



Soil Erosion Vulnerability Mapping in Selected Rural Communities of uThukela Catchment, South Africa, Using the Analytic Hierarchy Process

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Abstract

Soil erosion remains one of the main causes of land degradation, affecting many countries across the globe including South Africa. In rural communities with much reliance on agriculture, soil erosion is an important threat to food security. Therefore, mapping erosion-prone areas is an essential step towards adopting appropriate erosion mitigation and soil conservation measures. The objectives of this study were to (i) assess and model soil erosion vulnerability based on the Analytic Hierarchy Process (AHP) approach in Hoffenthal and KwaMaye communities within the uThukela Catchment, South Africa; and (ii) identify the relevant sustainable interventions and remedial strategies to combat soil erosion in the study area. The AHP was employed to map soil erosion vulnerability and derive the percentage weights of geo-environmental parameters contributing to soil erosion: rainfall, slope, drainage density, soil type, vegetation cover, and land use/land cover. The AHP model showed that slope, vegetation cover, and rainfall had the most considerable influence on soil erosion with factor weights of 29, 23, and 18%, respectively, in the study area. Further, this study revealed that high-risk soil erosion areas occupy 21% of the total study area, while very high-risk areas are about 14%, and the east and central areas are most vulnerable to soil erosion. Validation of the AHP model (overall accuracy = 85%; kappa coefficient = 0.70) results suggests that the predictive capacity of the model was satisfactory. Therefore, the developed soil erosion vulnerability model can serve as an important planning tool to prioritize areas for soil conservation and erosion management approaches like sustainable agriculture and bioengineering interventions.

Keywords Soil erosion · Erosion vulnerability · Analytical hierarchy process · Geo-environmental parameters · Interventions

1 Introduction

Soil erosion is a natural process that is usually accelerated by anthropogenic activities that predispose the topsoil to soil erosion (Beckedahl and de Villiers 2000; Kakembo and Rowntree 2003; Pimentel and Burgess 2013; Fetzel et al. 2018), leading to undesirable socio-economic and environmental outcomes. Soil erosion by water has been recognized as the major form of land degradation, involving three stages: (1) detachment of soil particles/aggregates from the soil mass; (2) transportation of detached material by runoff, and (3) deposition (FAO 2019; Lal 2003; Morgan 2009). Due to its negative effects on natural resources, such as soil and water, soil erosion has gained worldwide recognition as an important issue (Lal 2001). The most concerning erosional effects relate to reduced soil productivity and crop yields, especially in the face of the continuously

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growing global population and subsequent need for food production (Pimentel 2006; FAO 2019). On a global scale, approximately 10 million ha of cropland are abandoned every year due to lack of productivity caused by soil erosion (Faeth 1994). This lack of productivity is not surprising given that soil erosion on croplands averages about 30 t/ha-yr and ranges from 0.5 to 400 t/ha-yr (Pimentel et al. 1995). Although both developed and developing countries are subject to erosion, in developing countries, soil erosion is particularly severe on small farms that are often located on marginal lands with poor soil quality and steep topography (Pimentel 2006). Usually, soil erosion rates in such developing countries are often exacerbated by inappropriate agricultural practices.

South Africa (SA) is generally not an exception to the threats posed by soil erosion concerning agriculture, food security, community livelihood, and the environment (Department of Agriculture n.d.). Approximately 61 million ha of land in SA is classified as moderate to severely vulnerable to soil erosion, while 91 million ha is classified as low to very low vulnerable to soil erosion (Le Roux et al. 2008). In particular, KwaZulu-Natal (KZN) Province is one of the highest erosion-prone provinces in SA, and its south region is one of the most erodible areas in the province (Department of Agriculture n.d.; Le Roux et al. 2007). This can be attributed to the fact that some areas of the province are characterized by dispersive and erodible soil types, heavy rainfall events, steep slopes, and poor vegetation cover (Gibbs and Salmon 2015; Hoffman and Todd 2000; Le Roux et al. 2007). Therefore, assessing soil erosion vulnerability is essential, paying particular attention to the identification of areas with varying levels of soil erosion risk (i.e., from extremely high to low). This will serve as an initial step towards erosion risk management, leading to developing and implementing targeted soil erosion interventions and control measures.

In recent years, different quantitative model-based approaches incorporating remote sensing and spatial analysis have been employed to extract soil erosion vulnerability parameters and spatial distribution. For instance, Makaya et al. (2019a, b) successfully mapped soil erosion-vulnerable areas in Okhombe valley, KZN, SA using Sentinel-2 multispectral sensor, together with the Support Vector Machine algorithm and GIS techniques. Alexakis et al. (2019) mapped soil erosion in Akrotiri cape, Crete, Greece by implementing an integrated use of the Revised Universal Soil Loss Equation (RUSLE) approach, GIS, remote sensing data (Sentinel-2 and Landsat 8), field spectroscopy, and artificial neural networks. Although RUSLE has been widely used successfully worldwide (Rawat and Singh 2018; Mohammed et al. 2020; Waltner et al. 2020; Hateffard et al. 2021), it may be inaccurate in most parts of SA, especially in gully-dominated landscapes with steep slopes (Smith 1999;

Laker 2004; Sepuru and Dube 2018). In their prediction of soil erosion risk across the entire SA, Le Roux et al. (2008) found that RUSLE overestimated soil erosion risk for the very steep mountain ranges of the Western Cape and Limpopo Provinces. Consequently, RUSLE in SA is usually used in conjunction with other methods. For example, Flügel et al. (2003) used an erosion response unit (ERU), RUSLE, and a dynamic gully erosion model to delineate erosion-affected areas in KZN. Phinzi et al. (2021b) used RUSLE together with the random forest (RF) algorithm to assess soil erosion in eastern SA while Mhangara et al. (2012) combined RUSLE with object-based image classification to extract erosion features in the same region. Besides, most parts of the country often lack in-situ measured sediment yield data to validate RUSLE estimates. As a result, qualitative assessments of soil erosion vulnerability are usually conducted. The Analytic Hierarchy Process (AHP) is a useful tool for both determining the most important erosional factors and prioritizing erosion-prone areas in a specific catchment.

