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Gully erosion susceptibility modelling to support avoided degradation planning

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ABSTRACT

Restoration resources are usually limited and strategic information on and erosion susceptible areas are required to avoid further degradation. This study has potential in the Mzimvubu River Catchment, South Africa, where two large reservoirs are planned on the Tsitsa tributary. The Tsitsa River Catchment, however, consists of highly erodible soils with widespread gully erosion evident. It is important to prevent further gully erosion in the catchment due to the presence of duplex and dispersive soils. Therefore, this study modelled areas that are susceptible to gully development in the Tsitsa River Catchment, as well as estimated the sediment yield potential from the susceptible areas if gully development occurs. This was achieved by mapping gully-free areas in a GIS that have the same DEM-derived topographical variables, soil associations and land cover as gullied areas, followed by scenario analysis of the potential sediment yield. More than 30 000 ha (7%) of the catchment is intrinsically susceptible to further gully development, consisting of drainage paths with a large contributing area and erodible duplex soils. If not protected, these susceptible areas could contribute an additional 300 million m^3 of sediment to the river network, reducing the volumes of both reservoirs by more than 50%.

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Gully erosion; susceptibility; soil erodibility; GIS; catchment scale; avoided degradation

Introduction

Land degradation through soil erosion is a global issue threatening our long-term wellbeing through a reduction in ecosystem services (FAO, 2019). Gully erosion is one of the most severe types of erosion (Castillo & Gómez, 2016). Once initiated, gullies remove large volumes of soil, damage built and ecological infrastructure, enhance hillslope channel connectivity, drain soils and wetlands and has various negative offsite effects where the sediment is deposited (Addis et al., 2015; Boardman, 2013; Boardman & Foster, 2008; Croke et al., 2005; Khalili et al., 2013; Le Roux, 2018; Wang et al., 2016; Wasson, 1994). Land degradation is becoming more prominent with international agencies, such as the United Nations Convention to Combat Desertification (UNCCD). The UNCCD recently began promoting a response hierarchy that invests most resources to avoid future degradation, followed by a reduction in current degradation and lastly to restore degraded land (Cowie et al., 2018). This response hierarchy supports global sustainable development

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targets such as the SDG's, Paris Climate agreement and Aichi Targets. Since land management and restoration resources are limited, strategic information on sensitive and erosion susceptible areas are needed to avoid future degradation.

The mapping of areas susceptible to gully formation is not a new concept, but most case studies are based in the northern hemisphere and use multiple regression models relying on various topographic, soil type, land cover and land use characteristics (Conforti et al., 2011; Desmet et al., 1999; Kheir et al., 2007; Lucà et al., 2011; Tien Bui et al., 2019). Multiple regression models, however, tend to suffer from a limited sample design, subjectivity during factor rating, and a large percentage of variability is usually unexplained (Kheir et al., 2007). To map areas susceptible to gully formation at the large catchment scale, this study postulated that a zonal approach (overlay analysis of gully factor layers in a GIS) is more appropriate than correlation analyses generally utilized in erosion studies. Our approach has potential in the Mzimvubu River Catchment, the only large river network in South Africa without a large reservoir. Water resource development is planned in the Tsitsa tributary with highly erodible soils (Bannatyne et al., 2017). The Tsitsa River Catchment in which the Ntabelanga and Lalini Reservoirs will be built, has approximately 9 000 gullies, affecting an area of approximately 7 000 ha (Le Roux & Sumner, 2012). Based on sediment yield results and digital elevation data in a GIS, Le Roux (2018) estimated that the life expectancy of the Ntabelanga Reservoir could be less than 50 years without effective siltation and catchment management measures. Due to limited resources, it will not be feasible to rehabilitate these gullies with large and costly structures at a catchment scale. Not only are large structures costly, structures in the catchment will silt up rapidly, rendering them inefficient sediment traps with little benefit to local land users. It is postulated that structures in the catchment will cause further erosion due to the dispersive nature of the soils (Van Zijl et al., 2014). Structures in dispersive soils enhance subsurface accumulation of water and cause further erosion around structure walls (Russell et al., 2009).

It is important to prevent further gully erosion by protecting susceptible areas that are currently not eroded. Susceptible areas must be protected before erosion is extrinsically triggered or accelerated by land use and human-induced reduction of the vegetation cover (overgrazing and cultivation). Failure to do so will cause existing gullies to spread and new gullies will develop, threatening the planned reservoir lifespans. In this context, the aim of the study is to map areas that are susceptible to gully development in the Tsitsa River Catchment, as well as to estimate the sediment yield potential from the susceptible areas if gully development occurs. The aim will be achieved by building on work done by Le Roux and Sumner (2012) on factors controlling gully development in the Tsitsa River Catchment by mapping gully-free areas that have the same DEM-derived topographical variables and soil associations as gullied areas, followed by scenario analysis of the sediment yield if gully development occurs on these (currently gully-free) susceptible areas.

