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Leenaers, H.

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International Institute for Applied Systems Analysis □ A-2361 Laxenburg □ Austria

Telephone: (0 22 36) 715 21 * 0 □ Telex: 079 137 iiasa a □ Telefax: (0 22 36) 71313

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Foreword

The formulation of the environmentally sound and sustainable policy for land use and water resources management requires development of methods necessary to predict the consequences of various human activities on the environment. The IIASA *Water Resources Project* (WAT) addresses this issue in several ways, one of them is the development of a Decision Support System for Large River Basins. Its objective is to elaborate a set of models and PC-AT interactive software package capable of analyzing problems that may arise in developing hydropower and irrigation systems, land use management and agricultural activity. The Zambezi river basin was selected as a case study for the implementation of the above methodology.

This paper by Henk Leenaers, prepared within the framework of the IIASA 1989 Young Scientists' Summer Program, is devoted to soil erosion problem in the Zambezi river basin. Its importance for water resources planners arises inter alia from the fact that erosion processes may seriously influence the operation of reservoir systems due to silt deposition diminishing storage capacity. The model for estimating soil erosion hazard was used in combination with a number of land use scenarios. For these scenarios areas subject to particularly high erosion hazard were selected for the Zambezi. The paper presents a good starting point for further investigations on land use/climate/water resources interface.

B.R. Döös
Leader
Environment Program

ESTIMATING THE IMPACT OF LAND USE CHANGE ON SOIL EROSION HAZARD IN THE ZAMBEZI RIVER BASIN

*H. Leenaers**

1. INTRODUCTION

Soil erosion and associated land degradation are a major problem in many areas of the African continent and this problem is growing year by year in response to increasing population pressure on agricultural land. In a hydrobiological review of the Zambezi river basin, Pinay (1988) concludes that two main issues must be faced from the water management point of view: (1) the soil erosion problem due to intensive deforestation and (2) reservoir operations in order to optimize the hydroelectric power generation. These two main issues are interconnected in the sense that erosion processes may entail an increase in silt deposition in reservoirs diminshing their real storage capacity. From this perspective it is necessary for planning purposes to delineate areas susceptible to soil erosion in order to be able to adequately predict the consequences of land use change, both in terms of erosion hazard and of reservoir sedimentation.

A model for the estimation of soil erosion hazard in southern Africa (SLEMSA) has been developed and validated under field conditions in the Zimbabwe Highveld area by Elwell (1978), Elwell & Stocking (1982), Stocking (1981), and Stocking et al. (1988). By applying this empirical model, soil erosion hazard maps for the eight countries in the Zambezi River basin have been constructed and these will soon be published. The maps show erosion hazard zones that are based on the current land use and vegetation cover. However, in addition to static maps of the current situation, physical planners need to obtain insight in the consequences of future land use changes. Therefore, they need a means of data storage and manipulation that allows them to alter the current conditions and to repeat the mapping excercise for various land-use scenarios.

* Department of Geography, University of Utrecht, P.O. Box 80.115, 3508 TC Utrecht, Netherlands. CSO Consultants for Environmental Management & Survey, PO Box 30, 3734 ZG Den Dolder, Netherlands.

This paper describes how SLEMSA was linked to a PC-based Geographical Information System and how soil erosion hazard maps of the Zambezi River basin were produced for different land use scenarios. The vegetation map of Africa (White, 1983) was used as the basis for predicting soil erosion hazard for basin cover by natural vegetation. Four land use scenarios representing various stages of land pressure (due to cropping, grazing and deforestation) were used to delineate areas that are susceptible to soil erosion.

2. THE ZAMBEZI RIVER BASIN

2.1. General characteristics

The Zambezi River basin lies between 24–38°E and 12–20°S, and is the largest of the African river systems flowing into the Indian Ocean (Balek, 1977). The 2660 km long river rises on the Central African Plateau and flows southward. The larger part of the basin is occupied by the Central African Plateau and lies more than 900 m above sea-level, rising in places near the rim to over 2500 m. There seems to be no agreement about the size of the catchment: values reported in the literature vary between 1 193 500 km^2 (Balon & Coche, 1974) and 1 570 000 km^2 (Balek, 1977). The relative surface contributions of the eight occupying countries to the catchment area vary greatly and are largest for Zambia (40.7 %), Angola (18.3 %), Zimbabwe (15.9 %) and Mozambique (11.4 %).

Except towards the coast the climate in this region is continental in character with appreciable seasonal variations in temperature. Mean annual temperature varies from 18 to 24°C. Rainfall is between 250 and 2000 mm per year and in general decreases from north to south, but there are pronounced regional variations. There are three main seasons. The wet season from November to April is characterized by the occurrence of thunderstorms and heavy showers, with only rare periods of continuous rain. There is a fair amount of sunshine. In the cool season, from May to August, the day temperatures are moderately high with continuous sunshine, but night temperatures are low and ground frost may occur in sheltered valleys. The hot season is from September to November. Temperatures and atmospheric humidity progressively increase until the onset of the wet season. In the heart of the region dry-season precipitation is exceptional, and there is usually no measurable rain for six months or more.

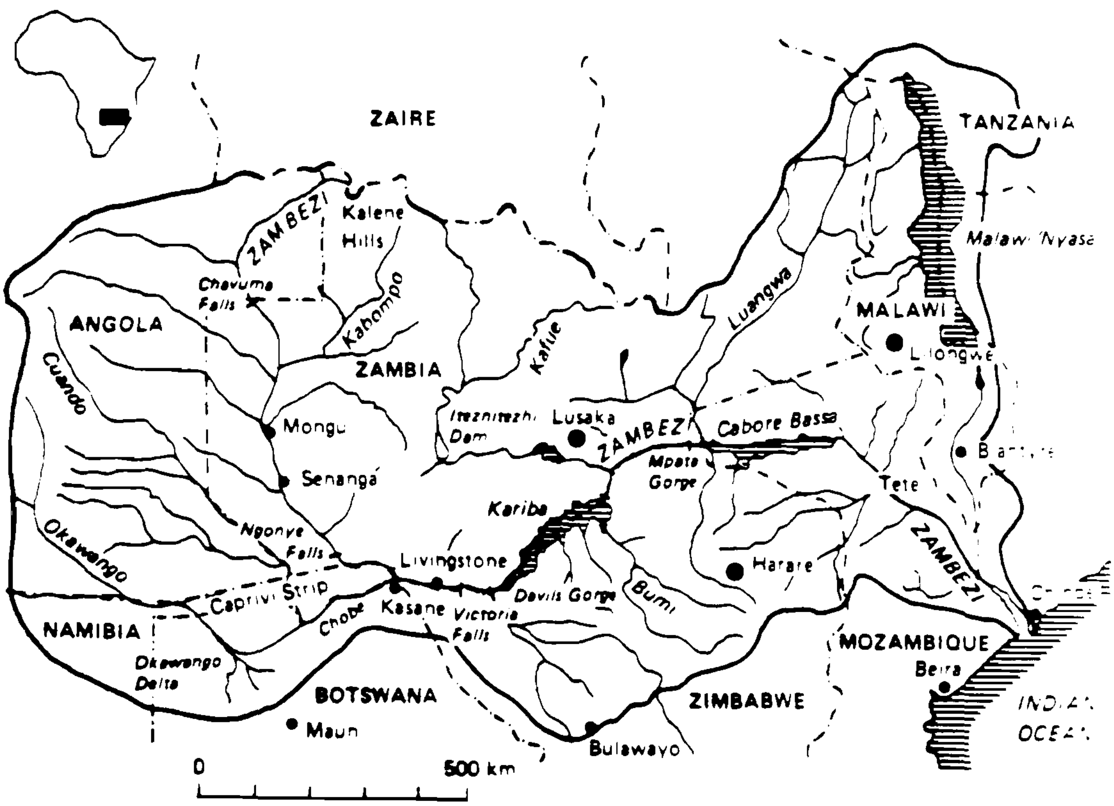

Figure 1a. Hydrography of the Zambezi river basin.