Recently, Makaya et al. (2019a, b) employed the AHP model to assess areas of soil erosion vulnerability in the Upper uMgeni catchment in KZN, SA. This study suggested that slope had the most considerable influence on soil erosion in the Upper uMgeni catchment, KZN, SA. Similarly, the AHP model was successfully used to assess soil erosion vulnerability in the Northeast Semnan Province of Iran (Arabameri et al. 2019b), and in the upper catchment of Markanda River in India (Saini et al. 2015). The flexible, intuitive, and rational nature of the AHP approach and its reliability in erosion vulnerability assessment makes it a useful tool to numerous decision-makers and researchers (Saaty 1980; Saaty and Vargas 1984; Gibbs and Salmon 2015). This is because the AHP approach relies on expert knowledge and experiences and field visits to the area studied (Saaty 1980). Furthermore, the AHP approach allows collective decision-making by experts; it disintegrates the decision problem into sub-sections; grades the input criteria and calculates the weight or influence of each factor; and finally, it helps control bias in the decision-making process by evaluating consistencies of the pair-wise comparison to the input parameters (Saaty 1980; Saaty and Vargas 1984; Gibbs and Salmon 2015). The success of the AHP model has been reported by various researchers, practitioners, and decision-makers in other natural phenomena and geo-hazards problems, such as landslide vulnerability (Kavzoglu et al. 2014), flooding vulnerability (Fernandez et al. 2016), soil erosion vulnerability (Kulimushi et al. 2021a; Kumar and Singh 2021), and tropical cyclone risk (Hoque et al. 2019).

Identifying areas critically vulnerable to soil erosion in rural communities of KZN, South Africa, such as Hofenthal and KwaMaye communities in the uThukela (also called Tugela) catchment, has received little attention from researchers. In particular, the application of the AHP model

in soil erosion vulnerability assessment in the entire KZN region, one of the most eroded provinces in South Africa, is scant. Additionally, although soil erosion generally results from a complex interaction of natural and anthropogenic forces (Phinzi and Ngetar 2019), site-specific factors are not well understood. This means the essential and initial information needed by the relevant authorities towards implementing appropriate erosion mitigation and soil conservation measures is lacking. Therefore, to fill these existing research gaps, this study seeks to (i) assess and model soil erosion vulnerability based on the AHP model in Hoffenthal and KwaMaye communities in the uThukela catchment, KZN, South Africa; and (ii) identify the relevant interventions and remedial strategies that can be employed by the appropriate authorities to combat soil erosion in the study area.

2 Materials and Methods

2.1 Study Area

The study area comprises KwaMaye and Hoffenthal communities situated in the upper uThukela catchment, KZN, SA. This area is located between latitudes $28^{\circ}45'26.27''$ S and $28^{\circ}49'16.47''$ S, and $29^{\circ}12'53.03''$ E and $29^{\circ}17'20.01''$ E (Fig. 1). The area is boarded by Woodstock Dam in the west, Woodstock Dam and uThukela River in the north, Drieldam

in the East, and the south by Maswazini and Ngoba communities. The vegetation is classified as semi-arid grassland and characterized by Southern tall grassveld, highland sour-veld, and dohne sourveld (Acocks 1988). It receives approximately 80% of its annual rainfall from November to April. The annual rainfall ranges from 1000 to 1500 mm (Rienecker et al. 2011). The terrain elevation varies from 1134 m in the north to 1575 m in the south (Farr et al. 2007).

KwaMaye and Hoffenthal communities are rural settlements and their main source of livelihood is subsistence farming based on livestock rearing and crop cultivation. Scattered agricultural land (mainly maize cultivation) near Woodstock Dam and uThukela River is also a notable characteristic of the study area. The open spaces without vegetation are covered by human infrastructure (roads and homesteads), erosion features (rills, sheets, and gullies), topographic ridges of varying geometry, and clastic sediment depositions. The main soil types in the study area are Chromic Acrisols and Leptic Regosol, both highly dispersive and erodible (Dijkshoorn et al. 2008). These soils are underlain by Mudstone of the Tarkastad Subgroup which dominates the upper reaches of the uThukela catchment. Even though naturogenic factors are considered major soil erosion contributing factors, in the Hoffenthal and KwaMaye communities, anthropogenic factors, such as overgrazing, poor cultivation practices, and human infrastructures, cannot be ignored.

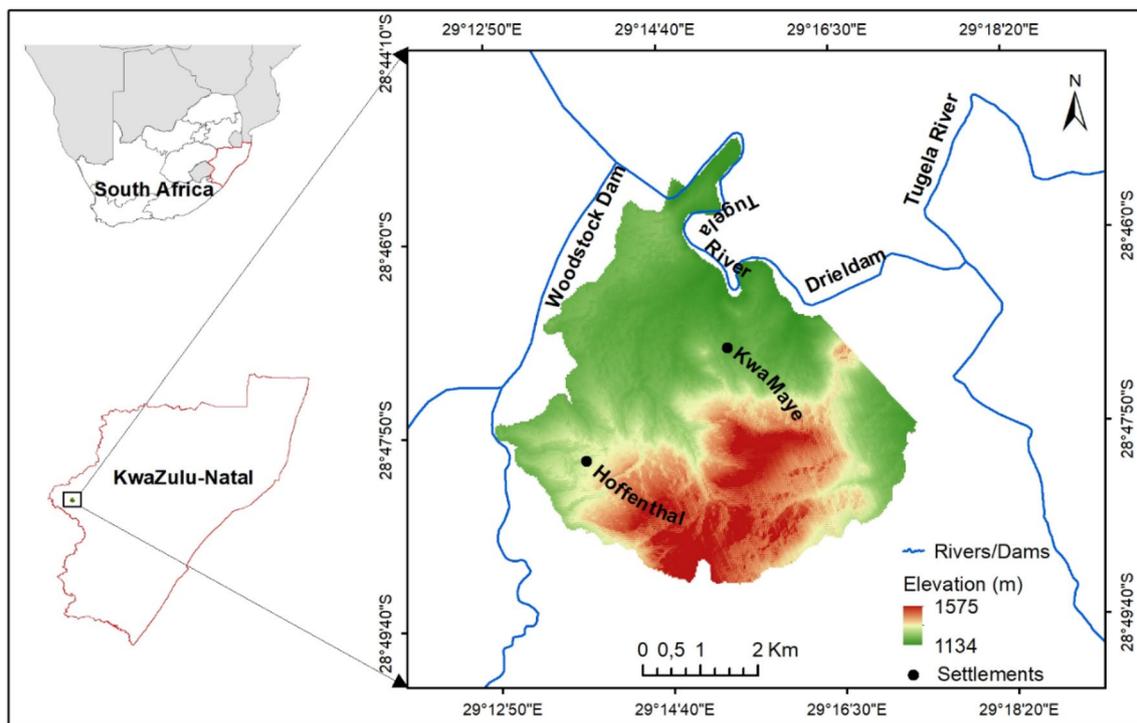


Fig. 1 The geographic location of the study area within the KwaZulu-Natal (KZN) Province, South Africa

2.2 Data

The data used in this study (Table 1) and the methods employed to achieve the objectives of this study include six steps (Fig. 2). These steps are (i) preparation of the geo-environmental parameters or spatial criteria layers, (ii) weighing of criteria by AHP, (iii) pair-wise comparison matrix, (iv) consistency ratio calculation, (v) preparation of the soil erosion vulnerability map (vi) model validation. The data used