Site description

The Tsitsa River Catchment is located in the Eastern Cape Province of South Africa and is characterized by a steep landscape and erodible soils. It has a drainage area of 4 924 km^2 and lies between 30° 46′ 58″ and 31° 28′ 55″ south and 27° 55′ 56″ and 29° 13′ 47″ east in the Eastern Cape Province of South Africa (see Figure 1). The Tsitsa River drains the Drakensberg Escarpment (approximately 2600 m a.s.l.) and flows east into the

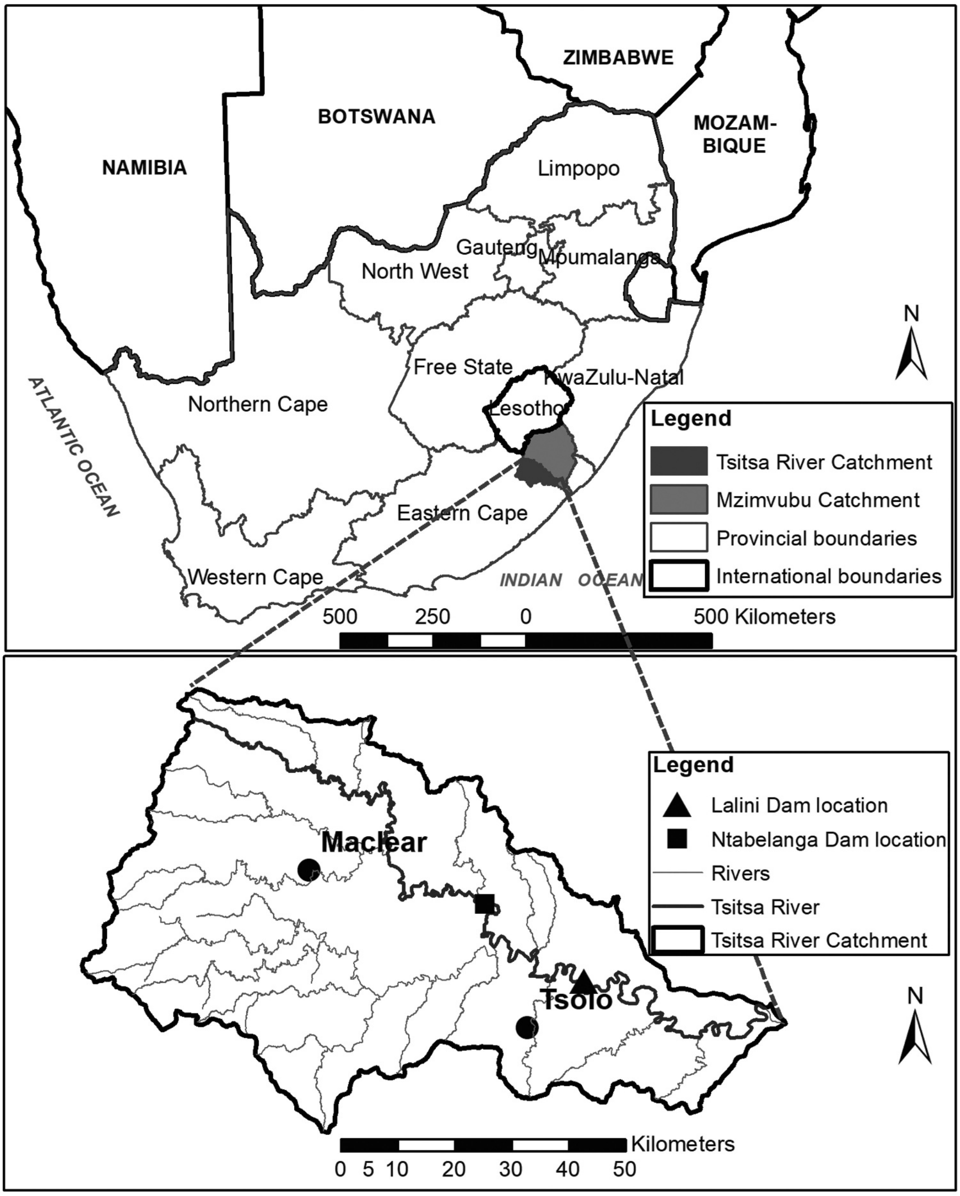

Figure 1. Location map of the Tsitsa River Catchment in the Eastern Cape Province, South Africa.