2.2. Hydrology

Figure 1 shows the Zambezi River system and the situation of the two large dams utilizing the rivers's energy, the Kariba Dam in Zambia/Zimbabwe and the Cabora Bassa Dam in Mozambique. Shortly above Victoria Falls the Zambezi is joined by the Kwando, both rivers drain a total of 507 200 km^2 in Zambia and Angola. Between Victoria Falls and the Kariba Dam the Zambezi receives water mainly from southern tributaries, i.e. the Gwai, the Sengwa and the Umniati draining northern Zimbabwe. The total area drained is 156 600 km^2. Below the Kariba Dam and above the Cabora Bassa Dam the Kafue and the Luangwe deliver water from Central and East Zambia. The last major tributary of the Zambezi is the Shire, the outlet of Lake Malawi, which joins the river 170 km above its outfall to the Indian Ocean. Along its course, the mean annual discharge of the Zambezi increases from 555 m^3/s at Chavuma Falls to 1237 m^3/s at Victoria Falls (Balek, 1977) and eventually it discharges some 100 km^3/year to the Indian Ocean (Borchert & Kempe, 1985). The Zambezi River flow regime is characterized by a pronounced seasonal hydrograph. The monthly 59-year average discharge at Livingstone is lowest for November and highest for April (Borchert & Kempe, 1985).

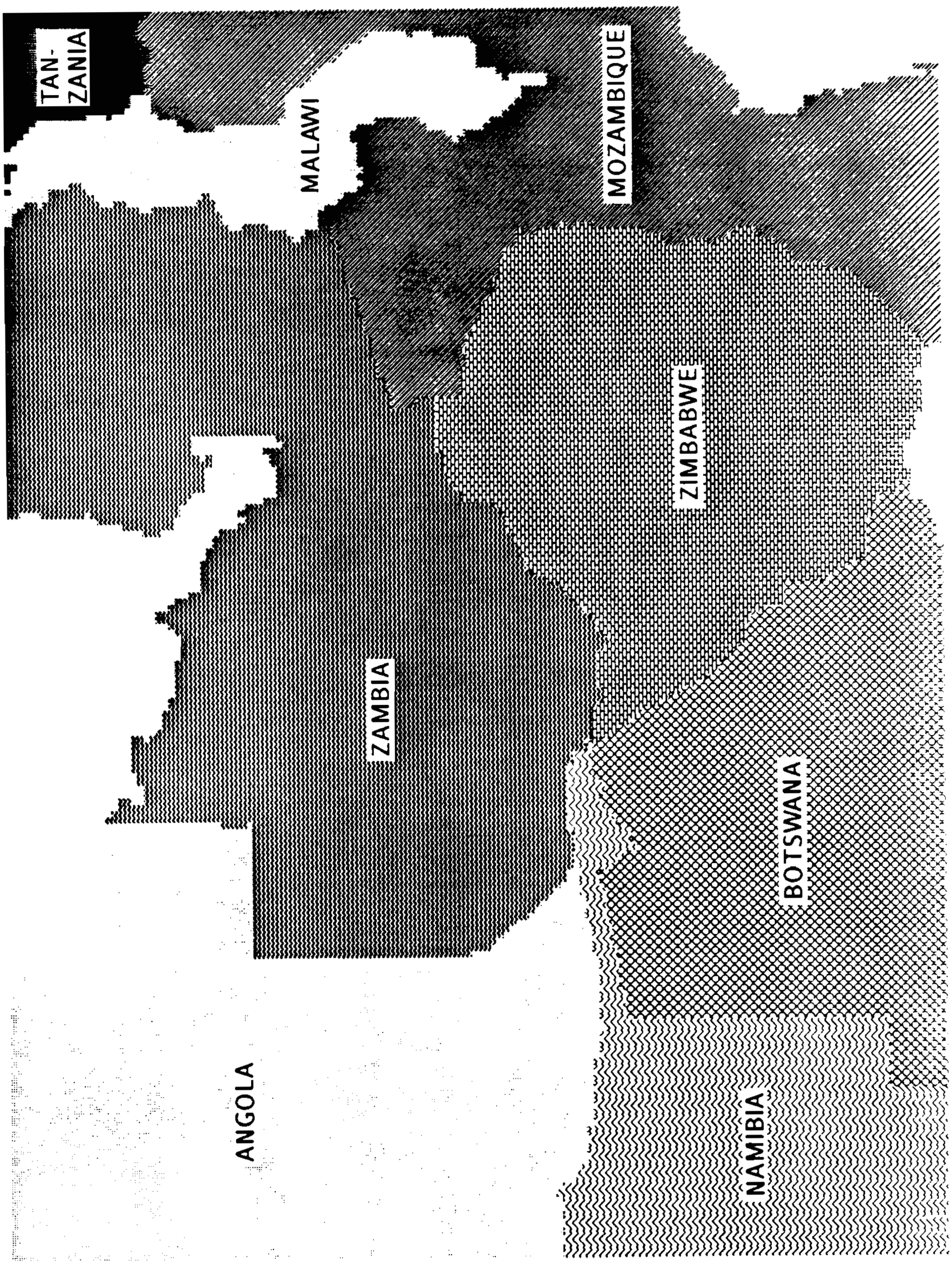

Figure 1b. Political boundaries of the Zambezi river basin.

2.3. Land use change and soil erosion

Table 1 lists land use data of the four large countries in the Zambezi River basin, derived from the FAO Production Yearbooks (1977-1987). It demonstrates that during the past 20 years large scale deforestation has occured in Zambia, Angola and Mozambique and that the area covered by arable land has grown in all countries. In Zimbabwe, there is an alarming rate of increase being put on communal lands. Stubbs (1977) reports that in the period 1961/62-1976/77 the number of cultivators increased by 88 %, the gross area under cultivation by 91 % and the number of cattle by 70 %. In 1966, 49 % of the communal lands were either overgrazed or had very little herbaceous cover (Cleghorn, 1966). In the current situation, 17 % of the communal lands in Zimbabwe is very severely eroded, 10 % severely eroded, 13 % moderately eroded and 60 % in relatively good condition (Whitlow, 1988). In a study area covering 165000 ha in Zambia, 13 % of the arable land was eroded by gullies, 23 % severely sheet eroded and 43 % moderately sheet eroded (Stocking, 1983). Current levels of soil loss from small-scale farms in the communal areas in Zimbabwe have been estimated to be of the order of 50 t/ha/yr (Elwell, 1985). The damage to the water resources in this country, as a result of land use changes followed by soil erosion, is large: 12-13 % of the dams in Masvingo Province are now totally useless due to siltation and 50 % of all dam structures have less than half of their full capacity left (Elwell, 1985). At the present rate of sediment input, the dead storage of Lake Kariba will be filled in 1600-16000 years and therefore the effect of sediment on the operation of the project may be ignored (Bolton, 1984). However, the sediment input rate to the Cahora Bassa reservoir appears to be a factor three larger than that of Lake Kariba (Pinay, 1988). Consequently, the dead storage would be filled in 60-600 years and the reservoir operation may be affected much sooner than expected.

3. SLEMSA: A SOIL LOSS ESTIMATION MODEL FOR SOUTHERN AFRICA

A simple model for estimating soil loss over large areas in southern Africa has been developed by the Soil and Water Conservation and Land Utilisation Coordination Unit of the Southern Africa Development Coordination Conference (SADCC). The model is thoroughly described by Elwell (1978), Elwell & Stocking (1982) and Stocking et al. (1988) and was validated under field conditions in the Zimbabwe Highveld. In this section a brief description of the model parameters and the equations used will be given. For more detailed information, refer to the original sources.

Table 1: Land use changes in the four largest countries in the Zambezi River basin (values in km^2).

