Erosion Response Units (ERU): A regional erosion concept for sustainable Integrated Catchment Management and its application in a semi arid catchment in Swaziland, Southern Africa

W. A. Flügel[a], M. Märker[b] and G. Rodolfi[b]

[a]*Institut für Geographie, Friedrich-Schiller-Universität Jena, Löbdergraben 32, 07743 Jena, Germany* (c5wafl@geogr.uni-jena.de)

[b]Dipartimento Scienze del Suolo e Nutrizione della Pianta, Università di Firenze, Piazzale delle Cascine 15, I-50144 Firenze, Italy;

Abstract: With respect to water quality problems, the understanding of the dynamics of integrated soil erosion processes in river basins is of crucial importance. This study is presenting the application of the concept of Erosion Response Units (ERU) in the upper Mbuluzi-river catchment (Kingdom of Swaziland). It was carried out within the framework of an interdisciplinary EU-funded Project aimed at developing an Integrated Water Resources Management System (IWRMS) for water resources analyses and prognostic scenario planning in semi-arid catchments of Southern Africa. ERUs are used to identify areas affected by different types of erosion, and are applied as modelling entities for erosion simulations. Input data were obtained by remote sensing techniques (API method, Landsat TM images processing) and GIS-analyses. The results carried out in the Swaziland test catchment prove that the ERU concept is appropriate to identify areas affected by different types of erosion. Moreover the concept allows the calculation of the amount of soil loss due to gully erosion and rill-interrill erosion processes. These processes consequently were regionalized for the entire basin to get information about the catchments susceptibility to erosion as a base for an improved and sustainable land management.

Keywords: Response Units; Erosion; Erosion modelling; Swaziland

1. INTRODUCTION

Soil erosion is one of the dominant environmental problems in southern Africa and is likely to become even more severe due to the successive population growth and potential climatic changes. *In situ* land degradation by soil erosion includes the loss of crop production and the reduction of soil fertility. Apart from direct impacts such as reservoir sedimentation, the sediments are a storage medium and a catalyst for chemical, physical and biological pollution thus making erosion to an essential component for integrated catchment management.

The study was carried out in the Kingdom of Swaziland, and its objective was to test the concept of Erosion Response Units (ERU) presented by Märker et al. [1999]. Erosion processes and forms are mainly interlinked with the hydrological dynamics and the basin's distributed physiogeographical properties. Consequently the response of terrain units towards specific erosion processes can be identified by modifying the concept of Hydrological Response Units (HRU) as proposed by Flügel [1995] towards Erosion Response Units (ERU) characterized by unique hydrologically related erosion processes [Flügel et al. 1999]. In this study, ERU are delineated representing areas of different but unique erosion dynamics, and applied as modelling entities for erosion simulations. Remote sensing techniques were applied to obtain the distributed physiographic and anthropogenic catchment properties such as land use, soil surface, topography etc., and by means of GIS overlay analyses ERU were obtained.

2. MATERIALS AND METHODS

2.1 Test Catchment

The Mbuluzi river (Figure 1) originates from the Ngwenya hills in the north western part of Swaziland and drains an average of 372M m^3 of runoff per annum from an area of 2958.9 km^2 before flowing into Mozambique in the east. The catchment is sharing the four physiographic regions of Swaziland, namely the Highveld, Middleveld, Lowveld and Lubombo Plateau. Altitudes range from 125m in the Lowveld to more than 1500 m in the Highveld. The catchment has a sub-humid temperate climate, receiving most of its rainfall from convective summer storms between October and March. Mean Annual Precipitation (MAP) seldom exceeds

700mm in the Lowveld, while it may be in excess of 1200mm in some parts of the Highveld. Temperatures vary by altitude, and daily minima and maxima exceeding 11 °C and 26 °C in winter (July) and 22 °C and 33 °C in summer (January). With mean temperatures ranging between 16 °C and 23°C in summer and 6 °C and 20 °C in winter, the Highveld is the temperate part of the catchment. Measured January A-pan data vary around 200 mm in January and are less than 100 mm in June [Schulze, 1997].

The geology of the upper Mbuluzi catchment is dominated by granites with some areas of precambrian sediments and volcanic outcrops. Granite and granitic gneisses with outcrops of dolerite and gabbro are found in the Middleveld while the Lowveld area is underlain by sedimentary and volcanic rocks of the Karroo period. The main soil types in the Highveld and Middleveld part of the catchment are deep, acid and freely drained red and yellow ferrisolic and ferralitic soils with embedded stone lines. In the lower Middleveld generally grey or red, slightly textured soils from granite and gneiss are common. The Lowveld is characterised by weathered red, brown and black clays from basalts.

