Identifying Gullies and determining their relationships with environmental factors using GIS in the Zhulube meso-catchment

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Abstract

The aims of this study were to determine the accuracy of using GIS and remote sensing techniques in gully identification and to test for significant relationships between gully characteristics and environmental factors. GIS, remote sensing and field surveys techniques were used to identify gullies within the Zhulube Meso-catchment of Zimbabwe. The data collection involved analysis of soil core samples and measurement of gully characteristics. GIS and remote sensing techniques were used to determine the sedimentation and stream power indices with the study area. The statistical analysis focused on the correlation between gully, soil and vegetation characteristics as a means of identifying areas susceptible to gully erosion. The results from this study illustrate that 36% of major gullies are discernible using Landsat TM imagery, 56% using Spot panchromatic imagery and 77% using Orthophotos. A significant relationship between gully depth and bulk density was evident at $r^2 = 0.87$ ($p<0.05$) with the soil clay content and its related minerals showing a significant relationship with gully development, showing a decline in erosion with an increase in clay proportions. Other significant relationships were evident between gully depths, stream erosive power and slope gradient at $r^2 = 0.62$ ($p<0.05$), while streams sediment loadings showed a non-significant effect on the gully depth with at $r^2 = 0.02$ ($p>0.05$). It therefore concluded that GIS and remote sensing techniques are applicable in gully identification, with variable accuracy levels depending on the spatial, spectral and temporal resolution of the imagery. It was also evident that the inherent susceptibility of soils to detachment and transport by various erosive agents is a function of topography, vegetation and soil properties (physical and chemical). In addition, Soil erodibility assessment using simulated stream erosive forces and sediment loadings revealed that sediment yield and erosive power of the streams in the study area increased with increasing slope gradient depending on the clay content of the soils.

Index Terms—Erosion, Gully, GIS, Environment, Satellite, Water
1. Introduction

Soil erosion is approximated to have occurred on 1.1 billion hectares of land globally (reference?). In the Zhulube Meso-catchment of Zimbabwe soil erosion and sedimentation are key limitations to achieving sustainable utilisation of land and water resources. The most prominent type of erosion in Zhulube is gully erosion which is geographically a widespread problem (Cooke & Reeves, 1976; Lal, 1992) and the worst stage of soil erosion. Anderson et al., (1993) state that in Zimbabwe alone an estimated 1 million hectares of land are affected by severe gully erosion with the figures rising to 29 million hectares of land in Africa at continental level. SARCCUS (1981) states that gully erosion is a permanent form of erosion which is difficult and expensive to control resulting in a depreciation of land value due to a lowered water table and depleted water reserves. Dregne (1990), in his survey of Zimbabwe highlights more than half of Zimbabwe’s communal land as from suffering irreparable gully erosion damage, mainly because of Zimbabwe’s land tenure policies [elaborate, explain how land tenure is causing soil erosion, this is important]. GIS and remote sensing techniques are most suitable for gully identification and the assessment of an area’s vulnerability to erosion. These techniques thus present an appropriate method of quantifying and combating the gully erosion which is a challenge to the concept of Integrated water resources management (Morgan, 1993).

2. Description of the study area.

The study area covered the Zhulube Meso-catchment, which falls within the Mzingwane catchment, in the Limpopo river basin with coordinates of 20° 47′ south and 29° 22′ east. The basin is located within four Southern African countries namely, Zimbabwe, Botswana, South Africa and Mozambique. The Mzingwane catchment is part of the seven catchments in Zimbabwe. Four sub-catchments covering 20% of the Matabeleland South and Midlands Provinces were created from the main catchment.

The study focused on ward 1 of Insiza district, which is located in the Upper Mzingwane sub-catchment. The Insiza district is one of the six districts in Matabeleland North province. There are 18 wards in Insiza district, 11 of which fall within Mzingwane catchment. The research work was conducted in the Zhulube village as shown in Figure 1. [figure 1 needs redoing: it shows Thobekile’s sites fine (I can see the lines pointing at them) but not yours. The main figure should show the area marked as project area in figures 2 and 3. The inset appers to suggest the main figure shows the whole of Insiza district; which it does not.].
3. Methods

The data acquisition process consisted of stereoscopic interpretation of multi-temporal satellite images and aerial photographs. Sequences of satellite images provided a time-series (Whitlow, 1986) from which gully changes were mapped while aerial photographs increased the spatial resolution. For the purposes of gully identification using remotely sensed imagery, the smallest scale images were selected from sequential aerial photographs and satellite images of various scales, which were used as the threshold for data extraction (Watson, 1990). Smaller scales lose detail and larger scales involve a sacrifice in terms of the synoptic view (Gelmroth, 1981 and Rossouw, 1997).