	Zambia		Angola		Zimbabwe		Mozambique	
Landuse	1965	1985	1965	1985	1965	1985	1965	1985
Arable	48150	51800	10500	29500	19810	26500	24560	28600
Permanent crop	50	80	5200	5500	150	840	2130	2300
Permanent pasture	300400	350000	3290000	290000	48560	48560	440000	440000
Forest	376310	293900	726000	531000	238100	238100	194000	150900
Irrigation	20	200	-	-	270	1750	460	820

3.1. Model structure

In SLEMSA, four broad factors are used to summarize erosion hazard: (1) rainfall, (2) soil, (3) vegetation and (4) relief. These factors are described by five control variables, which can be expressed numerically: seasonal rainfall energy, E (in $J/m^2/y$); soil erodibility, F (as an index); seasonal energy intercepted by the crop, i (in %); slope steepness, S (in %); and slope length, L (in m). These control variables have been arranged into three submodels: a principal submodel, K, yielding estimates of soil losses from bare fallow land at a specified slope steepness and slope length; a crop canopy cover model, C, giving a ratio to adjust from bare fallow to a specific crop type; and a topographic model, X, giving another ratio which enables soil losses to be estimated from slopes other than those specified in the K submodel. The first two submodels were developed from a limited amount of field plot data supplemented by expert opinion. The third submodel was derived from the slope factor relationship of the Universal Soil Loss Equation (Wischmeier & Smith, 1978). The submodels for the Zimbabwe Highveld are formulated as folows:

$$K = exp((0.4681+0.7663*F)*ln(E)+2.884-8.2109*F) \quad (1)$$

$$C = exp(-0.06*i) \text{ for } i < 50 \quad (2.1)$$

$$C = (2.3-0.01*i)/30 \text{ for } i \geq 50 \quad (2.2)$$

$$X = L*(0.76+0.53*S+0.076*S)/25.65 \qquad (3)$$

The main model expresses the relationship between the submodels and takes the form of their product:

$$Z = KCX \quad , \qquad (4)$$

where Z: predicted mean annual soil loss ($t/ha/y$);
K: mean annual soil loss ($t/ha/y$) from a standard field plot 30 m × 10 m at a 4.5% slope for a soil of known erodibility F under a weed-free bare fallow surface;
C: the ratio of soil lost from a cropped plot to that lost from bare fallow land;
X: the ratio of soil lost from a plot of length L under slope percent S, to that lost from the standard plot.

Although the above equation provides estimates of annual soil loss in t/ha, Stocking et al. (1988) strongly caution for quoting the results in these units. Instead, they suggest to express the results in dimensionless Erosion Hazard Units (EHU) on a scale of 1-1000. The EHU's will then give a relative idea of the degree of soil loss that might be expected on a field under the mean conditions used for the calculations.

3.2. Measuring the control variables

The rainfall factor is measured by mean seasonal rainfall energy (i.e. rainy season) E in $J/\text{m}^2/\text{y}$, which may be estimated from regression equations derived in Zimbabwe:

for areas prone to drizzle: $E = 17.37 * P;$ (5.1)
for normally agressive climates: $E = 18.84 * P,$ (5.2)

where P: mean annual rainfall (in mm).

Preliminary validations in Botswana, Lesotho and Swaziland shown no significant variations from the Zimbabwe relationships (Stocking, 1987).

The soil factor is described by an index of soil erodibility. Soils are rated on a scale of 1 to 10 (1 being most erodible, 10 having greatest resistance) according to limited experimental data and knowledge of relevant soil characteristics. This procedure yields a basic index for each soil type and modifiers are provided to account for locally important influences on soil erodibility such as crusting, topsoil texture, tillage, land use history and current crop management. The full scheme as determined for Zimbabwe soils is given in Elwell (1978), the soil erodibility ratings for FAO soil units in Mozambique is given in Stocking (1987).

The vegetation factor is measured by the mean seasonal interception of rainfall by vegetation. This gives the proportion of the erosive rainfall, i (in %), that is intercepted by a growing crop or vegetation in a growing season. The value of i takes into account the influence of crop type, planting date, plant density and management. A vegetal cover data bank is available for the region (Elwell and Wendelaar, 1978), which gives values of i for a whole range of crops.

The relief factor is measured by slope steepness (in %) and slope lenght (in m). Stocking (1987) suggested to determine the average slope using the method devised by Wentworth (1930).

4. EXPERIMENTAL PROCEDURES

4.1. Data acquisition, storage and processing

In the Global Environmental Monitoring System (GEMS) of the United Nations Environment Program (UNEP) several datasets were available for the Zambezi region. The datapoints are located on the intersections of a grid with a cell size of approximately 10 km. The data sets are held in the Miller Oblated Stereographic Projection and contain a.o. the following information: mean annual rainfall (mm), topsoil texture (according to the FAO texture diagram (FAO-UNESCO, 1974)), units from White's vegetation map of Africa (White, 1983) and general land use type (FAO-UNESCO, 1977). Topographical data (modal height, minimum height and maximum height) were derived from the Navy Fleet Numerical Oceanography Center (NFNOC, Solid Earth Division, USA), which supplies these terrain data with a horizontal resolution of 10 minutes. Coordinate corrections and a local linear interpolation procedure were carried out in order to match the latter dataset to the GEMS-dataset and to yield the same horizontal resolution of 10 $\times$ 10 km.

A geographical database was created by linking a relational database (dBase 3 Plus) to the grid based Geographical Analysis System IDRISI (Eastman, 1988). Equation (1) to (5) were formulated in the programming language provided by dBase3 Plus. After each run of SLEMSA, the resulting Erosion Hazard Units for each gridcell were segmented by using the same class boundaries as those used by Stocking (1987):

EHU	<= 10:	erosion hazard	= 1	(low)
	10 < EHU <= 25:	erosion hazard	= 2	
	25 < EHU <= 50:	erosion hazard	= 3	(medium)
	50 < EHU <= 100:	erosion hazard	= 4	
	EHU > 100:	erosion hazard	= 5	(high).

Maps displaying the erosion hazard classes were produced with IDRISI (see Figure 6a-e) and these were interpreted in terms of relative susceptibility to soil erosion.

4.2. Estimating the model parameters

The mean seasonal rainfall energy, E, was derived directly from equation (5.2). Given that we had no information on the location of areas prone to drizzle, it was not possible to use equation (5.1) for areas with a relatively gentle climate. However, since the occurrence of drizzle is restricted to relatively small areas along the coast, it was thought reasonable to assume that no large errors will be produced when assessing soil erosion hazard at the scale of the entire catchment. Another limitation is caused by the fact that the regression curves are based on mean annual rainfall data with a maximum of circa 1150 mm. In the northern part of the Zambezi basin, however, locally the mean annual rainfall may be as high as 2000 mm. In these cases it was decided not to extrapolate from the regression curves buth to take the largest value of E on the part of the regression curves that is supported by experimental data. Figure 2 shows the spatial pattern of E in the Zambezi River basin.

For the estimation of the index of soil erodibility, F, a slightly modified version of the indexing method presented by Elwell (1978) was used. Contrary to the later indexing schemes that are based on FAO soil units (Stocking, 1987), this scheme only takes into account soil texture. Because at the time of this study no indexing scheme that covers the entire range of FAO soil units in the Zambezi river basin was available, it was decided to employ this relatively simple method that requires less detailed data. The deriviation of