The dominant land use is grassveld and bushveld, and communal land is mainly used for grazing, and in the upper and middle section of the Mbuluzi river basin is also to a smaller extend converted to subsistence agriculture. The lower parts are dominated by intensive large-scale irrigated sugarcane plantations while the plateau is mainly covered by bushveld.

2.2 Delineation of ERU

As has been shown by Flügel et al. [1999] and Märker et al. [1999] different erosion process dynamics are linked to specific associations of system components and their physical properties. ERU consequently can be defined as follows: *"ERU are distributed three-dimensional terrain units, comprising specific component associations of the natural and human environment, which are heterogeneously structured and controlling a unique erosion process dynamics characterized by a small variance within the unit, if compared to neighbouring ones".*

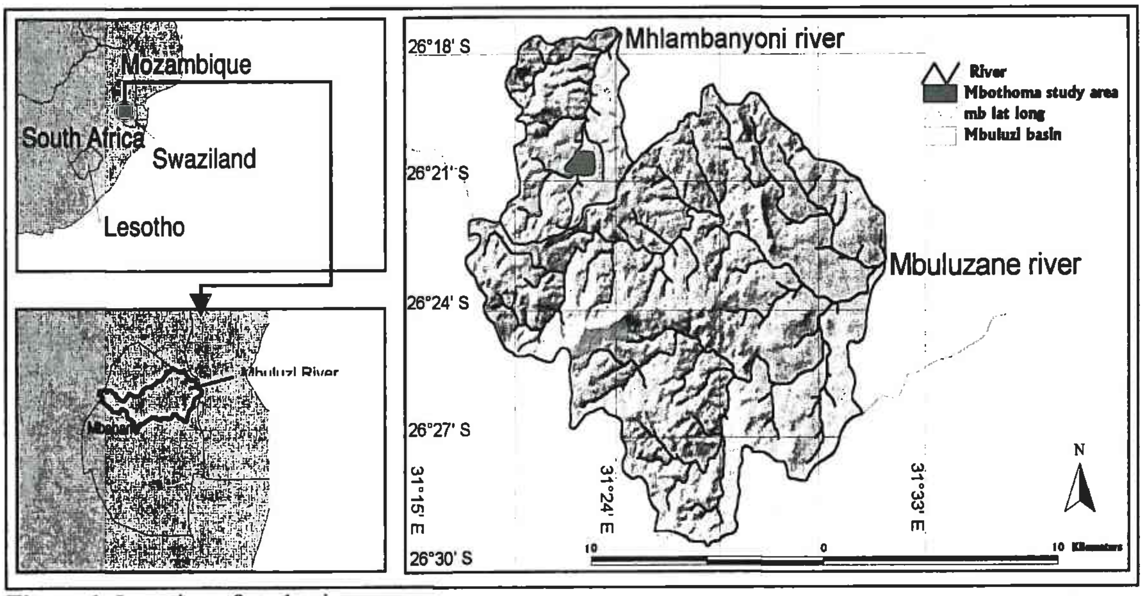

Figure 1. Location of study sites.

Table 1. Classification of erosion types and intensities with respect to vegetation cover [modified after van Zuidam 1985].

CLASS	Erosion Reference Unit (ERefU)	EROSION TYPE	VEGETATION COVER DENSITY (%)	DEGRADED AREAS (%)
1	None	no erosion	>90	<10
2	Slight	slight rill-interrill	>75	<25
3	Slight-moderate	Rill-interrill; shallow gully	>75	<25
4	Moderate	Rill; medium-deep gully	51-75	25-49
5	Severe	Rill, medium-deep to deep gully; landslides	26-50	50-74
6	Very severe	Rill, deep gully; badlands; sever e mass movement	< 25	>75

As ERU are based on the finite element concept they do not have a fixed scale such like raster pixels, and according to the definition they also comprise morphographic erosion features such as gullies. When applied as homogeneous erosion modelling entities, they transform the precipitation input into a corresponding surface and subsurface runoff generating erosion and sediment output specific for each ERU.