Mzimvubu River (at approximately 200 m a.s.l.) after a flow length of approximately 200 km. The climate is sub-humid with mean annual rainfall ranging from 625 mm in the lower plains to 1 327 mm in the mountains (ARC Climatology Staff, 2012). The catchment falls mainly within the Grassland biome, with narrow bands of Bushveld along the river networks in the lower part of the catchment, as well as pockets of Afromontane Forest in fire-protected ravines (Mucina & Rutherford, 2006). The main land use is extensive grazing with areas of pine and gum plantations and maize cultivation in the upper catchment (around Maclear, Figure 1). The geology consists of a succession of

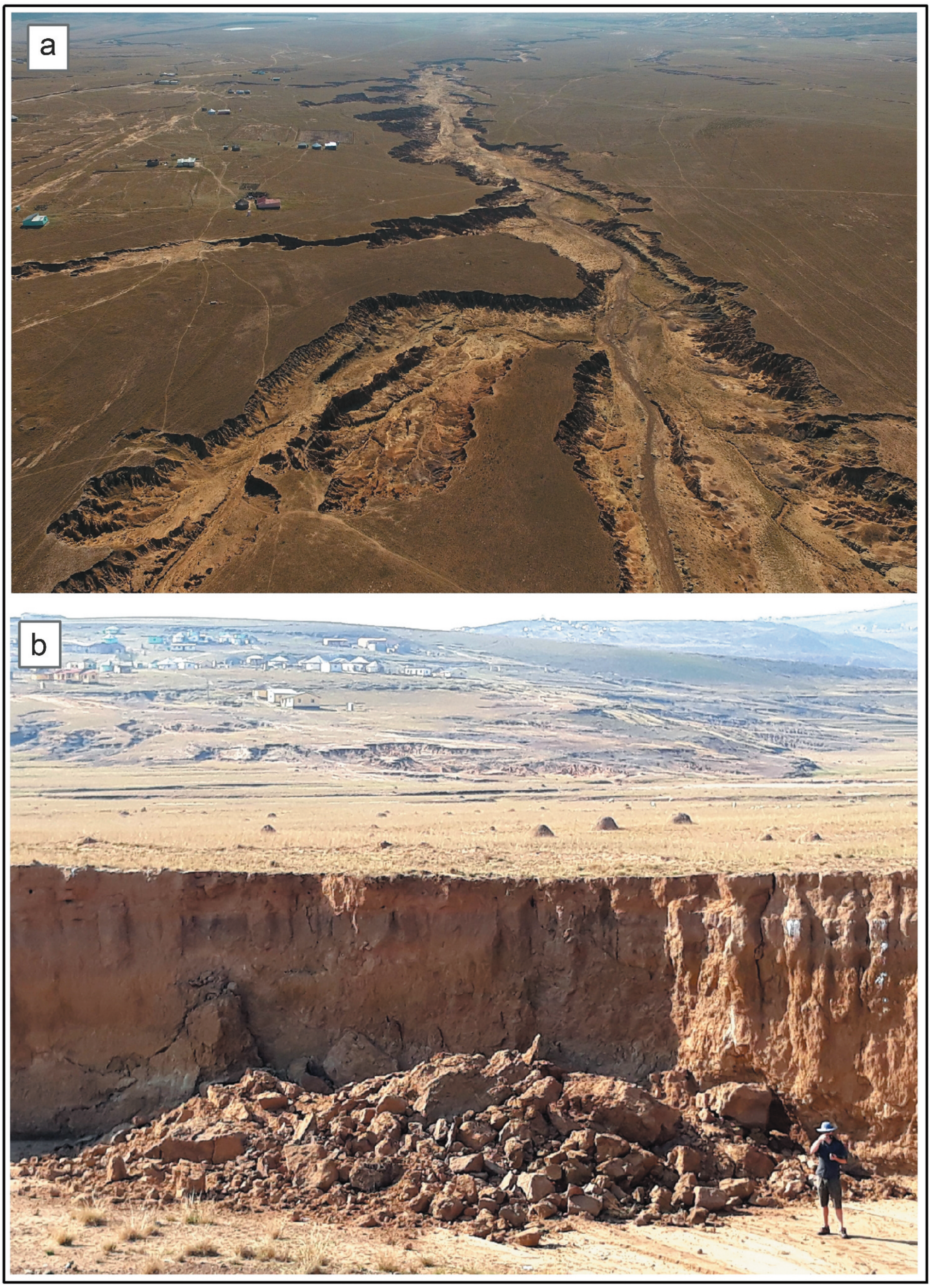

Figure 2. Photos of (a) large continuous gully in the Tsitsa River Catchment near Tsolo (photo by David Hedding), (b) experiencing gully wall collapse due to undercutting of a duplex and dispersible soil.

sedimentary layers of the Triassic age, including Adelaide mudrock succeeded by mudstones of the Tarkastad, Molteno and Elliot Formations (Council for Geoscience, 2007). Mudstones are overlain by sandstone and siltstone of the Clarens Formation and capped by

Drakensberg basaltic lava of the Jurassic age. Karoo dolerite sills and dykes are present in the sedimentary formations, leading to more resistant base-level controls.