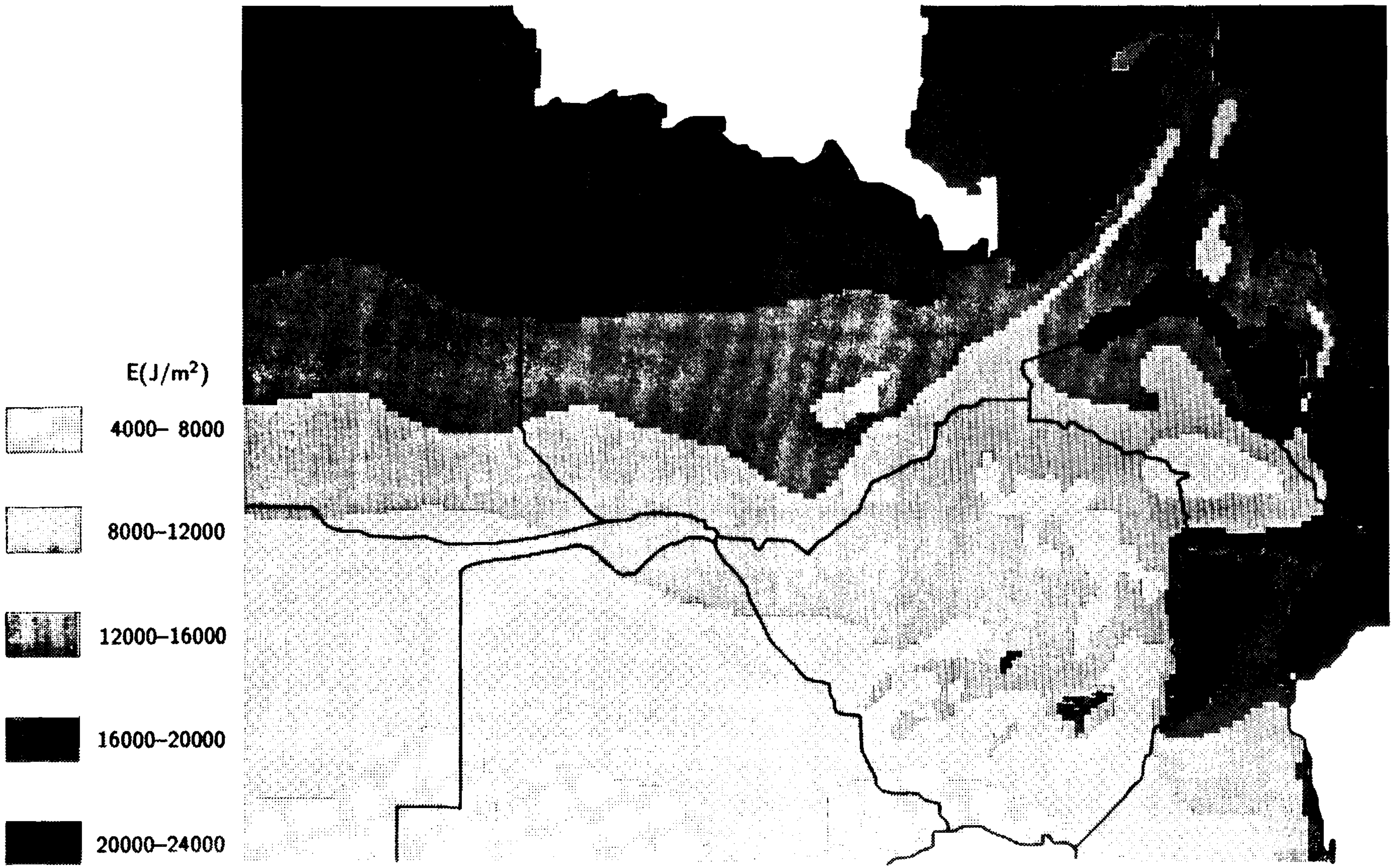

Figure 2. Distribution of mean seasonal rainfall energy (J/m^2) in the Zambezi river basin.

basic soil erodibility indices for three soil texture groups and the modifiers used are listed in Table 2. The spatial distribution of F in the Zambezi River basin is shown in Figure 3. Employing the estimated values of E and F, the mean annual soil loss from a standard field plot was then computed by equation (1).

Table 2: Index of soil erodibility (F) for different soil types

Soil Texture	Soil Type	Erodibility Index, F
Light	sands, loamy sands, sandy loams	4
Medium	sandy clay loam, clay loam, sandy clay	5
Heavy	clay, heavy clay	6

The minimum and maximum heights in the topographica data set were used to estimate the average slope (in %) in each 10×10 km gridcell. The difference between minimum and maximum height in each gridcell was divided by half the length of the diagonal of the gridcell. For the slope length we used a standard value of 100 m, as suggested by Stocking (1987). Equation (3) is based only on slopes up to 20%. Therefore, a slope of 20% was taken as the maximum slope for the calculation of X by equation (3). Figure 4 shows the distribution of X in the Zambezi River basin.

4.3. Land use scenarios

As a starting point for estimating the impact of land use change on the erosion hazard, SLEMSA was run for a situation in which the entire catchment is covered by 'natural' vegetation, i.e. the vegetation cover as described by White (1983). The vegetation map presented by White (1983) delineates a large number of units in the Zambezi River basin and, according to the density of the vegetation cover and potential landuse, for this study these were grouped into (1) forest (90% cover), (2) woodland and thicket (70% cover) and (3) grassland (70% cover). The first group includes Zambezian dry forest and Zambezian swamp forest and riperian forest, the second group consists of Zambezian transition woodland, Zambezian woodland, Zambezian thicket and Zambezian scrub woodland and the last group consists of Zambezian grassland (for detailed characterization of the map units,

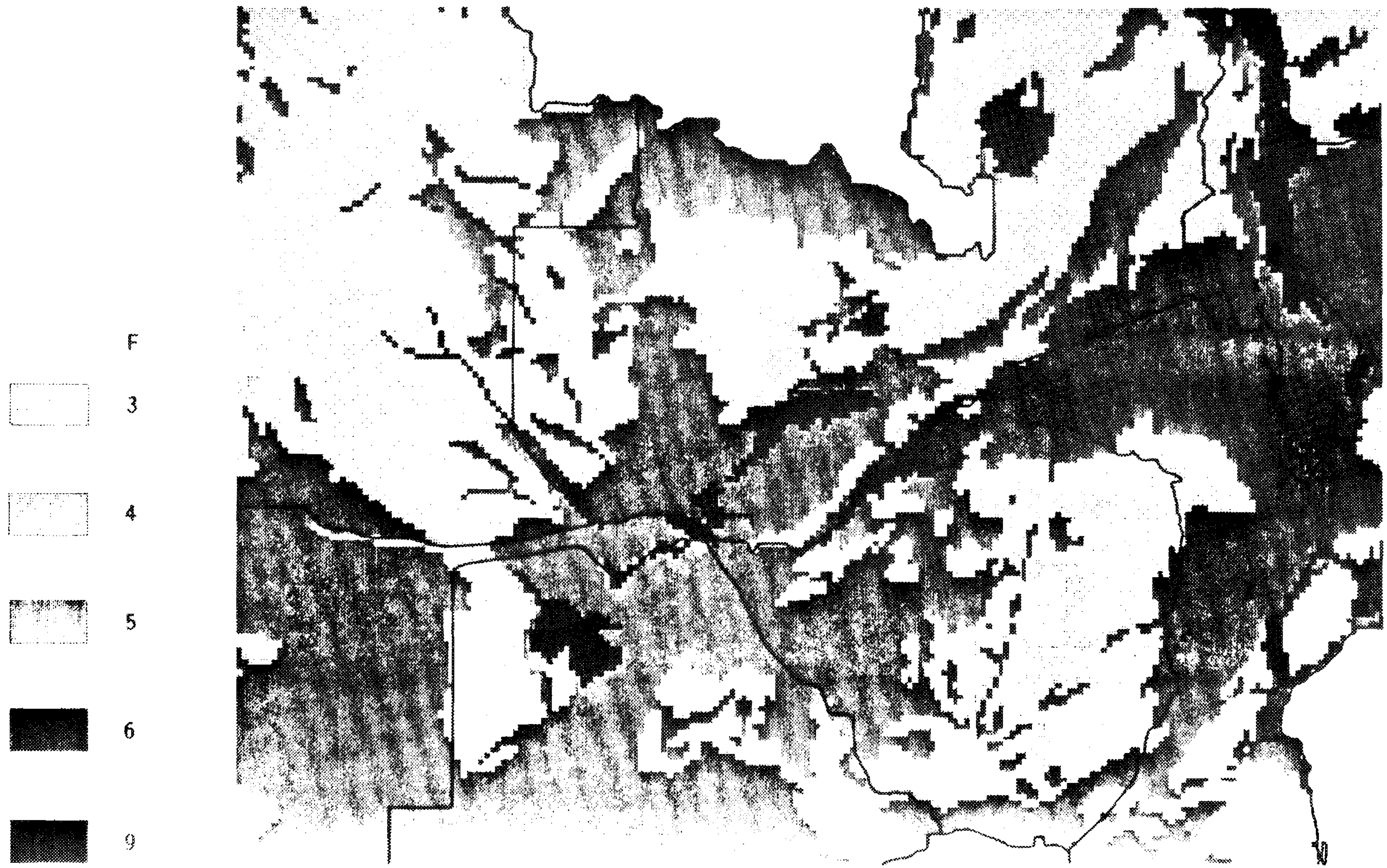

Figure 3. Soil erodibility in the Zambezi river basin.

refer to White (1983)).

Using this land use scenario as a basis, four other scenarios were designed whereby the percentage vegetal cover was gradually decreased, simulating increasing intensity of cultivation, increasing grazing pressure and increasing deforestation (see Table 3 and Figure 5). Scenario II was designed to represent a situation where well-yielding crops providing a good cover are grown in the cultivated areas, the grazing pressure is moderate in grassland areas and no deforestation of importance occurrs in forest and woodland areas. Scenarios III and IV then represent two situations where crops produce only moderate yields, the grazing pressure is heavy, and deforestation progresses. These two scenarios probably reflect best the current situation. In scenario V all vegetation is cleared and bare soils cover the entire catchment area.