Erosion Refernce Units (ERefU) in turn are used as calibrated ground truth units, and are defined by criteria derived by a thorough systems analyses. In the study catchment such ERefU criteria were derived also by means of stereo-aerial-photographs, orthophotos and GIS analyses and cross checked by an intensive field mapping campaign and photo documentation.

For the classification of the erosion features and the subsequent delineation of the ERefUs, the erosion type, the degree and extent of erosion, as well as the density of the erosion features, were mapped from 1990 aerial photographs at 1:30000 scale. For the analyses the adapted Aerial Photo Interpretation (API) method of van Zuidam [1985] was applied.

The final classification of erosion types and erosion intensities with respect to vegetation cover is shown in Table 1. Criteria applied for this classification were the specific erosion types, their density and frequency, and the percentage of vegetation cover. The resulting Erosion Reference Units (ErefU) represent different levels of erosion intensity.

ErefUs as well as topography, geology, land use, soils and erosion features, each described by their attributes, were converted into digital raster format with a specified pixel size of 25m x 25m. These information layers were reclassified in order to reduce the number of classes within each information layer. Table 2 shows the parameters used in the overlay and reclassification procedure done in the GIS.

2.3 Application of Erosion Response Units in Erosion Modelling

The concept of ERU supports a fully distributed modelling approach. In addition they permit the regionalization of erosion dynamics, as they account for the three dimensional physiographic characteristics of heterogeneousely structured terrain entities. In the Mbulizi catchment they represent the main erosion processes such as gullies and rill- interrill erosion.

The volume of sediments produced by gully erosion was simulated for a representative gully system using a dynamic gully evolution model [Sidorchuk 1999]. The model is physically based and was adapted to the physiogeographical conditions of the catchment. It was run over a period of 150 years till the final gully morphometry was established.

For the rill- interrill erosion the Revised Universal Soil Loss Equation, RUSLE, [Renard et al. 1991] was selected and was run for each ERU on a 25m x 25m pixel basis. The sediments produced in each ERU-area were routed through the catchment towards the river bed, but no further transport within the river bed was done.

2.4 Regionalisation of ERU Information and Modelling Results

Remote sensing applications in semi-arid and arid regions [Robinove et al. 1981] have established (i) a relation between increasing radiance and associated degrees of soil degradation (erosion, low soil moisture and organic matter, low agricultural productivity), and (ii) between a decreasing albedo and improved land use patterns (more soil moisture, organic matter and productivity, less erosion).

To calculate the entire amount of sediments produced by erosion processes in this subcatchment

Table 2. Parameter classification and overlay sequence used for the delineation of ERU combinations.

CLASS	ErefU	GIS-LAYER			
		Aspect 1	Land use 2	Slope morphology 3	Geology & soil texture 4
1	no erosion	North	Unimproved grassland	Convex/ concave slope < 1° & >60m	Alluvium/ peat
2	Slight rill-interrill erosion	east	Shrub bush & forest	convex slope 1-5° & > 60m	Rock outcrop
3	Rill-interrill; shallow gully erosion	South	Wetland & waterbodies	Concave slope 1-5° & > 60m	Loam
4	Rill; medium-deep gully erosion	West	Cultivated commercial/ subsistence	Convex slope 5-10°& > 30m	Clay
5	Rill; medium-deep to, deep gully erosion		Urban	Concave slope 5-10°& > 30m	Sand
6	Rill, deep gully erosion; badlands; severe mass movement		Degraded unimproved grass- & bushland	Concave/convex slope >10° < 60m	

the rill-interrill erosion volumes calculated with the RUSLE have to be complemented by the eroded sediment mass obtained by the gully model.

The latter was done for a representative test gully with the dynamic gully model, and consequently have been regionalised for the entire subcatchment. The areas of active gully erosion have been delineated within the GIS by overlaying the ERU data layers with the TSAVI (Transformed Soil Adjusted Vegetation Index) derived from Landsat TM 1996 analyses. It supplies reliable results for arid and semiarid grassveld landscapes [Purevdorj et al. 1998], as it's formula is accounting for different soil parameter (a,b,X) (Baret & Guyot 1991):

$$TSAVI = \frac{a(\mathrm{NIR} \cdot a\mathrm{R} \cdot b)}{a\mathrm{NIR} + \mathrm{R}\,ab + X \cdot (1 + a^2)} \quad (1)$$

The specific values for a (slope) and b (y axis intersection) are obtained from the "soil-line" which was derived from the scattergram of the relationship between the near infrared channel (NIR) and the red channel (R)