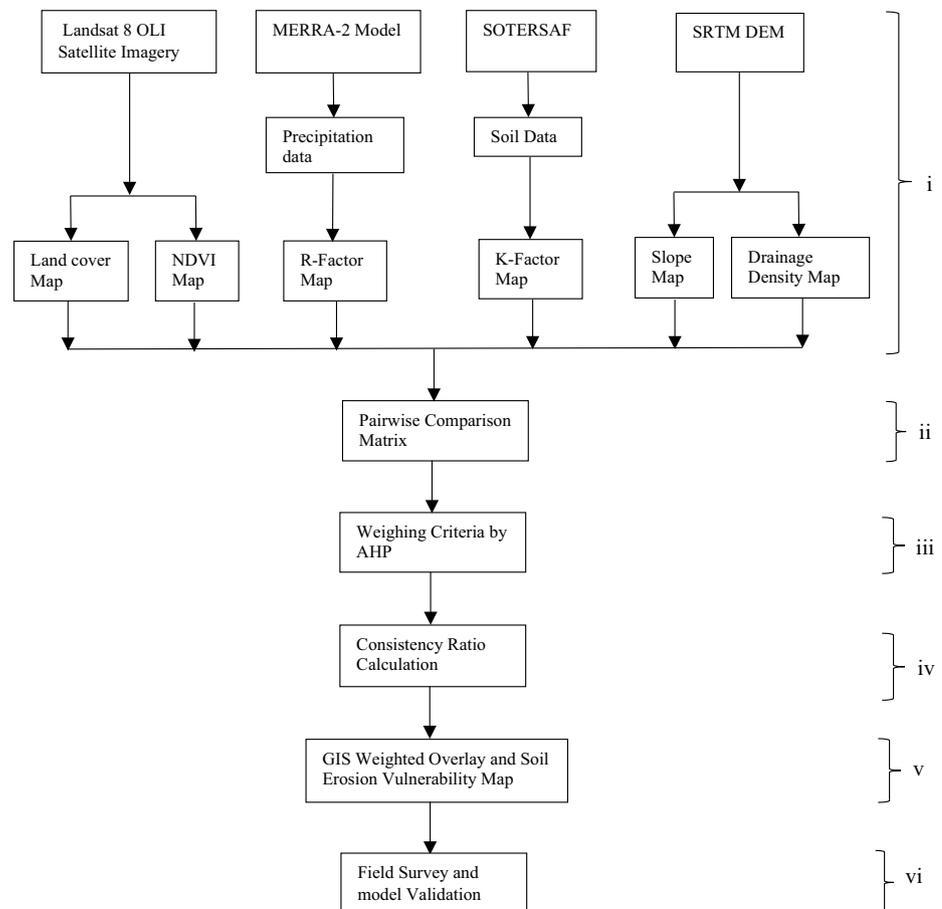
in this study were selected based on their influence on soil erosion. Thus, six geo-environmental parameters were used to map soil erosion vulnerability in this study were obtained from different sources (Table 1) and include land use/land cover, NDVI, R factor, K factor, slope, and drainage density (Fig. 3a–f). To perform the soil erosion vulnerability assessment in the GIS platform, the cell size, spatial resolution in the ArcGIS raster analysis environment was set to 30×30 m for each raster layer for consistency and accuracy.

Table 1 Map data used in this study and their sources

Data type	Source	Period	Scale	Mapping data
Satellite Imagery (Landsat 8 OLI)	USGS Earth Explorer	18-07-2019	30 m	Land use and cover
Satellite Imagery (Landsat 8 OLI)	USGS Earth Explorer	18-07-2019	30 m	Vegetation index (NDVI)
Precipitation	MERRA-2 model via Climate Engine Application	1983–2018	$0.5^\circ \times 0.625^\circ$	R factor
Soil types	SOTERSAF (1:250,000)	2004	1:250,000	K factor
SRTM DEM	USGS Earth Explorer	11-02-2000	30 m	Slope
SRTM DEM	USGS Earth Explorer	11-02-2000	30 m	Drainage density

SOTERSAF Soil and Terrain database for South Africa, *USGS* United States Geological Survey, *OLI* Operational Land Imager, *MERRA* Modern-Era Retrospective Analysis for Research Application, *SRTM* Shuttle Radar Topography Mission, *DEM* Digital Elevation Model