No detailed data were available on the extent of past and current deforestation practices and their effects on % vegetal cover. White (1983) reports that the area of Zambezian dry forest has been greatly diminished by fire and cultivation, and that nearly all the miombo woodland on the Central African Plateau has been subjected to agricultural practices of the 'citemene' type, a type of slash- and-burn shifting cultivation. Given that the exact locations of deforested areas were not known and that part of the deforested area is put to use for agricultural practices, it was decided to decrease the vegetal cover in these areas by an average percentage of 20 in both scenarios III and IV. Obviously, this value represents only a rough estimate and does not take into account local deviations due to efficient recultivation or complete destroyal of forest vegetation.

In order to increase the intensity of cultivation in scenarios II-IV, use was made of the landuse column in the geographic database, which distinguishes 'cropland' and 'cropland and/or natural mosaic' (thus, in these areas White's classification is overruled). In cropland areas we used values for percentage cover in dependence of yield, as provided by Elwell (1980b). In scenarios II and III/IV plant covers were set to 36% and 20% respectively, which corresponds to mean seasonal energy interceptions i of well-yielding maize (i.e. 4000 kg/ha) and poor-yielding maize (i.e. 1000 kg/ha) emerging on November 15th. The grazing pressure was changed in grassland areas according to data presented by Stocking (1987). In areas with rainfall less than 700 mm/year, i takes the value of 40% for moderate grazing pressure (i.e. 100-300 cattle-days/ha) and 20% for heavy grazing pressure (more than 300 cattle-days/ha). In areas with rainfall of more than 700 mm/year, these values are 60% and 30% respectively. In areas marked as 'cropland/natural mosaic' in the landuse column, we assumed that - in scenarios II, III and IV - 50% of the area is covered by cropland and 50% of the area by grassland with a grazing pressure more or less equal to that in the other grassland areas.

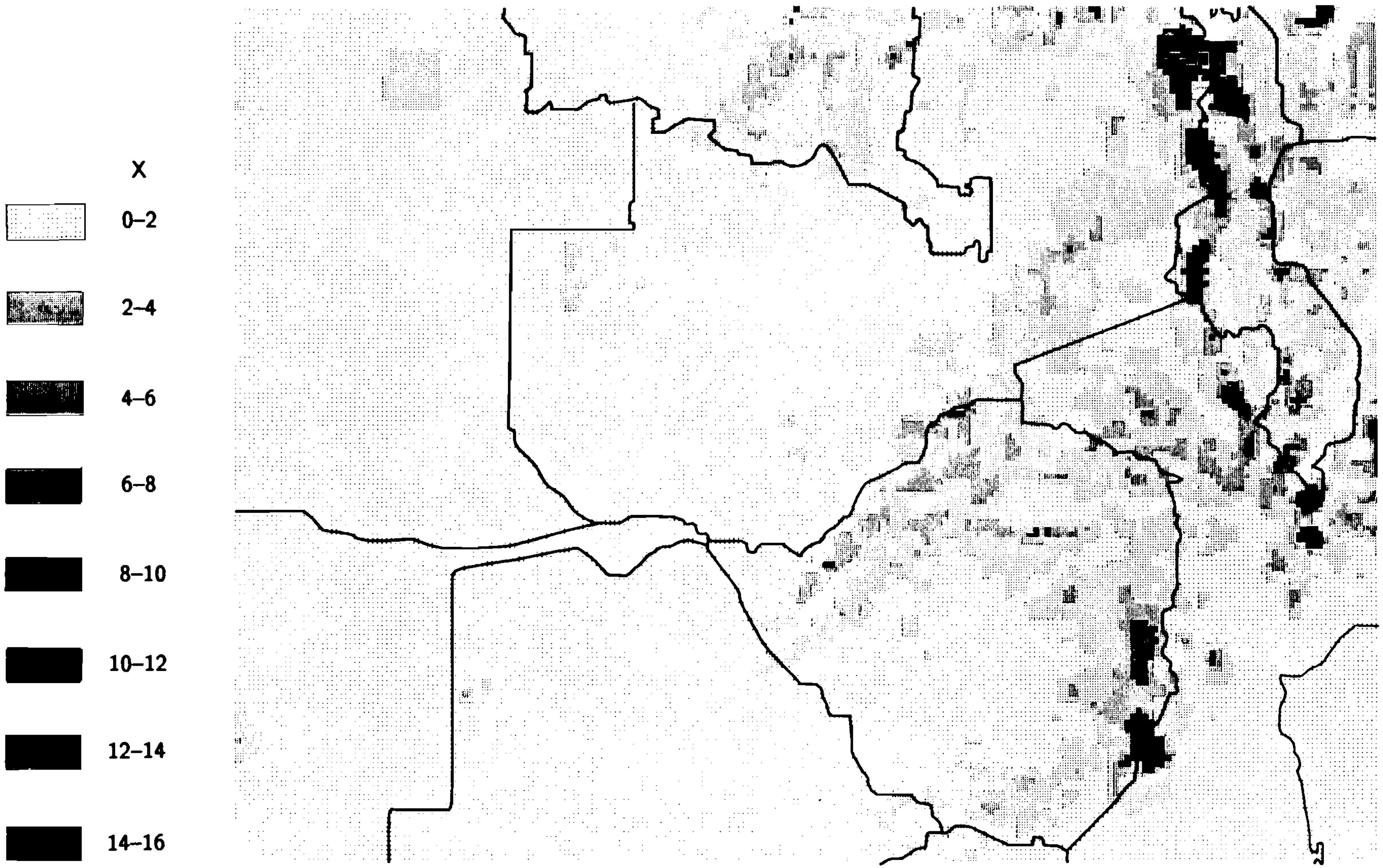

Figure 4. Topographic ratio in the Zambezi river basin.

Table 3: Percentage rainfall energy interception as a function of vegetation for the five land use scenarios.

Land use/ vegetation	% energy interception for scenario *)				
	I	II	III	IV	V
Forest	90	90	70	50	0
Woodland	70	70	50	30	0
Grassland	70	60/40	30/20	30/20	0
Cropland	-	36	20	20	0
Cropland/ Natural mosaic	-	43	23	23	0

*I. natural vegetation

II. well-yielding crops, moderate grazing pressure

III. poor-yielding crops, heavy grazing pressure, limited deforestation

IV. moderate-yielding crops, heavy grazing pressure, intensive deforestation

V. bare soil

In addition to changing the value of i for the different land use scenarios, the index of soil erodibility was modified in accordance with the estimate of soil erosion hazard in the previous scenario. If the land use scenarios are considered as subsequent phases in the change of vegetal cover due to the activities of man, then the rate of soil degradation in e.g. scenario IV depends on the soil erosion hazard in scenario III. Therefore, the index of soil erodibility in each scenario was changed in relation to the classified value of EHU in the previous scenario, as follows: erosion hazards of 2, 3, 4 and 5 in a previous scenario lead to a reduction of the value of F in the current scenario by 0.5, 1, 1.5 and 2 respectively. This modification procedure was adopted from Elwell (1978), who suggested to reduce the value of F by 0.5 for slight to moderate surface crusting or for soil losses of 10-20 t/ha in the previous year, and by 1 for detoriation in soil structure due to excessive soil loss in the previous year (> 20 t/ha) or for poor management.

5. RESULTS AND DISCUSSION

5.1. Erosion hazard under 'natural' vegetation cover

Figure 6a provides a soil erosion map of the Zambezi River basin for scenario I as computed by equation (4) and provides some idea about 'natural' soil erosion rates. The larger part of the basin falls in category I, i.e. a low erosion hazard. Namibia and Botswana are entirely covered by this category, whereas in the other countries locally higher erosion risks are predicted. In the flat areas of Angola and the western part of Zambia erosion hazards of 2 and 3 are found because of the high rainfall energy (see Figure 2) and the relatively high soil erodibility (see Figure 3). In the eastern part of Zambia and in Malawi, Zimbabwe and Mozambique, the rainfall energy is generally lower (see Figure 2) and the soil erodibility smaller (see Figure 3), but in these areas the topographic ratio is high due to the occurrence of steeper slopes (see Figure 4). As a result, the erosion hazard may locally fall in the categories 3, 4 and 5 (medium to high). Areas with a high erosion hazard always coincide with areas characterized by steep slopes and are mainly found in the Luangwe basin. In sum, when the catchment is covered by natural vegetation the erosion hazard is generally low, with exceptions for areas with poor soils in Angola and few small areas characterized by steep slopes in the eastern part of the catchment.