Potential degraded areas show negative TSAVI values (see Figure 2). If this negative values are combined with the ERU information on present erosion forms and intensities (ERefUs) as shown in Figure 3 areas of active gully can be detected. Regions with similar litho-pedologic conditions in the Mhlambanyoni area permit the regionalization of the gully erosion rates calculated by the dynamic gully model. In a further step the erosion rates obtained for the test gully were averaged over the areas of active gully erosion resulting from the TSAVI/ERefU overlay analysis. Subsequently the simulated sediment loss for each modelling unit (RUSLE and gully modelling entities) has been routed down to the catchment outlet following the flow path of the overland flow by means of a flow accumulation procedure developed in *ARCInfo*.

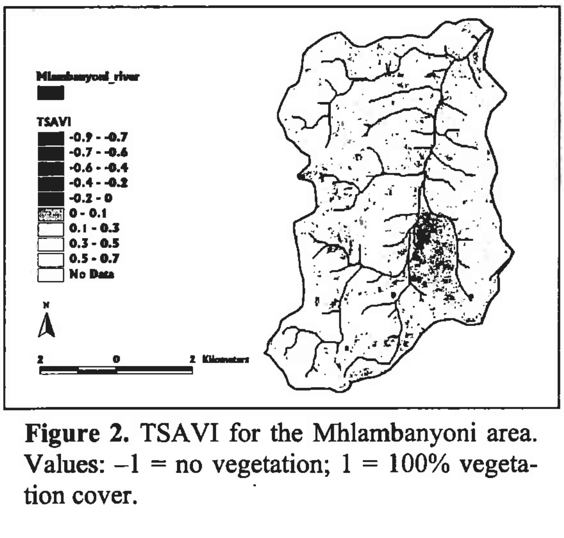

Figure 2. TSAVI for the Mhlambanyoni area. Values: –1 = no vegetation; 1 = 100% vegetation cover.

3. RESULTS AND DISCUSSION

The distribution of the different erosion types and their intensity (Table 1) is shown for the Mhlambanyoni subcatchment in Figure 3. Rill-interrill erosion and gully erosion are predominant in the Mbuluzi catchment, but deep gully erosion was identified mainly in the upper part of the Mbuluzane River catchment and in the Mhlambanyoni catchment (Figure 3). About 8% of the Mhlambanyoni catchment is directly affected by severe deep gully erosion (classes 4, 5 and 6 in Figure 2, whereas 40% of the area shows slightly signs of erosion.

It should be noted that the zone of intensive erosion is situated along a north - south running system of amphibolite/serpentine and dolerite/granophyre dykes. This lithology consists of highly erodible saprolites [Scholten et al. 1995], and the densely populated area accomodates a high livestock concentration. Consequently, overgrazing is common especially on communal land such as the Mbothoma area. Livestock tracks and pathways are visible on the aerial photographs and analyses of different time series show that gullies often develop along them.

The results of the RUSLE simulation is shown in Figure 4, giving the distribution of eroded sediments in $tha^{-1}annum^{-1}$ for the Mhlambanyoni subcatchment. The calculations have been visually verified and crosschecked to identify the trend and the actual range of the spatial distribution of the interrill-rill erosion processes. The single pixel values range from less than 0.13 $tha^{-1}annum^{-1}$ to 395 $tha^{-1}annum^{-1}$ in the Mbothoma area. The mean value is about 13 $tha^{-1}annum^{-1}$.

The sediment yield calculated by the technique described above results in 55153.5 $tannum^{-1}$ for the 4208 h large Mhlambanyoni catchment. This is an averaged soil loss of about 13 $tha^{-1}annum^{-1}$.

In the Mhlambanyoni and upper Mbuluzane catchments, a high density of gullies has been identified using the ERU method, and the dynamic gully erosion model developed by Sidorchuk [1999] for similar environmental conditions, was used.

When applied for the Mbothoma gully system the model predicted an eroded volume of 1.04 million m^3 for a gully catchment of 42.63 ha which contained an active gully area 25 ha. The dynamics of the gully system is characterised by a rapid growth rate of gully's maximum length, followed by the growth of the total gully area, mean gully depth and, finally, the growth rate of the total gully volume.

