and mean gully GSI. Lastly, at 15 randomly selected gully validation sites, the GSI model showed appropriate susceptibility indicators towards gullying, except for one area that was identified as having a high GSI, despite no gullies being observed. This triple validation shows that the GSI model is generally robust, identifying areas of contrasting susceptibilities. In addition to the validation methodologies, the GSI model broadly converges with other susceptibility metrics, which has been derived by different methodologies. These methods include a qualitative soil degradation assessment derived by Hoffman and Todd (2000), a water erosion risk map produced by Le Roux et al. (2008) and, more recently, a continental gully headcut susceptibility model by De Geeter et al. (2023).

The GSI model shows that 13.8% of SA is highly susceptible to gully erosion. However, the risk of gullying is not evenly distributed and is skewed to the east. The higher skewed risk in the former homeland areas shows that past social injustices continue to have a legacy impact on contemporary gully susceptibility and erosion. Although large portions of the Karoo are classified with a moderate GSI, gully susceptibility here may be underpredicted, especially in the Northern Cape, where lower GSI classifications were predicted (and GSI performance was poor compared with validation), because of rainfall variability and scant vegetation cover.

4.3 | Adoption prospective in other geomorphic and climatic regions

The GSI model, blending literature directives with a statistical approach to model gully susceptibility on a regional scale (in this case national in SA), proved successful and robust. There is thus potential to apply this approach using literature at different scales and areas with varying geomorphic environments. The methodology can be used as a standalone tool to aggregate data mined from a literature review only, as in this study, to conduct a gully susceptibility assessment. Additionally, primary data (e.g., a localised study investigating causes of gully erosion) can be merged with the GSI model to provide contextual data for the primary study or provide additional input points to refine the GSI.

Requirements for this methodology implementation to achieve acceptable results regarding GSI are the availability of existing datasets and the quantity and distribution of research study sites. Existing datasets need to be at a scale (e.g., in this study on a national scale) at which susceptibility will be modelled, and output will be affected by accuracy and spatial resolution. Optimally there should be an even distribution of gully research sites from which its locality and local driving and control factors can be extracted, although the GSI models performed well even with scattered datasets in SA. Although the GSI model performed well in several underrepresented provinces, it was more successful in the Eastern Cape and KwaZulu Natal where most gully-specific research sites were located.

4.4 | Limitations and future research

Although the authors took great care in developing a systematic, semi-automated approach to identify the (*x*, *y*) coordinate point or each gully, manually digitising the gullies remained an essential initial step. Manually digitising gullies seemingly introduces uncertainties, as it is subjective, resulting in extent differences due to varying interpretations (Vanmaercke et al., 2021). In our case, the same user digitised all gullies, and a sensitivity analysis showed a minor impact within the pixel size of the input datasets. The sensitivity analysis outcome is encouraging, and we consider using a manual approach as an initial step to be valid. However, establishing an automated method for gully headcut identification would be advantageous, as it would remove user bias.

The spatial resolutions of the input datasets introduce further uncertainty. The 20-m DEM would smooth topography and is, therefore, unable to represent larger-scale topographic fluctuations, which may be important to gully initiation and severity. Similarly, RDN, which was used as a proxy for rainfall intensity, was calculated from data with a 10′ resolution. The coarse resolution may be a poor predictor of local extreme rainfall events and the impact of topography on rainfall distribution, which would be important in attaining gully susceptibility. Although land-cover/-use suffers from the same resolution limitation, its uncertainties may be less than the two datasets above because it is a discrete data type.

The distribution of gully research sites in SA remains sparsely scattered and partially confined to certain areas. The reason for the bias towards certain study areas is not always forthcoming. However, a justifiable assumption can be made that empirical research is more focused on areas where gully erosion is more prevalent. This assumption is evident from the activity weights assigned to gullies.

Despite these limitations, validation data indicate that the GSI model performed well, even in several underrepresented provinces such as the Free State, Limpopo, Mpumalanga and the Western Cape. Future work can investigate model improvements and further applications.

Conducting work at underrepresented regions in SA, including stable gully erosion sites, would provide further insight into regional gully dynamics and yield more distributed data to be used as input, delivering a more precise model. Furthermore, higher-resolution datasets could be generated to refine GSI reductions. In SA, a 2-m DEM (GeoSmart Space, 2020b) exists for a large part of SA, and smaller regional studies can be undertaken to test model accuracy dependency on DEM resolutions. Similarly, it would be useful to determine a higher-resolution climate dataset to represent rainfall intensity, as it has been shown to be pivotal in gully initiation and expansion (Vanmaercke et al., 2016).