5.2. The impact of increasing land pressure

The erosion hazard maps for land use scenarios II to IV are shown in Figures 6b, 6c and 6d respectively. The map for scenario II, representing a situation with good crop cover and moderate grazing pressure, exhibits a generally higher erosion hazard as compared to the situation under natural vegetation, but the spatial distribution of susceptible areas is quite similar. In scenarios III and IV the land pressure is further increased (intensive cultivation and heavy grazing) and deforestation takes place in the evergreen forests and the woodland areas. The results of these activities are clearly shown in Figure 6c and 6d: large areas in west Angola, east Zambia, Malawi, Mozambique and Zimbabwe fall in erosion hazard categories 3 (medium), 4 and 5 (high). Moreover, it can now be seen that, contrary to the situation in scenarios I and II, the areas susceptible to soil erosion are no longer restricted to sloping areas or areas with highly erodible soils. For example: the grassland areas in west Zambia, the cropland areas south of the Luangwe valley (east of Chipata), in the Zambezi valley near its mouth and in central Zimbabwe all exhibit an erosion hazard in the range 3-5. In these areas, the increased erosion hazard is believed to be for the larger part the result of the increased land pressure. Namibia and Botswana

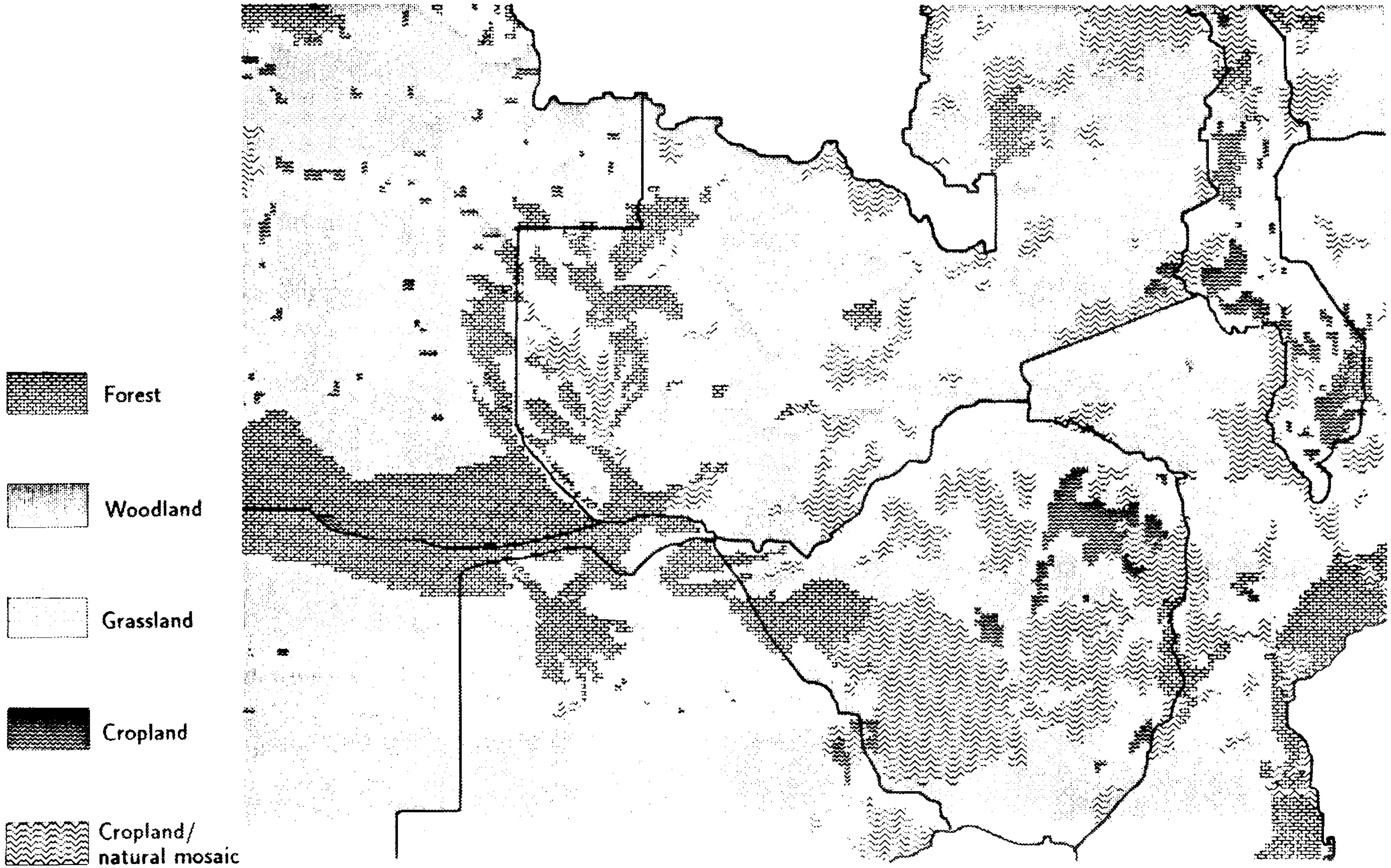

Figure 5. Distribution of natural vegetation and cultivated areas in the Zambezi river basin.

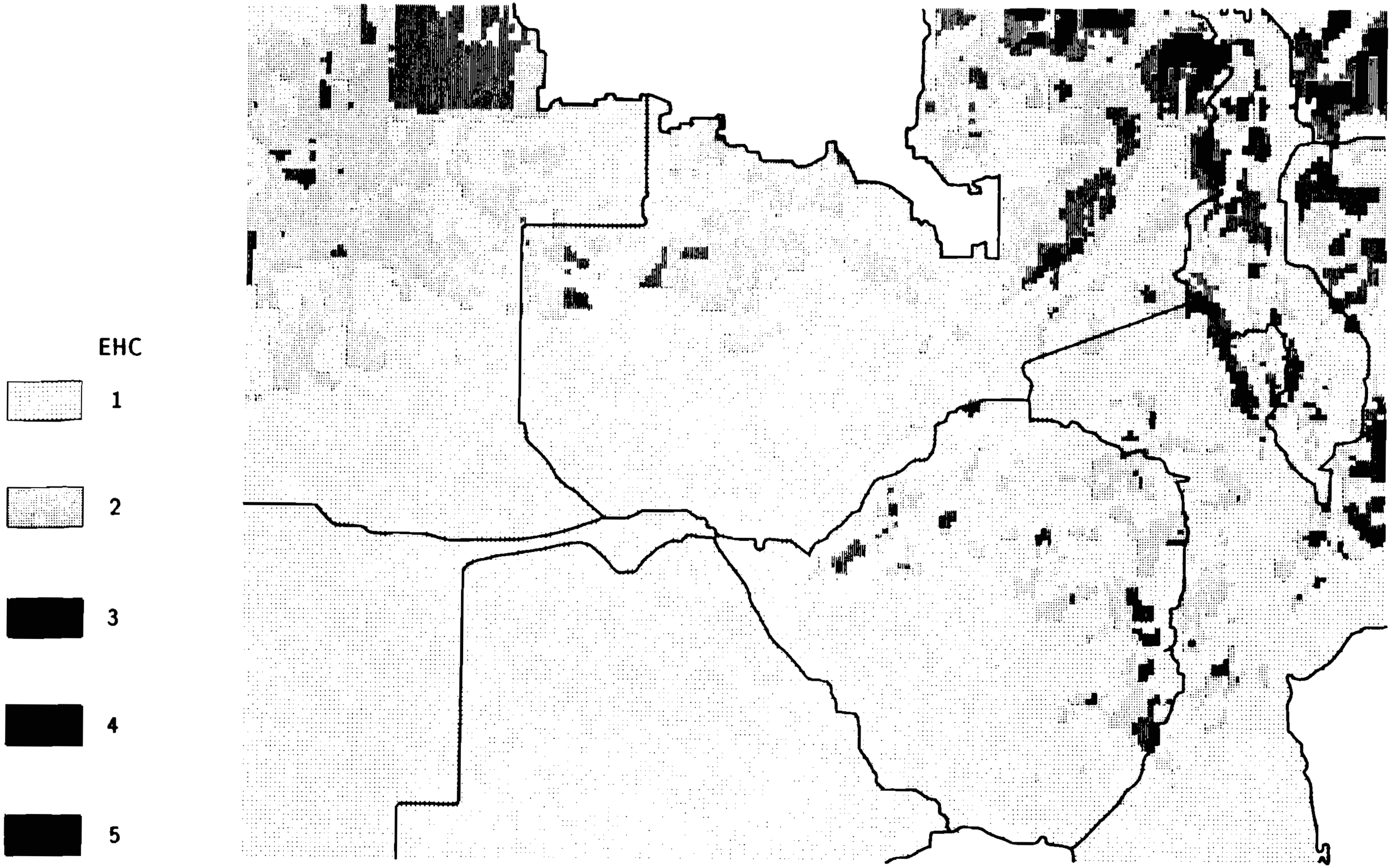

Figure 6a. Soil erosion hazard in the Zambezi river basin – natural vegetation.

remain unaffected by land use change due to the prevailing low rainfall energy, the lack of steep slopes, the generally low soil erodibility and the relatively low land pressure.