3.1 Selection of sampling transects

GIS sampling tools (which ones) were used to select nine transects incorporating the major gullies, discernible range in plant species composition and physiognomy. All the transects generated from this option are random both in the placement of the starting point and direction although these can be random placed within a specified direction by setting lower and upper azimuth limits for transects.

3.2 Soil sampling and erosion mapping

The soils in the Zhulube Meso-catchment vary from clayey loams in the north to sandy soils in the south with a rugged high ground. Thus the area was subdivided into homogeneous sections, from which nine sampling sites were located for soil samples. Between 10 and 20 sub-samples where collected and sub-sampled from each transect. The Sub-samples were small enough that the composite sample was of a size that can be completely processed for analysis. Factors like vegetation cover, type and ground hardness determined the sampling depth. An excavated profile pit at the Zhulube dam site, collapsed gully walls and supplement auger borings were used to demonstrate lateral and vertical changes in the soil properties, and for the full description of type soils and for the taking of soil samples for chemical and physical analysis. Soils were mapped at a scale of 1:25,000 by, which the pattern of soils in individual fields could be identified. Figure 2 shows the sampling sites within the study area as selected using GIS and ground truthing methods.
3.3 Botanical methods

Discrimination between vegetation classes was based predominantly on the pattern and presence of plant communities. Twenty points were systematically spaced over each transect and the presence of bare or occurrence of an herbaceous plant tuft was recorded. Stunting is a conspicuous feature of the woody species on sodic soils and transects incorporated observed range in height of the dominant woody species. Within each transect all individuals of a species were grouped into 1 m and greater than 2 m height classes. Three broad vegetation classes were chosen to facilitate consistent and easy interpretation from the orthophotos and satellite images. Field verification of the mapped vegetation classes involved surveying transects through GPS data collection in the study area and the spatial extent of the area under study restrict the use of Landsat NDVI.s. For each height class the bush density, canopy diameter, mean cross sectional area of the stem, that is the breast height of the stem was calculated. Tree height classes lower than two meters were classified as shrubs and the cross sectional area was recorded from the lowest browseable material.

3.4 Quality control, data analysis and management.

The process of data cleaning and quality control was achieved by making sure the data were in the same formats. The data-handling component of the study involved capturing the mapped vegetation, gully and erosion data into the ESRI ArcView 3.2a, ArcGIS 9.1 and Microimages TNT MIPS softwares.

3.5 Statistical analyses

Statistical analysis of the research data included correlation determination and regression analysis for vegetation, slope gradient, gully and soil properties. Nineteen variables were collected per site: seventeen soil variables from the collected soil samples, percentage herbaceous cover and depth of sampling. The Spearman rank order correlation coefficient was computed by ranking all values of each variable, then computing the Pearson Product Moment Correlation coefficient, $r$, and ranking the parameters.

4. Results and discussion

4.1 Remote sensing of gully development in the Zhulube meso-catchment.
Figure 3 (a, b and c) shows gullies identified from three images, Landsat TM, SPOT and an Orthophoto. Figure 3(a), illustrates the gullies that were identified from the Landsat TM image. The smallest gully width was six meters. Figure 3(b) illustrates the gullies that were identified from the SPOT Panchromatic image. It can be observed that the SPOT interpretation achieved 56% accuracy (explain how you get this figure), with a smallest gully width of six meters. Figure 3(c), illustrates the gullies that were identified from the Orthophoto. Figure 3(c) also shows a gully identification accuracy of 77% (explain how you get this figure), more information on the occurrence of the gullies becomes evident mainly due to its fine spatial resolution of two and a half meters, with much is less than the average gully width of 17m within the study area. When carrying out the groundtruthing exercise the gullies identified by the satellite imagery are shown as in Figure 4.