Fig. 2 Flowchart representing the methodology employed in the study



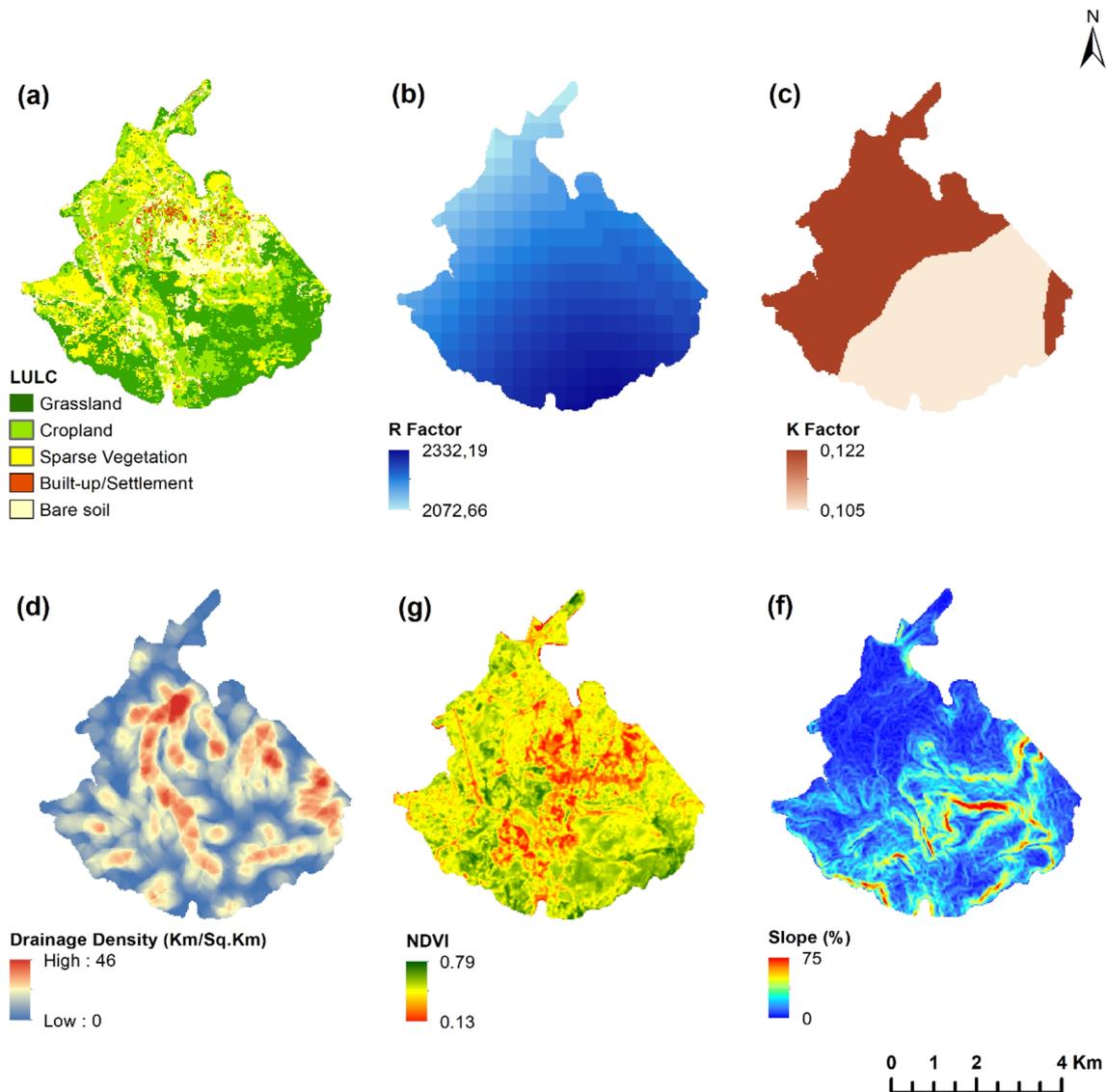


Fig. 3 Geo-environmental parameters used in the soil erosion vulnerability analysis (carried out from July to October 2019) in this study: **a** Land cover, **b** NDVI, **c** R factor, **d** K factor, **e** Drainage density, **f** Slope

2.3 Geo-environmental Parameters

2.3.1 Land Cover and Vegetation Index

Soil erosion varies among different land cover types. Areas with exposed topsoil and poor vegetation cover are more vulnerable to soil erosion. Thus, land use and land cover are important parameters in soil erosion modeling (Szilassi et al. 2006). The land use and land cover classified map were developed from Landsat 8 OLI satellite imagery for the study area using the random forest supervised image classification algorithm (Sahebjalal and Dashtekian 2013). The types of classes identified relevant to this study are grassland, cropland, sparse vegetation, built-up/settlement, and

bare land (Fig. 3a). The overall accuracy of this classification was 0.93 which is adequate for this study. Besides, a vegetation cover proxy map, the normalized difference vegetation index (NDVI) map (Fig. 3b) of the area was produced from the Landsat 8 OLI satellite imagery.

2.3.2 Rainfall (R Factor)

Daily precipitation data (1983–2018) extracted from the Modern-Era Retrospective Analysis for Research Application (MERRA-2) model via Climate Engine Application at $0.5^\circ \times 0.625^\circ$ resolution (Rienecker et al. 2011) were aggregated to obtain monthly totals for the study period. Monthly precipitation data of the Bergiville

station (−28.75 S; 29.25 E) covering the study period were also collected for validating the MERRA-derived rainfall estimates. Three statistical metrics consisting of Pearson's correlation coefficient (r), root mean square error (RMSE), and relative BIAS were used to evaluate the agreement between the MERRA product and gauge observations (Amekudzi et al. 2015; Gao et al. 2018). Pearson's correlation coefficient (r) indicates how well the estimates correspond to the ground observations while the RMSE and BIAS describe the error and bias, respectively, of the estimates compared to the ground observations (Gao et al. 2018; Atiah et al. 2020). These statistical metrics were calculated based on Eqs. (1) to (3):

$$r = \frac{N \sum_{i=0}^n G_i V_i - \sum(G_i) \sum(V_i)}{\sqrt{N \sum G_i^2 \sum(G_i)^2 (N \sum V_i^2 - \sum(V_i)^2)}} \quad (1)$$

$$\text{RMSE} = \sqrt{\sum_{i=0}^n \frac{(V_i - G_i)^2}{N}} \quad (2)$$

$$\text{BIAS} = \frac{\sum_{i=0}^n (V_i - G_i)}{\sum_{i=0}^n G_i} \times 100\% \quad (3)$$

where V_i is the estimate, G_i is the observation and N is the number of observations. The MERRA data had a strong correlation ($r = 0.91$, $p < 0.05$) with station observations at a monthly scale, recording an RMSE of 48.51 mm and a BIAS of 0.06%.

Rainfall erosivity (R factor) is one of the selected factors that influences soil erosion vulnerability. Areas with a relatively high amount of rainfall and intensity are more vulnerable to soil erosion (Blanco and Lal 2008). The R factor is a multi-annual average index that measures rainfall's kinetic energy and intensity to describe the effect of rainfall on soil erosion, and it is calculated by multiplying the total storm energy (E —MJ/m²) by the maximum 30-min intensity (I_{30} —mm/h) (Renard et al. 1996), however, in this study, data on storm intensity were not available, prompting the use of monthly data. Thus, the R factor (Fig. 3c) for this study was computed using Wischmeier and Smith (1978) empirical relation explained by Eq. (4).

$$R = \sum_{i=1}^{12} 1.735 \times 10^{\left(1.5 \log \frac{p_i^2}{p} - 0.8188\right)} \quad (4)$$

where R represents erosivity factor (MJ mm ha^{−1} h^{−1} yr^{−1}), p is mean annual precipitation (mm), and p_i is total monthly precipitation (mm).

2.3.3 Soil (K Factor)

Different soil types exhibit varying degrees of erodibility, thus resulting in varying degrees of soil erosion vulnerability. Soil erodibility (K factor) is the average long-term rate of soil erosion susceptibility in response to rainfall and runoff (Blanco and Lal 2008). The K factor map (Fig. 3d) in this study was prepared from the Soil and Terrain (SOTER) database for Southern Africa with a scale of 1:250,000 (Batjes 2004), using the Eq. (5) (Williams and Singh 1995).

$$K = f_{csand} \cdot f_{cl-si} \cdot f_{orgc} \cdot f_{hisand} \quad (5)$$

where K represents erodibility factor (t.ha.hr/ha.MJ.mm), f_{csand} is a factor that provides low soil erodibility for soils with high-coarse sand contents and high values for soils with little sand, f_{cl-si} is a factor that provides low soil erodibility for soils with high clay to silt ratios, f_{orgc} is a factor that decreases soil erodibility for soils with high organic carbon content and f_{hisand} is a factor that decreases soil erodibility for soils with extremely high sand contents.