Currently, the model uses a single point to represent a gully. Additionally, the model presently applies one additional data mined variable from literature, namely, activity. Model improvements could be achieved by investigating ways of introducing a gully or gully headcut density metric that replaces the single point or making use of zonal statistics per gully feature instead of points. Furthermore, additional properties could be data mined and used in the model to improve GSI prediction. We argue against using the age of gullies as a proxy to model severity, as gully activity is nonlinear, with varied fluctuations between activity severity during its lifetime (Grellier et al., 2012; Hayas et al., 2017). However, capturing data regarding gully morphology and connectivity; moreover, mitigation and rehabilitation measures could be integrated into the GSI model. These inputs should be tested for implementation and may produce a more precise model. Mitigation measures may be most beneficial, as mitigation works in SA are extensive, for example, Meadows (2003) (having such a dataset for the entire extent of your modelled region could be even more practical). De Geeter et al. (2023) also found poor accuracy in their regional gully susceptibility map, which could be related to the need for a spatial mitigation dataset.

The GSI model could also be extended in scope by adding connectivity and rainfall variability to produce an off-site gully erosion impact map. The output of such a map could be quite different to a susceptibility map, for example, in the Karoo, which consists of a large area with a moderate GSI, that may have a much lower off-site impact because of the tendency of Karoo gullies to meander and flood-out due to rainfall variability (Grenfell et al., 2014; also see Boardman et al., 2017). An off-site impact could be a substantial asset to land managers in identifying high-priority areas and mitigation goals.

The GSI model could also be used in conjunction with gully detection methods, for example, constraining semi-automated methods to highly susceptible areas, which can reduce computational time and the geographic extent to which detection methods need to be applied to. Combining these two types of methodologies would produce information regarding gully occurrence and dimensions in susceptible areas spanning different geo-environments. Additionally, if applied temporally, gully erosion rates can be quantified for various gully typologies and geo-environments within susceptible regions, which continues to be lacking in gully erosion research (Vanmaercke et al., 2021).

Lastly, the GSI model could be tested in modelling different environmental change scenarios by changing RDN and land-cover/-use data. Gully erosion is expected to be impacted by climate change (Vanmaercke et al., 2016), and deriving information regarding gully susceptibility evolution under environmental change is essential for land managers and policymakers. Although the GSI model can produce environmental change outputs, interpretations of such outputs need to consider that the model is static, thus unable to model positive and negative feedback mechanisms between gullying and environmental change.

5 | CONCLUSION

Gully erosion has been identified as a severe land degradation process with environmental and socio-economic consequences. Identifying areas susceptible to gully erosion is essential to help the development of strategies to inhibit future degradation. We introduce a novel approach that blends literature directives with statistics to map gully susceptibility on a regional/national scale. The GSI model was validated using an existing, published gully inventory map of SA (Mararakanye & Le Roux, 2012) and primary data obtained from randomly allocated 1-km^2 tessellation zones. The GSI model output shows robust performance, even performing well in certain provinces, which are underrepresented in gully erosion sites. However, uncertainties remain, which propagate through the execution process. Gully headcut location mapping, increasing the distribution of gully erosion sites and obtaining higher spatial resolution datasets should be given future attention and could improve prospective future modelling. Despite the uncertainties, the GSI model shows promise because of its validation statistics and convergence with other gully susceptibility metrics derived from different methodologies in SA. Because of the empirical research span across the world, the GSI model could be implemented in various countries. Additionally, the GSI model could be used to predict the impact of environmental change on regional gully susceptibility by incorporating RDN inputs for predicted climate change and combining them with expected land-use changes. Lastly, the low data input, simplistic model could be helpful to land managers to effectively identify gully-susceptible areas where costly mitigation works would have the most impact.

AUTHOR CONTRIBUTIONS

(a) Conceptualisation: George Olivier, Marco J. Van De Wiel and Willem P. de Clercq; (b) funding acquisition: George Olivier, Marco J. Van De Wiel and Willem P. de Clercq; (c) methodology: George Olivier, Marco J. Van De Wiel and Willem P. de Clercq; (d) investigation: George Olivier; (e) resources: George Olivier; (f) software: George Olivier; (g) supervision: Marco J. Van De Wiel and Willem P. de Clercq; (h) writing—initial draft: George Olivier; and (i) writing—reviewing and editing: George Olivier, Marco J. Van De Wiel and Willem P. de Clercq.

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CONFLICT OF INTEREST STATEMENT

All authors have approved the manuscript and agree with its submission to Earth Surface Processes and Landforms. The authors declare no conflict of interest. The funders were not involved in the design of the study, the collection, analysis and interpretation of the compiled data, in writing, reviewing and editing the manuscript, or in which academic journal to publish.

DATA AVAILABILITY STATEMENT

The data are described and available in the text. Links and supplier data for the input data are provided, and the coordinate data for the research study sites are provided in the supplementary material. If access to the GSI output map, in its entirety or regional areas of it, is required, the author can be contacted to provide a copy of it.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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