4.2 Relationships between gully erosion and vegetation characteristics.

Statistical analysis using the Spearman Correlation Matrix between the gully characteristics (gully depth, gully length, gully area, gully width), with soil chemical characteristics (Bulk density (g/m3), Clay (%), Soil pH, Electrical Conductivity (µS), Particle density, Sand (%), Silt was done. There was a significant relationship \( p < 0.05 \) between the gully depth and most of the other components (Bulk density, clay, calcium, magnesium, iron, manganese and slope). Other interesting observations are the significant correlations between gully width and a (which?) components. Table 1 shows the Spearman Correlation Matrix.

4.3 Relationships between gully depth and other properties.

The Pearson correlation analysis showed that the soil chemical characteristic, bulk density had a highly significantly \( p < 0.05 \) effect on gully depth as shown in Figure 5. The relationship shows linear increase in gully depth as the bulk density of a soil increases due to the vertical removal of soil mass by flowing water. The results also show that site 3 had a higher tree density than other sites; a look at the collected vegetation data shows that even though there are adequate woody species around the gully with a tree density of 600 plants per hectare and a tree index of 3.6 is not enough to hold the soil from further erosion.
Figure 6 shows illustrates that a slight increase in the proportion of clay within the soils causing significant \( p \leq 0.05 \) declines in gully depth across the sampling sites. The clay content showed great inter-sites variation ranging from 2% to 8% between the sampling sites, indicating that the study area was dominated by sandy soils, which are weak and prone to erosion. The trend depicted by the four minerals that had a significant effect on the gully depth indicate a similar pattern, with all four chemical components presenting a negative significant correlation coefficient with the exception of sodium. This can be explained by the fact that magnesium, iron, manganese and sodium are major constituent of clay minerals, which include the layer silicates, the metal oxides and crystalline chain silicate minerals like kaolinite, chlorite, illite and montimorilonite.

[NO: figure 7 shows the DEM, thus the absolute topography, not the slope.] The possible severity of erosion can be estimated roughly by considering the degree of the slope and other related environmental factors. The graph (which graph: put one like figure 6 instead of your map for figure 7) illustrates a positive significant relationship with a correlation coefficient \( R^2 = 0.62 \). This can be interpreted as a resultant increase in gully depth as the slope gets steeper, as the erosive power of a flowing water body increases linearly with an increase in slope.

Stream power varied within the study area, (how, I cannot read figure 8 as I am colour blind: say where it is higher, lower) (Figure 8). There is a high positive correlation of stream power with gully depth \( (R^2 = ?) \), meaning that if the stream flow increases the gullies increase in their depths.

The sediment transport index (figure 9) illustrates the potential sources and transportation of sediments. The dark colours indicate potential sources of sediments while the lighter toned colours show areas of potential sediment deposit within the catchment. Low sediment loads are indicated within the greater parts of the Meso-catchment but it is evident that the final sampling transects fall in close proximity to areas of high sediment transport indices, meaning around these areas the erosivity of the streams is high thus resulting in relatively deep gullies. The is a significant \( p \leq 0.05 \) increase in sediment transport values as you move closer to site 10, which show very high sediment loading values and these tally with the field collected data as these were some of the deepest and broadest gullies in the study area. (no graph here)
Regression of the gully depth and the sediment transport index show a weak correlation between the depth of the gullies and the amount of sediment that is transported.

5. Conclusions and recommendations

The general conclusion that can be drawn from this study is that significant relationships exist between vegetation types, soil characteristics (physical and chemical), and topography and gully development. The use of high resolution imagery and GIS techniques can aid in gully identification with high and desirable levels of accuracy. The inherent susceptibility of soils to detachment and transport by various erosive agents was a function of the physical and chemical properties of soil. The interactive effects of the topographic, vegetation cover and rainfall factors in turn influence these factors. Sampling sites at lower slope gradients had reduced stream power and sediment loads than those located at areas with higher slope gradients like site. Soil erodibility assessment using simulated erosive force (stream power index) and sediment loadings (stream power index) in the study site revealed that sediment yield or the erosive power of the streams in the study area increased with increasing slope gradient depending on the clay content of the soils. The higher the clay content the lower the erodibility factor as shown by the relationship between clay content and the gully depths. (so can you conclude that gullies have formed in the areas with least clay and steepest slopes?)

References


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