2.3.4 Slope

The slope is a very important factor in determining soil erosion vulnerability because it controls soil erosion and other related geomorphic processes like transportation and sedimentation related to rainfall-runoff (Phinzi and Ngetar 2019). It has been well established that the steeper the slope, the higher the vulnerability of soil to erosion and vice versa (Seutloali and Beckedahl 2015). The slope map presented in Fig. 3e was derived from the SRTM 30 m digital elevation model (DEM) (Farr et al. 2007) using the spatial analyst slope tool in ArcGIS software. As a readily and freely available DEM product with global coverage, the SRTM DEM has been widely used in many erosion studies (Kulimushi et al. 2021b; Senamaw et al. 2021), because of its relatively high accuracy compared to other freely available DEM products (Szabó et al. 2015).

2.3.5 Drainage Density

Drainage density provides a measure of the total length of streams, rivers, and channels in an area divided by the surface area. The drainage density of an area above the critical value of 0.90 km/km² has a higher vulnerability to soil erosion (Leopold et al. 2020). The drainage density map (Fig. 3f) was derived from the SRTM 30 m digital elevation model (DEM) (Farr et al. 2007) using the spatial analyst hydrologic toolset in ArcGIS software.

2.4 The Analytical Model

The AHP model, a GIS-based Multi-criteria decision analysis (MCDA) approach, was used to generate the soil erosion vulnerability maps (Saaty 1980) and their classifications based on the severity of the six geo-environmental parameters. The development of the model included the pair-wise comparison matrix of the six geo-environmental parameters using the AHP approach, relative weight calculation, consistency ratio (CR) calculation, and model validation.

2.4.1 Pair-Wise Comparison Matrix and Weighting Each Geo-environmental Soil Erosion Parameter

Employing the AHP approach to develop the pair-wise comparison matrix and assign weights to the geo-environmental parameters that influence soil erosion allowed for a logical and well-structured decision-making process to be followed (Makaya et al. 2019a, b; Vijith and Dodge-Wan 2019). Each geo-environmental parameter is assigned a weight based on its relative importance in influencing soil erosion within the catchment (Kumar and Singh 2021). A pair-wise comparison matrix is a tool that grades a set of decision-making criteria (the geo-environmental soil erosion parameters) and rates the criteria on a relative scale of importance (Saaty 1980; Saaty and Vargas 1984).

The normalized pair-wise comparison matrix was derived based on the rating of each soil erosion parameter on the

basis of relative importance varying from 1 to 9 using Saaty and Vargas (1984) scale for comparison (Table 2) as a guide (where 1 is given when both criteria under comparison are of equal influence, and 9 implies one criterion is extremely relevant over the other). Thereafter, the normalized weight of each parameter was obtained (Table 3). However, to ensure the accuracy of derived weight for each parameter, the quality of the pair-wise comparison was assessed using the consistency ratio calculation.

2.4.2 Consistency Ratio (CR) Calculation

The outcome of the pair-wise comparison is subjective. Thus, the quality of the comparison (i.e., the suitability of individual parameters and their classes) can be assessed using an index of consistency, known as the consistency ratio (CR), as shown in Eq. 5 (Saaty 1977). A CR value less than and equal to 0.1 is acceptable because the pair-wise comparison possesses an acceptable level of consistency. The consistency ratio for the pair-wise comparison in this study is 0.08, indicating that the pair-wise comparison and the weight derived for the individual parameters are adequate.

$$CR = \frac{CI}{RI} \tag{6}$$

Where RI represents the Random index and CI is the consistency index and it is determined using Eq. (7) below:

$$CI = (\lambda_{max} - n)/(n - 1) \tag{7}$$

where λ_{max} represents the largest eigenvalue of the matrix.

2.4.3 Soil Erosion Vulnerability Model

The acquired weights of the six geo-environmental parameters were used to calculate the soil erosion vulnerability model using a simple weighted linear sum approach as illustrated in Eq. (8).

$$V = LULC(9\%) + RF(18\%) + KF(13\%) + DD(7\%) + NDVI(23\%) + SLOPE(29\%) \tag{8}$$

Table 2 Scale for pair-wise comparison of Saaty’s method

Scale of importance	Description
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
Intermediate (2, 4, 6, 8)	Intermediate values between adjacent scale values
Reciprocals (1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9)	Values for inverse comparison

Table 3 Normalized pair-wise comparison matrix and weights of the geo-environmental parameters

Criteria	Drainage density	R factor	K factor	Land cover	NDVI	Slope	Weights (%)
Drainage density	1.00	0.33	0.33	0.50	0.33	0.50	9
R factor	3.00	1.00	1.00	3.00	1.00	0.33	19
K factor	3.00	1.00	1.00	1.00	0.50	0.33	16
Land cover	2.00	0.33	1.00	1.00	0.33	0.33	8
NDVI	3.00	1.00	2.00	3.00	1.00	1.00	21
Slope	2.00	3.00	3.00	3.00	1.00	1.00	28