Although soils in the catchment vary significantly, those from the mudstone parent material in the central part of the catchment are associated with duplex soils that are highly erodible with widespread gully erosion. Duplex soils are classified as Planosols by the FAO International Soil Classification System; having a marked increase in clay content from the topsoil to subsoil and having an abrupt transition with respect to texture, structure and consistency (Land Type Survey Staff, 2012). Soil forms that often have duplex properties include Katspruit, Kroonstad, Sterkspruit, Estcourt, and to a lesser extent Valsrivier, Swartland and Bonheim (Fey et al., 2010). These soils limit intrinsic permeability since water does not move readily into the subsurface matrix, which often leads to increased subsurface flow (Van Tol et al., 2013) causing tunnel and subsequent gully erosion (Beckedahl, 1996; Beckedahl & De Villiers, 2000). Intrinsic permeability can be limited by various different subsoils such as gley and/or gleyic horizon, as well as subsoils that show signs of wetness. In the Tsitsa River Catchment, however, duplex soils often have prismacutanic subsoils that can easily be identified by the large structured prisms that are exposed on gully sidewalls or where the topsoil is completely eroded. Importantly, the subsurface matrix of duplex soils is often dispersive as a result of high sodium absorption (Van Zijl et al., 2014).

Methodology

The first step was to map gully-free areas that are susceptible to gully development in the Tsitsa River Catchment by means of overlay analysis of gully factor maps of Le Roux and Sumner (2012) including DEM-derived topographical variables, soil associations and land cover. Second was to estimate the sediment yield potential from the susceptible areas if gully development occurs in future.

Map gully-free areas susceptible to gully development

Several factors contribute to gully development including topographical variables (e.g. Desmet et al., 1999; Kakembo et al., 2009; Kheir et al., 2007), parent material-soils interactions (e.g. Laker, 2004; Valentin et al., 2005) and cover management (e.g. Boardman & Foster, 2008; Gutierrez et al., 2009). The study of Le Roux and Sumner (2012) utilized a zonal approach in a GIS in order to determine the gully factors that are dominant in the Tsitsa River Catchment. According to Le Roux and Sumner (2012), areas prone to gully development in the catchment are gentle footslopes in zones of saturation along drainage paths with a large contributing area, erodible duplex soils derived from mudstones, and poor vegetation cover due to overgrazing. Therefore, in this study, areas susceptible to gully development were identified by mapping gully-free areas that have the same characteristics as gullied areas in the Tsitsa River Catchment. These include DEM-derived topographical variables (contributing area and terrain units), soil associations and land cover. The gully factor maps are illustrated in Figure 3, whereas descriptions of the gully factor maps, methods of derivation and data sources are summarized in Table 1. Each gully factor layer was categorized into two classes that, according to observations, uniquely influence gully development.