With respect to the hazard of reservoir siltation due to increased soil loss and sediment transport, notable differences can be observed between the upstream catchment areas of the two main reservoirs in the basin. As for Lake Cabora Bassa, the upstream catchment area of the Luangwe River is already characterized by the local occurrence of high erosion hazards in scenario I (natural vegetation) and the highly susceptible areas grow rapidly in size as the vegetation cover is further decreased (see Figures 6b-d). These estimates are confirmed by the reported excessive occurrence of soil erosion in the entire Luangwe basin due to high natural rates of erosion (Webster, 1959) and human activities (Albrecht, 1973). In the Kafue basin the situation is more favourable, with relatively small areas that have an erosion hazard of 2-3 in scenarios II and III and only locally a high erosion hazard in scenario IV. These results suggest that the Luangwe probably accounts for the larger part of the sedimentation in Lake Cabora Bassa, as was already noted by Bolton (1983).

The catchment area of Lake Kariba lies for the larger part in west Zambia and east Angola. In these areas the erosion hazard lies in classes 1 and 2 for land use scenarios I and II, indicating that natural rates of soil erosion are fairly low as compared to e.g. the Luangwe basin. When the land pressure is increased during scenarios III and IV, the erosion hazard in west Zambia remains relatively low, although it is locally high in the grassland areas. Then, areas with a high erosion hazard upstream of Lake Kariba are mainly found in Angola. However, even in scenario IV the larger part of the area drained by this part of the Zambezi River has a low erosion hazard. Given the latter and the large travelling distance from Angola to Lake Kariba it seems unlikely in the short term that land use changes followed by increased sediment transport will significantly decrease the large storage capacity of this reservoir.

5.3. The worst case scenario: bare soil

Scenario V (see Table 3) represents a situation where all vegetation is cleared and provides some idea about the potential erosion hazard in the Zambezi River basin. Figure 6e shows that almost the entire basin has a potentially high erosion hazard, i.e. erosion hazard class 5. In Zambia, where steep slopes are rare, the high rainfall energy and large soil erodibility are the main factors that govern the spatial distribution of soil erosion hazard. With an exception for the areas around Lake Bangwuelu and Lake Chiposya and a few small areas in the southwest, the entire country has a high erosion potential. Malawi

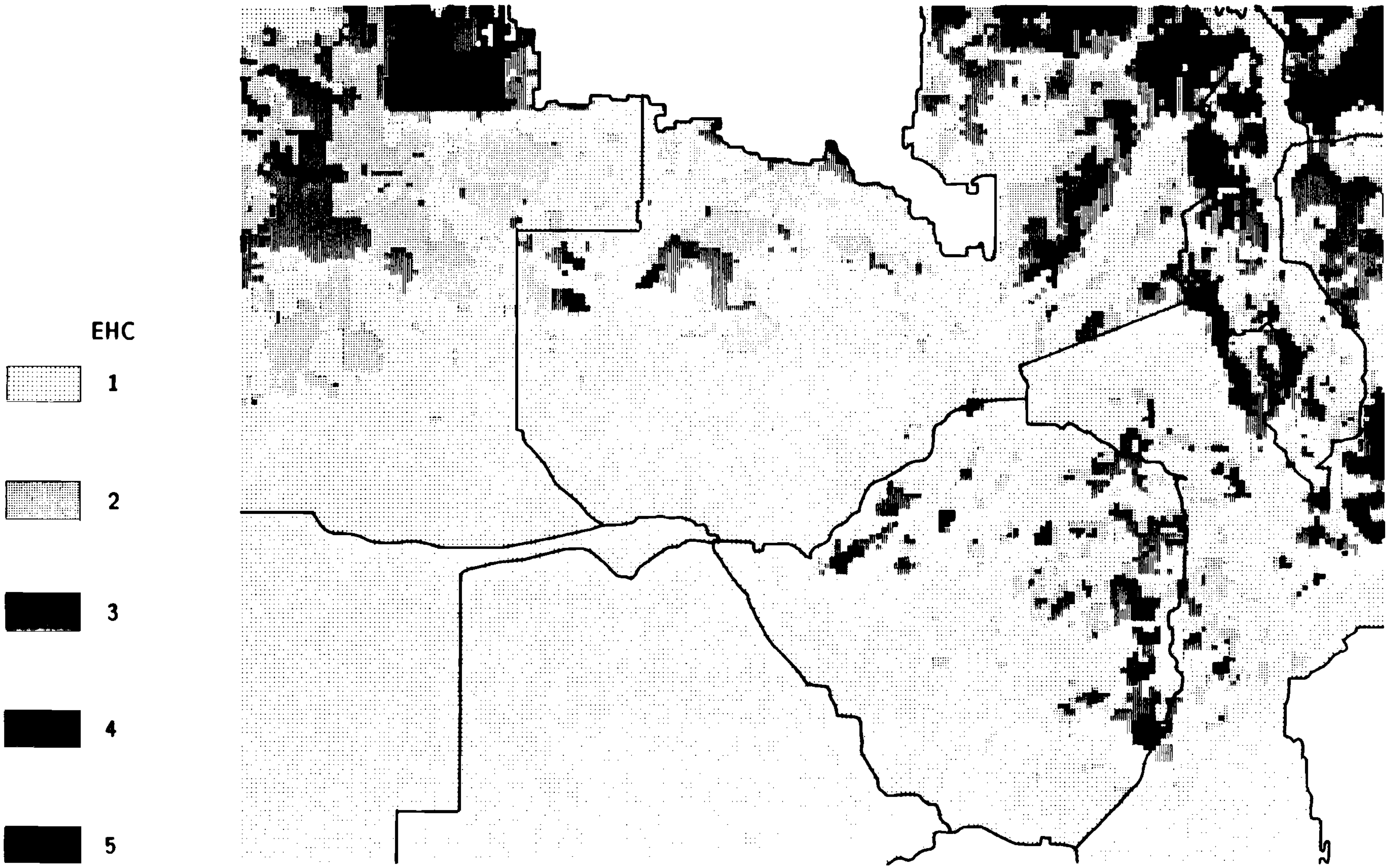

Figure 6b. Soil erosion hazard in the Zambezi river basin – limited cultivation and moderate grazing.