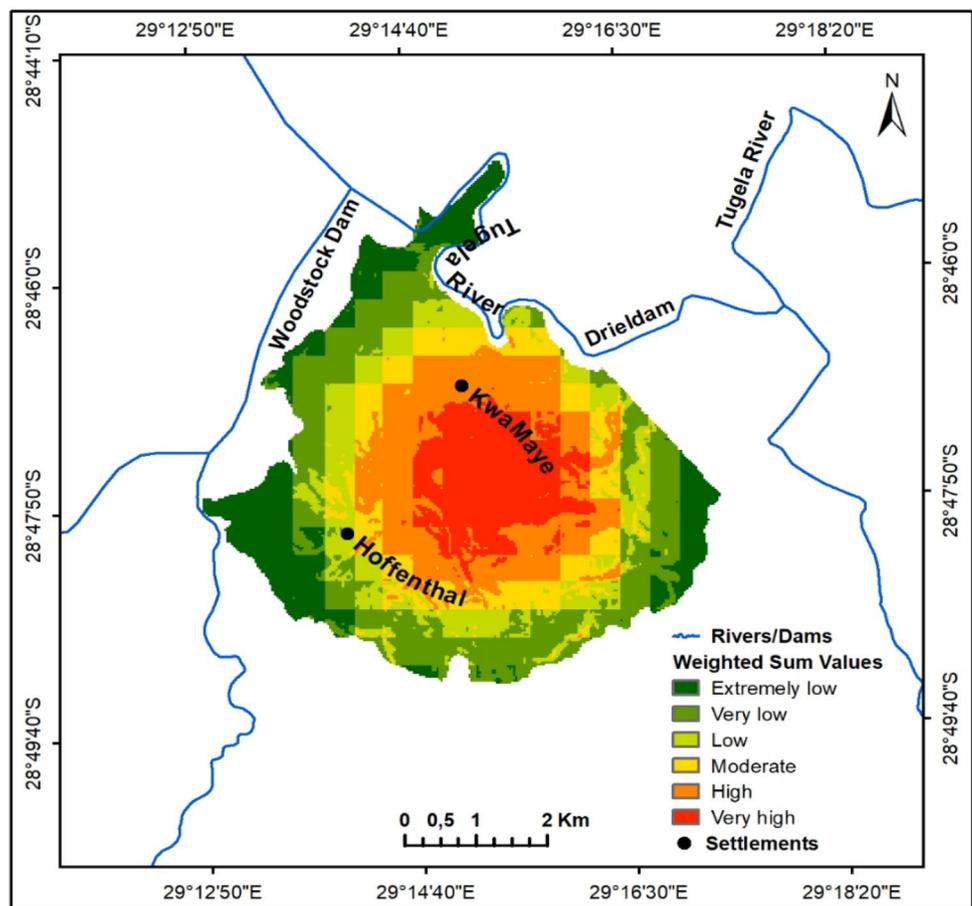
2.4.4 Model Validation

A combination of a field visit (Fig. 4) and a high-resolution aerial photograph was used to verify if the predicted model represented the soil erosion risk in the study area. The six soil erosion vulnerability classes (very low, low, moderate, high, very high, and severely high) used to represent soil erosion risk in the study area were validated in relation to the presence and absence of soil erosion, using a confusion matrix. Very low to low areas of soil erosion were merged into one class called “non-erosion” while moderate to extremely high classes were merged into another class called “erosion” (Le Roux et al. 2008). Randomly selected points (120) were generated for the “non-erosion” and “erosion” classes using an equalized stratified random method. A hand-held GPS receiver was used to obtain the geographic coordinate for each selected point; both the “non-erosion” and “erosion” classes were each assigned 60 points. Thereafter, a confusion matrix, a widely used and accepted method for accuracy assessment, was computed to assess the accuracy of the AHP-based soil erosion vulnerability map. It consists of various accuracy metrics (overall accuracy, kappa coefficients, user’s accuracy, and producer’s accuracy) (Congalton 1991).

3 Results

Weights determined (Table 3) for the six geo-environmental parameters used in the AHP model revealed that the slope (29%), vegetation cover (23%), and rainfall (18%) had the greatest influence on soil erosion vulnerability in the Hoffenthal and KwaMaye communities. The spatial distribution of soil erosion vulnerability map of the study area (Fig. 4) shows that erosion vulnerability varied from very high vulnerability to moderate vulnerability in the north and central parts of Hoffenthal and KwaMaye communities, respectively. These areas occupy approximately 47% of the total study area (Figs. 4 and 5), and they are characterized by steep and long gentle slopes, high rainfall, dispersive soils, and poor vegetation cover. Conversely, areas with low, very low, and extremely low erosion vulnerability are mainly in the east and west of KwaMaye, and the southern part of Hoffenthal. These areas occupy about 52.81% of the total study area (Figs. 4 and 5), and they are mainly flatlands covered by dense natural vegetation and some cropping activities. Thus, we suggest the interdependence of rainfall, slope, and poor vegetation cover as the main drivers of soil erosion development in our study area. However, field observation indicated that some areas with high to very high erosion vulnerability

Fig. 4 Soil erosion vulnerability map of Hoffenthal and KwaMaye communities



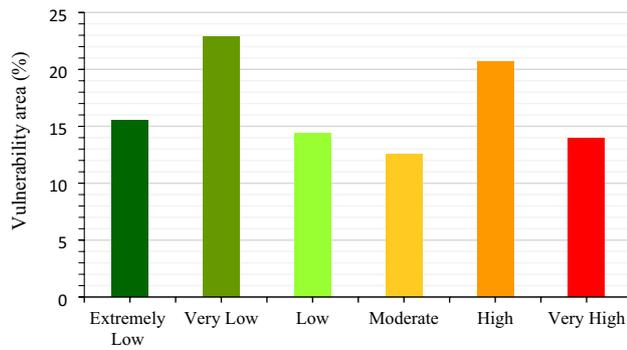


Fig. 5 Soil erosion vulnerability zones ranging from extremely low to very high erosion

are found in gently sloping lands dissected by extensive permanent gullies (Fig. 6). The prevalence of gullies in gentle slopes is common in South Africa, especially in agricultural areas (Mararakanye and Le Roux 2012; Phinzi et al. 2021a). Inappropriate agricultural practices such as overgrazing, combined with highly erodible soils, are probably the main drivers of soil erosion in such areas (Mararakanye and Le Roux 2012).

Various accuracy indices used to evaluate the classification and the reliability of the AHP-based soil erosion vulnerability model showed reasonable performance of the model

(Table 4). Particularly, the model performed exceptionally well concerning PA (87%), overall accuracy (85%), and UA (82%). Except for the kappa coefficient (0.70), all other accuracy metrics were above 80%, an acceptable accuracy threshold often recommended for practical purposes (Everitt et al. 2008; Phinzi et al. 2020).

4 Discussion

The observed relationship between the soil erosion drivers in our study area, suggests that high rainfall intensity causes detachments of fine particles from coarse particles, particularly in the central parts of the study area with sparse vegetation cover and bare soil. The detached particles are transported downslope, resulting in soil instability (Chen et al. 1980). From field observations, the fluvial and runoff associated landforms/erosion features including gully and rill/inter-rill erosion were evident across grasslands as well as in some active and abandoned agricultural fields. In grasslands, the process of erosion is partly facilitated by overgrazing, leading to the poor vegetation cover which exposes the highly erodible and dispersive soils (Chromic Acrisols and Leptic Regosol) to the direct effect of rainfall and thus lacks the ability to reduce the erosive effect of rainfall (Dijkshoorn et al. 2008; Mills and Fey 2004). This can be attributed to