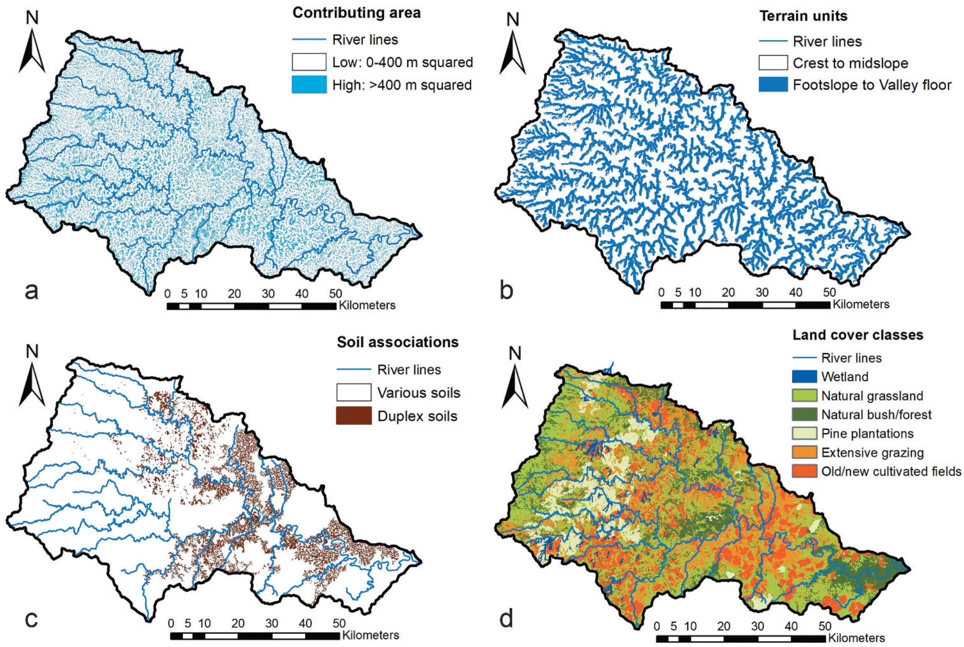

Figure 3. Spatial datasets that were created/used to map gully susceptible areas of the Tsitsa River Catchment including: (a) upslope contributing area, (b) terrain morphological units, (c) duplex soil associations and (d) land cover map.

Table 1. Description of the gully factor maps and methods of derivation.

Factor layer	Description and method of derivation; *class #: range (area- km^2)*	
Upslope contributing areas	Upslope area per unit width of contour (in m^2) extracted from 30 m resolution SRTM-derived DEM using the D-Inf multiple flow algorithm in TauDEM© (see Figure 4(a));	
	Class 1: Low 0–400 (3923)	*Class 2: High >400 (964)*
Terrain units	Five terrain morphological areas mapped/modelled from a 90 m SRTM DEM (Rodriguez et al., 2005) interpolated to 30 m, using typical topographical algorithms of Schmidt et al. (2003) in combination with manual vectorization (Van Den Berg & Weepener, 2009) (see Figure 4(b));	
	Class 1: Crest to midslope (4697)	*Class 2: Footslope to valley floor (265)*
Soil associations	Duplex soil associations are soil polygons with unique soil attributes assigned from field observations (n = 318) and remotely sensed data (soil colour) of the Tsitsa River Catchment (Van Den Berg & Weepener, 2009) (see Figure 4(c)) – Land Types are polygons that display a marked degree of uniformity in terms of macroclimate, terrain form, and soil pattern at a 1:250 000 scale;	
	Class 1: Relatively stable soils (3256)	*Class 2: Duplex soil associations (1280)*
Land cover	A land cover map with 5 (initially 12) classes were created by means of unsupervised classification on SPOT 5 imagery acquired in 2011 (see Figure 4(d));	
	Class1: *Natural grassland,* *Natural bushveld/forest,* *Pine plantations* *(2841)*	*Class 2:* *Old (abandoned) and new cultivated fields,* *Extensive (subsistence) grazing* *(2096)*

First, upslope contributing areas higher than 400 m^2 have high flow accumulation (number of upslope cells that flow into each cell) and was therefore used in this study to

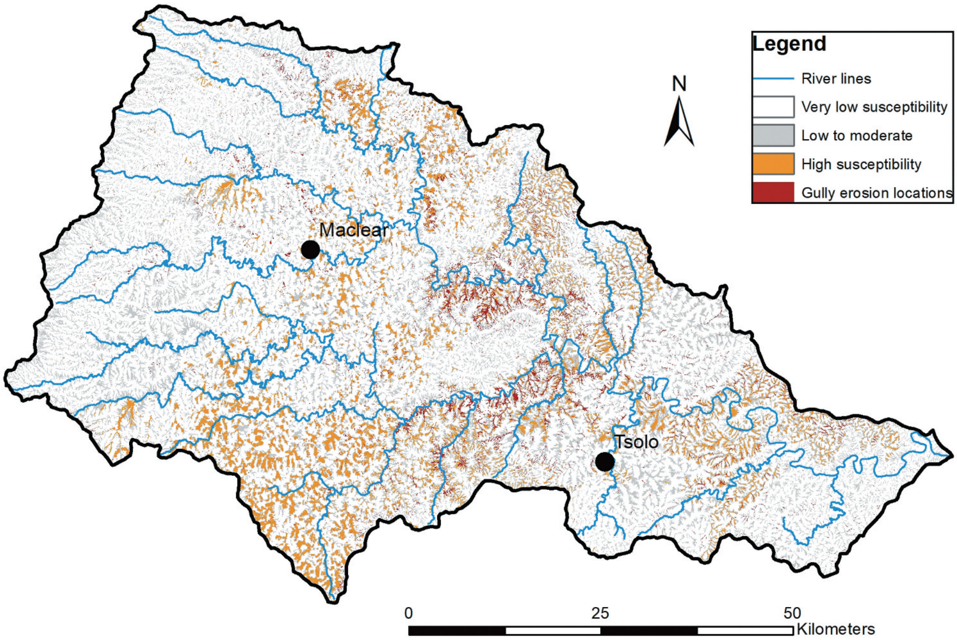

Figure 4. Areas susceptible to gully erosion in the Tsitsa River Catchment.