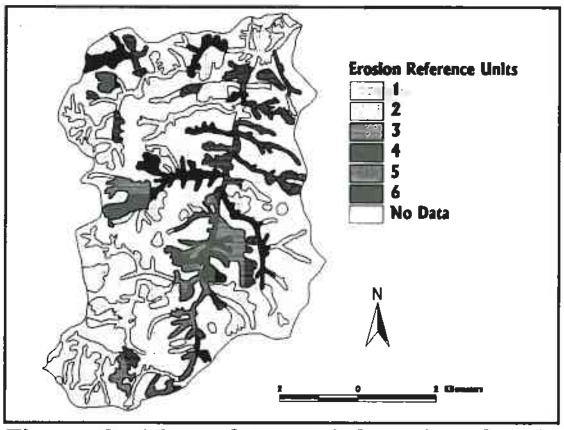

Figure 3. Map of ERU information for the Mhlambanyoni catchment. 1) no erosion; 2) slight rill interrill erosion; 3) rill interrill, shallow gully erosion; 4) medium gully rill erosion; 5) deep gully rill erosion; 6) very deep gully erosion badlands.

Assuming a soil density of 1.2 g·m^{-3} and a gully life span of 150 years the averaged soil loss for the active gully area to be 8320 tannum^{-1} i.e. 190 tha^{-1} annum^{-1} for the entire gully catchment and 332.8 tha^{-1}annum^{-1} for the active gully area.

To include the soil and substrate loss produced by gully erosion, the gully erosion rates have to be regionalized overlaying the ERU information with a TSAVI derived from a Landsat TM image taken in 1990.

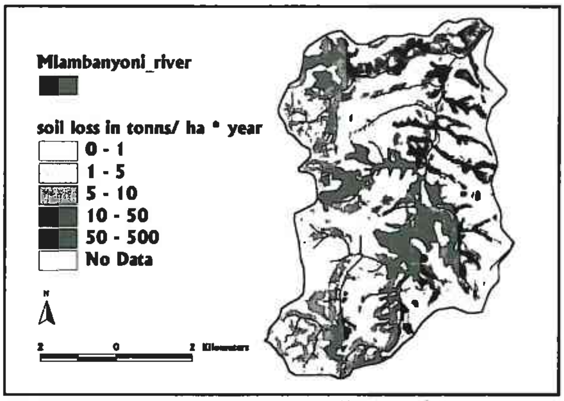

Figure 4. Values of eroded sediments in tonnes per hectare and year for the Mhlambanyoni catchment

The area of active gully erosion features have been estimated to be 89125 ha, which is only 2% of the entire Mhlambanyoni catchment. Consequently, the amount of sediments produced by active gully erosion was calculated with the active gully erosion rate to be 29670 tannum^{-1} which is more than 53% of the total sediment yield predicted by the RUSLE model for the rill-interrill erosion. Integrating the amount of sediments derived from both erosion processes (gully, rill-interrill) leads to a total sediment yield of 84814 tannum^{-1}, which then equals to about 20 tha^{-1}annum^{-1} for the Mhlambanyoni catchment.

4. CONCLUSION

Within this study areas subject to different erosion processes and intensities have been identified using the concept of Erosion Response Units (ERU). The Mhlambanyoni river basin in the Kingdom of Swaziland, characterized by a high erosion risk was chosen to test the concept and to model erosion volumes. ERU proved to be capable to account for distributed lithologies such as saprolites, which are highly vulnerable to erosion. They also were able to represent different erosion processes and features contributing to the erosion dynamics of the catchment. As such sediments derived from gully erosion can not be simulated by a RUSLE-type model a integrated modelling approach simulating the rill-interrill and gully erosion dynamics was applied in the catchment.

The rill-interrill erosion processes were simulated using the RUSLE approach [Renard et al. 1991], and a dynamic gully erosion model developed by Sidorchuk [1999] were applied for annual time steps. The sediment volumes calculated with the two different models for the individual ERU have been regionalized and routed down the river network according to the overland flow paths.

For the entire Mhlambanyoni catchment, it was estimated that active gully erosion delivers more than one third of the total sediment yield, while covering only 2% of the entire catchment area. Carefully calibrated the RUSLE can deliver suitable reference values for rill-interrill erosion on a annual basis.

The erosion modelling exercise in the test catchment provided evidence, that for a detailed erosion estimation within complex catchments a fully distributed modelling strategy has to be applied.

The ERU concept proved to provide sufficient flexibility for the identification of erosion processes and their areal distribution on various temporal and spatial scales. They also provide a physically based mean to include gully erosion processes as an important component for an integrated erosion modelling approach on a catchment scale.

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