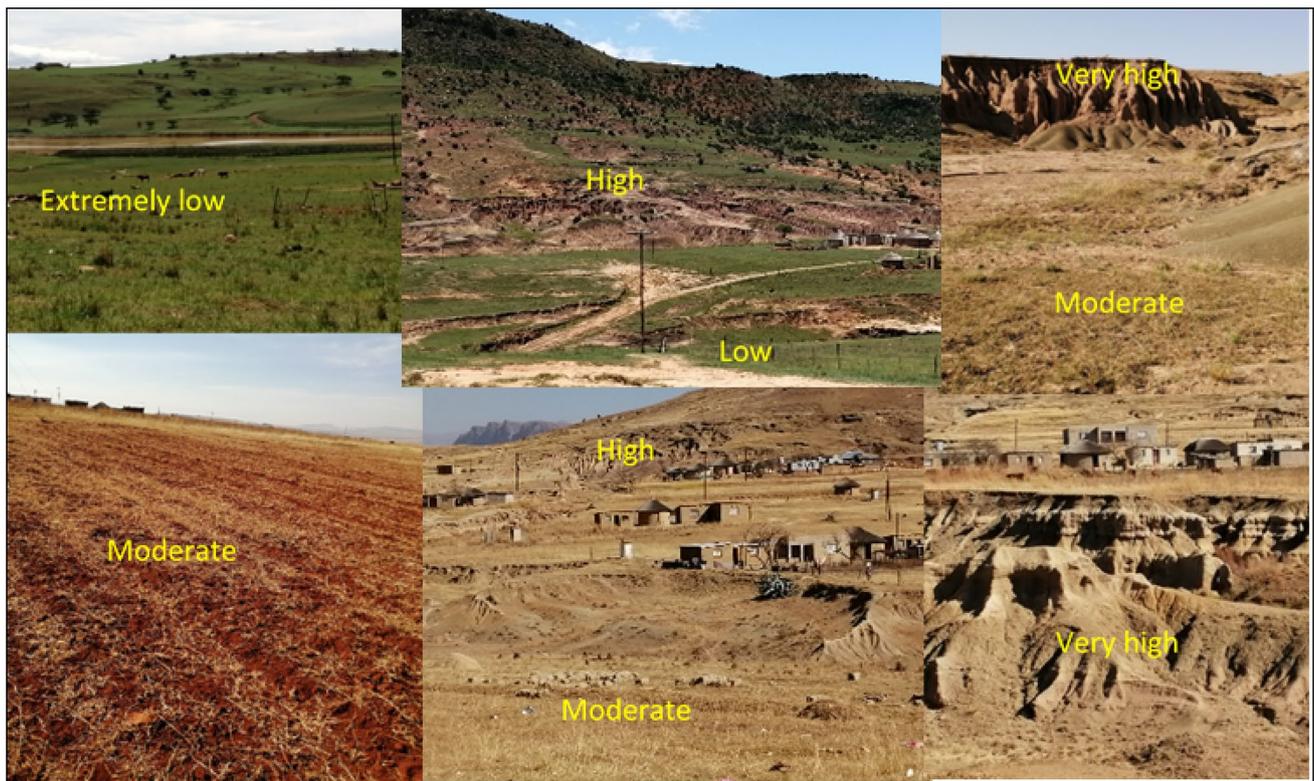


Fig. 6 Field photos of the observed soil erosion in the study area

Table 4 Confusion matrix of AHP-derived soil erosion vulnerability results

	Non-erosion	Erosion	Total	UA	OA	Kappa
Non-erosion	53	7	60	88%	–	–
Erosion	11	49	60	82%	–	–
Total	64	56	120	–	–	–
PA	83%	87%	–	–	–	–
OA	–	–	–	–	85%	–
Kappa	–	–	–	–	–	0.70

PA Producer's accuracy, UA User's accuracy, OA Overall accuracy

the fact that poor vegetation decreases soil water retention, promotes runoff by decreasing pathway tortuosity, reduces infiltration rate, and increases the sediment carrying capacity of the runoff (Rees et al. 2002; Findeling et al. 2003; García-Orenes et al. 2009). Apart from the reduced vegetative cover due to overgrazing, livestock (cattle, goats, and sheep) and human footpaths/tracks encourage surface runoff concentration, leading to rill erosion. Most rill erosion features are a direct product of concentrated runoff from such animal and human footpaths especially in hilly and mountainous southern parts of the study area. Footpath erosion has been reported in other mountainous parts of the uThukela Catchment (Garland 1987). It appears that this type of erosion tends to increase with slope steepness exponentially as observed in this and other studies (Quinn et al. 1980; Coleman 1981). Generally, a similar relationship between the soil erosion drivers in this study was reported in other studies conducted in South Africa (Makaya et al. 2019a, b; Phinzi et al. 2021b), Tunisia (Kachouri et al. 2015) India (Saini et al. 2015), China (Khan et al. 2016) and Iran (Arabameri et al. 2018, 2019b). For example, Makaya et al. (2019a, b) observed that areas with high soil erosion vulnerability in Edendale, South Africa, were characterized by slope gradient above 36%, rainfall values above 892 mm, and very low vegetation cover. Similarly, Khan et al. (2016) demonstrated how a poorly vegetated area in Sichuan Province, southwest China, with slope steepness from 15°, and rainfall intensity of 94 and 120 mm h⁻¹ resulted in significant sediment loss. However, Le Roux and Sumner (2012), Phinzi et al. (2021b), and Arabameri et al. (2019a) suggested that gentle slope areas are also highly vulnerable to gully erosion in Eastern Cape, South Africa and Semnan province, Iran. Such gully erosion vulnerability is due to surface flow accumulation and easy accessibility by humans and grazing animals, thus resulting in overgrazed and poorly vegetated lands (Arabameri et al. 2019a; Le Roux and Sumner 2012; Rahmati et al. 2016). These poor land management practices are a historical problem in South African communal settlements and can be attributed to environmental and political abandonment (Department of Water and Sanitation 2003). However, during our field data collection, we also observed that some of the gentle slope areas with dense vegetative cover

had extensive gullies eroded from sidewalls. It is therefore highly possible that the rainfall intensity and highly dispersive soil types in the study area, rather than steep slope and poor vegetation cover, are responsible for gully sidewall erosion. Another possible factor contributing to gully erosion in the study area is the slope angle. Martinez-Casasnovas et al. (2004) note that high slope angle facilitates tension crack development which promotes gully wall collapse.

An important limitation in this study was a lack of field-measured sediment data to validate the AHP-derived soil erosion. Consequently, this study did not attempt to quantify the absolute values of soil loss, instead, the study assessed erosion-vulnerable areas based on qualitative analysis of erosion risk (ranging from extremely low to very high). However, an attempt was made to objectively quantify the level of agreement between the AHP-estimated erosion risk and actual soil erosion on the ground using the confusion matrix. This method of validation proved useful in previous erosion studies, especially where relevant validation data are lacking (Martinez-Casasnovas et al. 2004; Mhangara et al. 2012; Phinzi et al. 2021b). Various accuracy metrics used including OA (85%), Kappa coefficient (0.70), PA (87%), and UA (85%) confirmed that the AHP model correctly identifies soil erosion in the study area. On an overall basis, these findings are comparable to those of previous erosion studies conducted in different catchments in SA. Mhangara et al. (2012) obtained an OA of 79% in the Keiskamma Catchment while Phinzi et al. (2021b) reported an OA of 78% in the Umzintlava Catchment. Similarly, at a national scale, Le Roux et al. (2008) reported an OA of 77%. Thus, to a large extent, it is possible to rely on the AHP-based soil erosion vulnerability despite the apparent lack of in-situ sediment data. The AHP model showed that soil erosion vulnerability is relatively high in the east and central regions of Hoffental and KwaMaye communities, respectively. Such high soil erosion vulnerability in Hoffental and KwaMaye communities suggests that the productive potentials of the lands may be at risk, arising from loss of arable potentials (through loss of topsoil and soil nutrients), loss of grazing potentials, and the loss of biodiversity. Consequently, subsistence and small-scale farmers' sources of livelihood (crop and livestock production) are threatened (Le Roux et al. 2007).