identify drainage areas and flow paths that could support gully erosion. Second, terrain units 4 and 5, namely footslopes and valley floors were used in this study to identify preferred pathways of flow where overland flow is concentrated. Third, duplex soil associations were used to account for highly erodible duplex soils. These soils promote tunnel erosion, which rapidly develops into a gully after roof collapse (Beckedahl & De Villiers, 2000). Fourth, land cover was used to identify cultivated fields, as well as overgrazed grasslands where vegetation cover is poor and gully development is favoured. According to Le Roux and Sumner (2012), grassland areas that are extensively grazed in the catchment are affected by gully erosion due to overgrazing and trampling along cattle tracks.

Finally, a gully erosion susceptibility map was created by means of overlay analysis (of the gully factor layers) in a GIS. Spatial overlay resulted in areas classified as class 1 being indicative of a low susceptibility, whereas areas in class 2 are indicative of a high susceptibility. More specifically, areas were classified as having a high susceptibility if all the overlaying gully factor layer cells had a value of 2, whereas areas were classified as having a moderate susceptibility if one or more of the four overlaying cells had a value of 1. For validation, the gully susceptibility map was compared to data collected during field observations.

Validation of duplex soil map

The gully susceptibility map (see Results and discussion) was validated by means of an error matrix between mapped and observed susceptible areas (see Table 1). Field observations (n = 200) of Le Roux and Sumner (2012) were separated into points where susceptible areas were observed, and points where more stable areas were observed. Emphasis was put on the presence or absence of duplex soils, since soil is the overriding factor in the catchment (Le Roux & Sumner, 2012). Points where duplex soils were observed were spatially correlated with duplex soils on the map, whereas the observation of other soils were correlated with other, non-duplex soils, on the map. In this context, the error matrix shown in Table 2 indicates that the overall accuracy of the susceptibility map is 75%.

Estimation of sediment yield potential

The last step was to estimate how much sediment will be yielded from susceptible areas if gully development occurs. Potential sediment yield contributions from susceptible areas were estimated by calculating their potential volumes (using surface area, soil depth and average bulk density). Surface areas were calculated in a GIS (see Results below). Volumes were calculated by multiplying surface area with soil depth. Soil depths were allocated by overlaying the susceptible areas with soil depth classes given in the Land Type Database of SA (Land Type Survey Staff, 2012), in conjunction with gully depth information of Le Roux (2018). Gully depth ranged between 0.4 and 2.0 m with an average of 0.8 m. Soil depth was used since most gullies in this region deepen only until they reach bedrock. Next, the surface areas (in m^2) and soil depth information (in m) were used to determine potential volumes (in m^3), by using an average bulk density of 1.5 $Mg.m^{-3}$ for duplex soils. Bulk density measurements ($n = 8$) were limited to duplex soils, since most of the gullies develop on these soils (Le Roux & Sumner, 2012).

Results and discussion

The outcomes of this study include a map of gully-free areas that are susceptible to gully development in the Tsitsa River Catchment, as well as the sediment yield potential from susceptible areas, if gully development occurs.

Gully erosion susceptibility map

Figure 4 illustrates the gully erosion susceptibility map of the Tsitsa River Catchment. Three classes of susceptibility are shown from very low (72% or 356 184 ha), low to moderate (21% or 103 786 ha) and highly susceptible (7% or 32 531 ha). Surface areas of susceptible areas range from 0.025 ha to 5 33 ha with an average of approximately 2 ha. More than 7% of the catchment is highly susceptible to further gully development. These

Table 2. Error matrix between predicted and observed duplex soil associations.

		Observed		
		Moderate to high (*n*)	Low (*n*)	Row Total
Predicted	Moderate to high (*n*)	19	9	28
	Low (*n*)	42	130	172
	Column Total	61	139	200
	Omission	0,31	0,94	
	Commission	0,68	0,76	
	Total accuracy	0,75		

areas occur on gentle footslopes in zones of saturation along drainage paths with a large contributing area, erodible duplex soils derived from mudstones and poor vegetation cover due to cultivation or grazing pressure. Areas with a low to moderate susceptibility (21% of catchment) also occur on gentle footslopes in zones of saturation along drainage paths with a large contributing area, but generally exclude erodible duplex soils. Areas with a very low susceptibility occur in areas with small contributing areas, generally stable soils and where vegetation cover is relatively good due to cover management or natural conditions. Conforti et al. (2011) also attained similar results in the Turbolo Catchment in Italy, except that susceptible areas occurred on steep slopes (>20°) instead of gentle slopes. Similar to the gentle slopes in our study, however, the steep slopes in the study of Conforti et al. (2011) had large contributing areas (long slope lengths, promoting flow accumulation and high runoff velocities).