Furthermore, the quality, quantity, and ecological integrity of water bodies close to the communities (especially Driel dam and Tugela River, the largest river in KZN) may also be at risk arising from siltation and nutrient load. These consequences combined with climate variability are possible factors causing local farmers to abandon their lands, and ultimately contributing to food insecurity, particularly among the rural poor (Department of Environmental Affairs 2016). Therefore, soil erosion controlling and/or ecological restoring strategies that involve collaborative support from the SA Department of Forestry and Fisheries through the LandCare Programme and Department of Agriculture and Rural Development in KZN, and cooperation from the local communities are required to protect the land and water resources.

Relevant governmental agencies should consider capacity development and implementation of ecological interventions to prevent soil erosion and rehabilitate eroded areas (Mori- aque et al. 2019). The capacity development should be aimed at educating and enlightening the local communities, especially the local farmers on the benefits and how to implement sustainable agricultural practices, such as conservation agriculture and organic farming (mulching, mixed cropping and inter-cropping, early planting, crop residues, agroforestry, minimum cultivation, cover cropping, and green manures), contour farming and rotation grazing (to protect the natural vegetation from overgrazing) (Prosdocimi et al. 2016; Keesstra et al. 2019). Already, in some parts of KZN, such as Msinga, Bergville, and Ndwedwe, farmers have increased yield productivity after receiving agricultural training from governmental institutions, such as the Department of Agriculture, Land Reform and Rural Development (DALRRD) and non-governmental organizations such as Farmers Support Group (FSG) (Sotshongaye and Moller 2000; Vilakazi et al. 2019). In the upper uThukela catchment where the study area falls, soil and water conservation have been prioritized by governmental and non-governmental organizations (Vilakazi et al. 2019). Similarly, there have been efforts to address farming and livestock management by DALRRD (Turpie et al. 2021). However, such governmental interventions have not been successful, and are currently not taking place in the study area. In part, this failure could be attributed to lack of continued funding to ensure sustainability and desired outcomes given the extent of erosion in the entire uThukela catchment (Turpie et al. 2021).

A variety of cost-effective soil and water bioengineering interventions can be implemented to ensure sustainable agricultural practices (Tardio et al. 2017; Rey et al. 2019). These are ecological approaches that integrate human society and its natural environment while controlling soil erosion and restoring degraded land based on soil erosion severity and the desired short or long-term land restoration strategy (Rauch et al. 2014; Rey et al. 2019). Immediate

bioengineering interventions that can be implemented include, brush layering (it can offer deep-seated protection), live pole drains or drain fascines (it drains excess water to encourage vegetation growth), jute netting (stabilize the slope and enhance vegetation), vegetated crib walls (that immediately protect watercourse banks), brush mattresses (that provides roughness against the flow) (Rey et al. 2019) and wattle fencing (Tardio et al. 2017). Other relevant bioengineering interventions that can be considered include mixed check dam (Tardio et al. 2017; Rey et al. 2019), erosion blankets (biodegradable materials that supports plant growth while simultaneously preventing soil erosion), grass buffer strips, palisades, sowings with straw mats and vegetated bench, prefabricated wooden structure, hydroseeding and river modeling (Rey et al. 2019). Several structural means can be used to rehabilitate gullies. These include reshaping gully banks, fitting gabions, constructing silt fences, and reseeded or replanting vegetation (Turpie et al. 2021). Preferably, given the high costs associated with gully rehabilitation, gullies should be prevented from forming or the rehabilitation should be carried out in the early stages of their formation (Valentin et al. 2005; Turpie et al. 2021). The successes of these bioengineering interventions have been reported extensively in studies conducted in Nepal (Dhital et al. 2013), Northern Scotland (Tardio and Mickovski 2016), and Spain (Tardio et al. 2017). Even though the implementation of the bioengineering interventions ultimately conserves energy and are cost-effective, they can be labor-intensive and their construction requires energy (von der Thannen et al. 2020). Therefore, the need to prioritize soil erosion-vulnerable areas based on the severity and urgency is important for efficient allocation of limited financial resources.

Our study suggests that the AHP approach can be used to prioritize areas vulnerable to soil erosion and highlight the significance of soil erosion on land and water resources and biodiversity. Studies on soil erosion trends incorporating time-series satellite imagery and field surveys are suggested to capture the seasonal variation of soil erosion to support the spatial variation of soil erosion vulnerability and improve the implementation of relevant soil erosion control measures. Also, soil erosion studies that incorporate data on chemical soil degradation are essential because soil acidification arising from chemicals is becoming a significant issue, especially in communal, low-income cropping regions or small-scale farming areas (Department of Environmental Affairs 2016). Furthermore, studies based on practitioners' experiences (for example, the cost, duration of installation, choice of materials, and human resource management) of bioengineering interventions will help better understand the benefits of implementing these approaches.

5 Conclusion

The AHP approach revealed that soil erosion vulnerability is relatively high in the east and central regions of Hoffenthal and KwaMaye communities, respectively. This is due to the interdependence of rainfall, slope, and poor vegetation cover exacerbated by anthropogenic activities like overgrazing and agricultural pressures. The findings of this study suggest that the predictive capacity of the AHP of our model was satisfactory based on OA (85%), Kappa coefficient (0.70), PA (87%), and UA (85%). Thus, the developed model can serve as an important planning tool to prioritize conservation and control measures based on soil erosion severity. A variety of cost-effective soil and water bioengineering interventions is suggested including among others: (i) brush layering which offers deep-seated protection against erosion, (ii) live pole drains or drain fascines that drain excess water to encourage vegetation growth, (iii) jute netting stabilizes the slope and enhances vegetation, and (iv) vegetated crib walls immediately protect watercourse banks. Due to the high costs associated with rehabilitation, this study emphasizes that gullies should be prevented from forming or the rehabilitation should be carried out in the early stages of their formation. This research has the potential to assist in preventing soil loss in KwaMaye and Hoffenthal communities, sustain crop and livestock production, and prevent sedimentation in the surrounding dams. We recommend future studies on soil erosion trends incorporating time-series satellite imagery and field surveys to capture the seasonal variation of soil erosion to support the spatial variation of soil erosion vulnerability and improve the implementation of relevant soil erosion control measures.

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Data availability statement Publicly available datasets including Landsat, SRTM DEM, precipitation, and soil data were used in this study. Landsat and SRTM DEM data can be found at <https://earthexplorer.usgs.gov/>, precipitation data can be found at <http://climateengine.org/data>, while soil data can be found at <https://files.isric.org/public/soter/SAF-SOTER.zip>

Declarations

Conflict of interest The authors declare no conflict of interest.

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