Prediction of gully development at the catchment scale, however, remains a major challenge. A limitation of the approach followed in this study is the question why susceptible areas are still gully-free? Limited available data and field observations in the Tsitsa River Catchment suggest that susceptible areas are still protected by some degree of vegetation cover, ranging from poor (cultivated and overgrazed grasslands) to good cover (wetlands, pine plantations as well as natural grassland and forest). Areas with poor vegetation cover are particularly susceptible to gully development. Gullies will probably develop in these susceptible areas once the vegetation cover is further reduced, completely removed or downstream base-levels are lowered. In the extensive reviews on gully erosion by Castillo and Gómez (2016) and Poesen (2018), it is also stated that once vegetation cover is removed, soil is rapidly removed due to concentrated runoff along hydrological pathways where hydrological connectivity is enhanced. Therefore, susceptible areas must be protected before erosion is extrinsically triggered or accelerated by removal of the vegetation cover.

Figure 5 illustrates areas that are intrinsically susceptible to gully erosion, yet are vegetated and gully-free, around the future Ntabelanga Dam. Most of the susceptible areas (shown in orange) are relatively small and are scattered between eroded areas (shown in red). These areas are relative small since they represent zones of saturation along drainage paths. Therefore, it was decided to group susceptible areas with high densities into cluster polygons (black outline) to assist strategies targeted at area-specific management (e.g. fencing to avoid overgrazing). Table 3 shows that there are 14 susceptible cluster polygons around the Ntabelanga Dam. Cluster sizes range between 88 and 1 268 ha, totalling 4 700 ha, whereas their perimeters range between 3 728 and 15 023 m, totalling 100 925 m. Susceptible clusters must be protected before erosion is extrinsically triggered or accelerated by land use. Failure to do so will cause existing gullies to spread and new gullies will develop, as well as lead to increased sedimentation of the future dams.

Sediment yield potential

If not protected, susceptible areas could contribute a maximum of 445 million tons or 297 million m^3 of additional sediment to the river network (see Table 4). An estimated 209 and 88 million m^3 of sediment could be deposited into the future Ntabelanga and

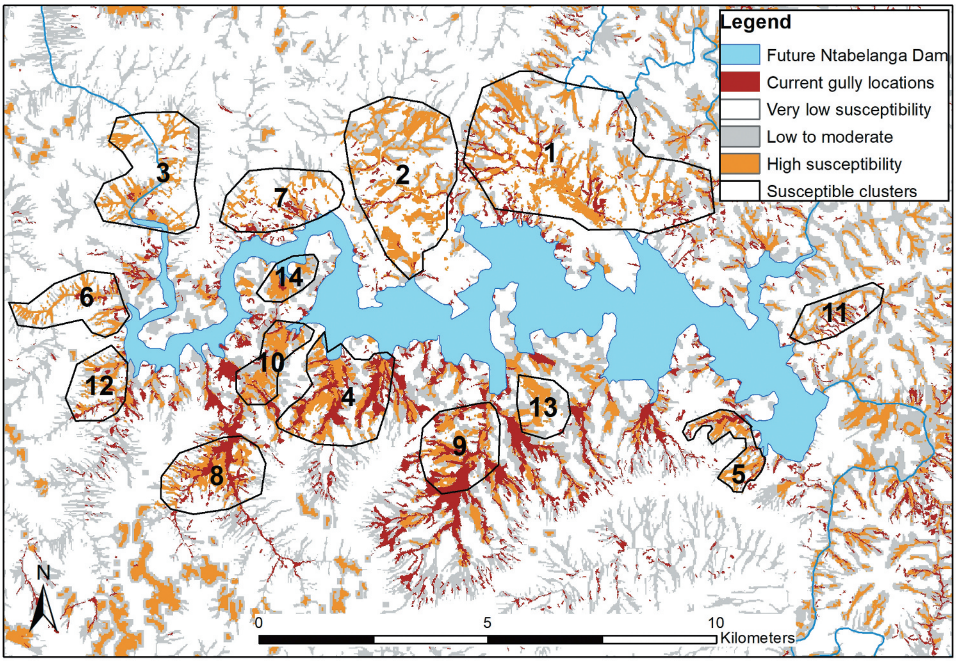

Figure 5. Areas susceptible to gully erosion near the future Ntabelanga Dam.

Table 3. Sizes and perimeters of 14 susceptible clusters around the future Ntabelanga Dam.

Cluster #	Area (m^2)	Perimeter (m)
1	12,680,021	15,023
2	6,854,239	10,390
3	4,641,046	9128
4	3,940,965	8897
5	1,251,675	7640
6	2,289,527	6827
7	2,919,824	6781
8	2,943,240	6429
9	2,760,688	6126
10	1,482,656	5687
11	1,445,344	5200
12	1,640,430	4806
13	1,281,153	4263
14	883,927	3728
Total	47,014,735	100,925

Lalini Dams, respectively. This worst-case scenario will result in an estimated 51% and 59% reduction of their respective volumes.

Not all sediment eroded from susceptible areas will make it into the dams; some will be stored along pathways (hillslopes and channels) or sinks (small dams and wetlands) (Fryirs, 2013; De Vente et al., 2007). Furthermore, estimations do not account for the water available to transport sediment (Verstraeten et al., 2007) or sediment residence time (Wilkinson et al., 2006). It is also recognized that some areas will not erode (as

Table 4. Volumes of the proposed dams and the volume of soil of areas susceptible to gully erosion.

	Dam volume (million m^3)	Potential loss (million m^3)	% of dam volume
Ntabelanga Dam	490	209	51
Lalini Dam	150	88	59

modelled). The rate of the sediment delivery depends on ongoing land use pressures and associated landscape connectivity (Van der Waal & Rowntree, 2017) and changes to climate. Predictions of more frequent droughts and more intense rainfall are likely to promote gully formation of these sensitive areas. This implores a new approach to land management to avoid the degradation of these identified areas. Literature promotes good vegetation cover of the sensitive areas and their catchments to reduce free water and subsurface erosion and subsequent gully formation (Van Tol et al., 2014; Van Zijl et al., 2014). This can only be achieved by improved grazing management to prevent overgrazing. Soil erosion prevention will not only reduce the sediment yield and increase dam life expectancy, but will also benefit the local communities by preventing further land degradation and supporting the delivery of ecosystem services.

Conclusions and recommendations

Increasing water demands require water resource development in the Tsitsa River Catchment of SA. However, previous studies indicate that the catchment consists of thousands of gullies, potentially feeding massive amounts of sediment into the river network. Le Roux (2018) estimated that the life expectancy of the Ntabelanga Reservoir could be less than 50 years without effective siltation and catchment management measures. Due to limited resources, it will not be feasible to rehabilitate these gullies with large and costly structures at a catchment scale. Since resources are limited, strategic information on sensitive and erosion susceptible areas are needed to avoid future gully development. Building on work done by Le Roux and Sumner (2012), this study successfully modelled areas that have a high susceptibility to gully erosion. More than 7% of the catchment is highly susceptible to further gully development. If not protected, it is estimated that a total of 297 million m^3 of additional sediment could be deposited into the future Ntabelanga and Lalini Dams, resulting in a 51% and 59% reduction of their volumes, respectively.

Appropriate strategies to avoid degradation need to be designed for these susceptible areas. Strategies need to protect and improve the current vegetation cover, as well as protect existing sediment sinks (wetlands and small dams). This is in line with the thinking that is promoted around Land Degradation Neutrality (Cowie et al., 2018). These strategies will only be successful if local stakeholders are involved, e.g. following a Community-Centred Participatory Research and Development Approach (see Biggs et al., 2019; Fabricius et al., 2016; Smith, 2006). Conventional rehabilitation structures should be avoided in dispersive soils, since structures usually enhance subsurface accumulation of water and cause further erosion around the structure (worsening the problem). Vegetation with deep root systems, as well as flexible above-ground matter, are more appropriate as flow barriers in dispersive soils. However, aforementioned options are not effective in large active gullies that feed massive amounts of water and sediment downslope during rainfall events. The rehabilitation of large active gullies in dispersive soils remains a major challenge (Cowie et al., 2018).

The mapping of susceptible areas can be applied elsewhere since this study used general predisposing gully factors similar to Conforti et al. (2011), including topographical variables, parent material-soil associations and land use-cover interactions (Castillo & Gómez, 2016 & Poesen, 2018). Further refinement will be possible given additional research. It is recommended that the soil factor layer (duplex soil associations) is improved by means of digital soil modelling techniques (Van Zijl, 2019; Wahren et al., 2016). The degree of soil stability against dispersion is currently excluded in soil erosion prevention modelling due to the lack of spatial information at a regional scale. Correlation between gully erosion susceptibility and clay dispersibility requires further investigation. Furthermore, topographical data (upslope contributing areas) can be improved using unmanned aerial vehicle (UAV) technologies (Cook, 2017). Lastly, susceptible areas can be ranked from most to least important according to landscape position, gully-river connectivity, growth potential, and sediment delivery potential.

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