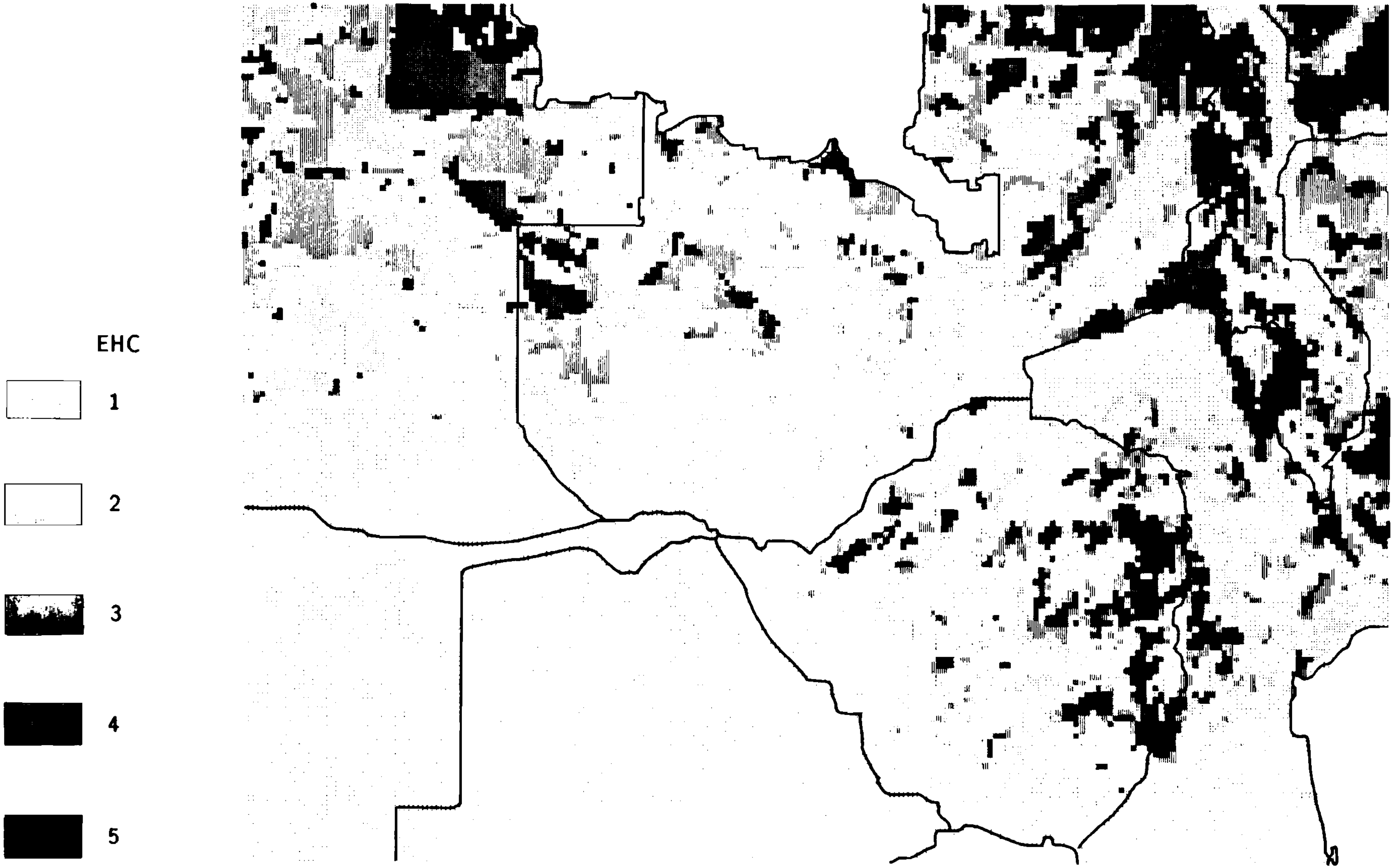

Figure 6c. Soil erosion hazard in the Zambezi river basin – intensive cultivation, heavy grazing pressure and limited deforestation.

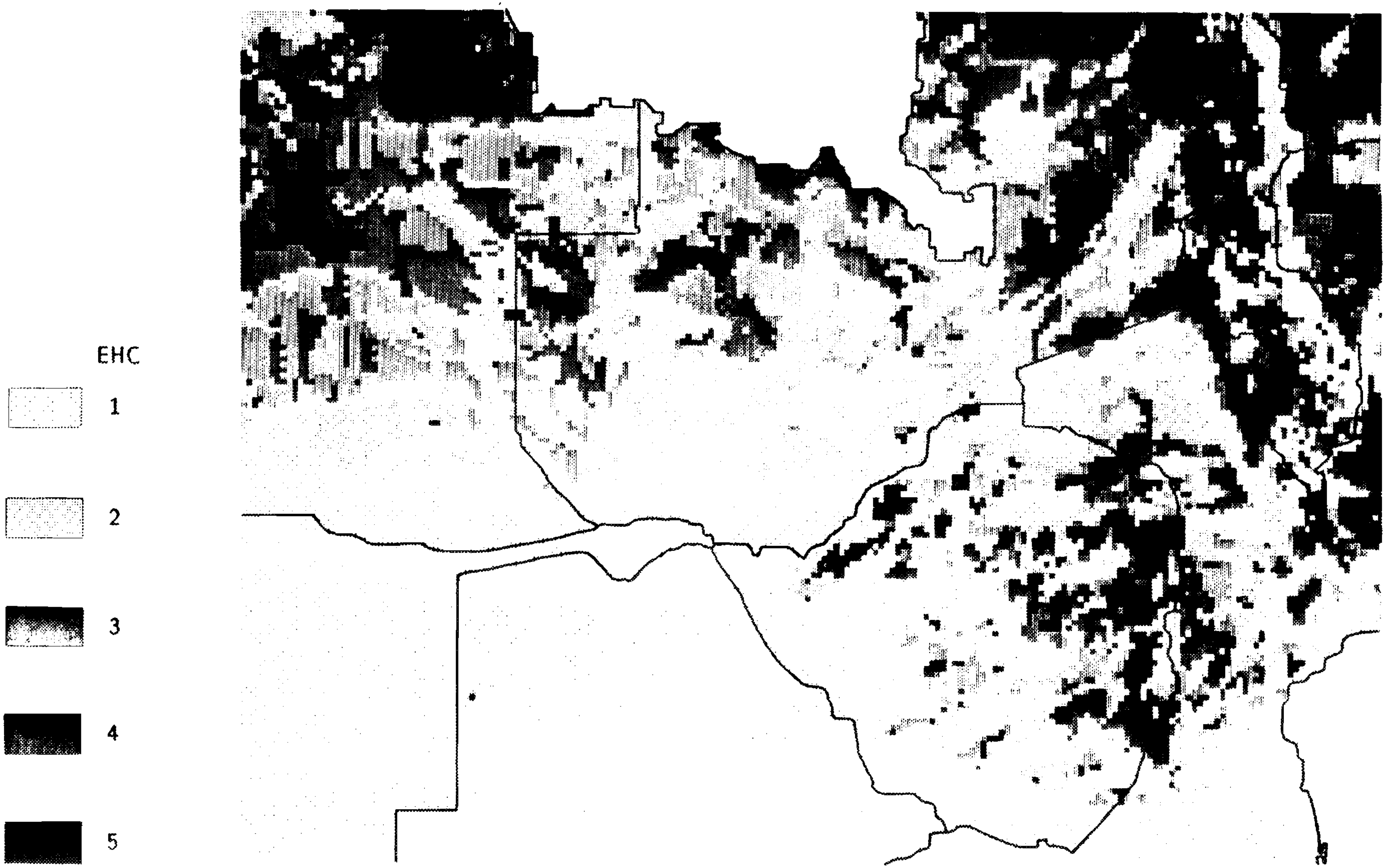

Figure 6d. Soil erosion hazard in the Zambezi river basin – intensive cultivation, heavy grazing pressure and intensive deforestation.

and Mozambique fall almost entirely in erosion hazard class 5. A combination of unfavourable conditions (high rainfall energy, high soil erodibility and steep slopes) prevails in the northern and eastern parts of Zimbabwe, causing a high soil erosion potential. Although Botswana and Namibia receive about the same amount of rainfall energy as Zimbabwe, the lack of steeper slopes explain why these countries have a much lower erosion potential.

Again it is clear that the area upstream of Lake Cabora Bassa is more likely to cause problems of sediment transport followed by reservoir sedimentation than the area upstream of Lake Kariba. A large area directly upstream of Livingstone has a low soil erosion potential and only in the area north of Mongu soil erosion problems are to be expected. In contrast, almost the entire area drained by the Luangwe and Kafue Rivers have a high soil erosion potential.

6. CONCLUSIONS

Estimated rates of soil erosion under a natural vegetation cover in the Zambezi River basin are generally low. Locally, exceptions are found due to high soil erodibility (Angola and Zambia) or very steep slopes (Malawi, Mozambique and Zimbabwe).

Three land use scenarios representing different rates of human land pressure were employed to delineate soil erosion hazard zones in the Zambezi River basin by running SLEMSA. Upstream of Lake Kariba high erosion hazards are mainly found in Angola and in a few scattered areas in Zambia. A large area directly upstream of the reservoir is characterized by a low soil erosion hazard and therefore no problems of sediment transport and reservoir siltation are to be expected in the short term. The Luangwe basin upstream of Lake Cabora Bassa is for a large part characterized by a high soil erosion hazard and may contribute to a very large extent to the sediment load of the Zambezi River as it flows into Lake Cabora Bassa.

By running a 'bare soil' scenario the erosion potential in the catchment was estimated. Zambia, Malawi and Mozambique all exhibit a high erosion potential, whereas the erosion potential in Namibia and Botswana is low. Although the larger part of Zimbabwe is located in a low rainfall-energy zone, the coincidence of steep slopes and large soil erodibility in the northern and eastern part of the country causes a high erosion potential in these areas.

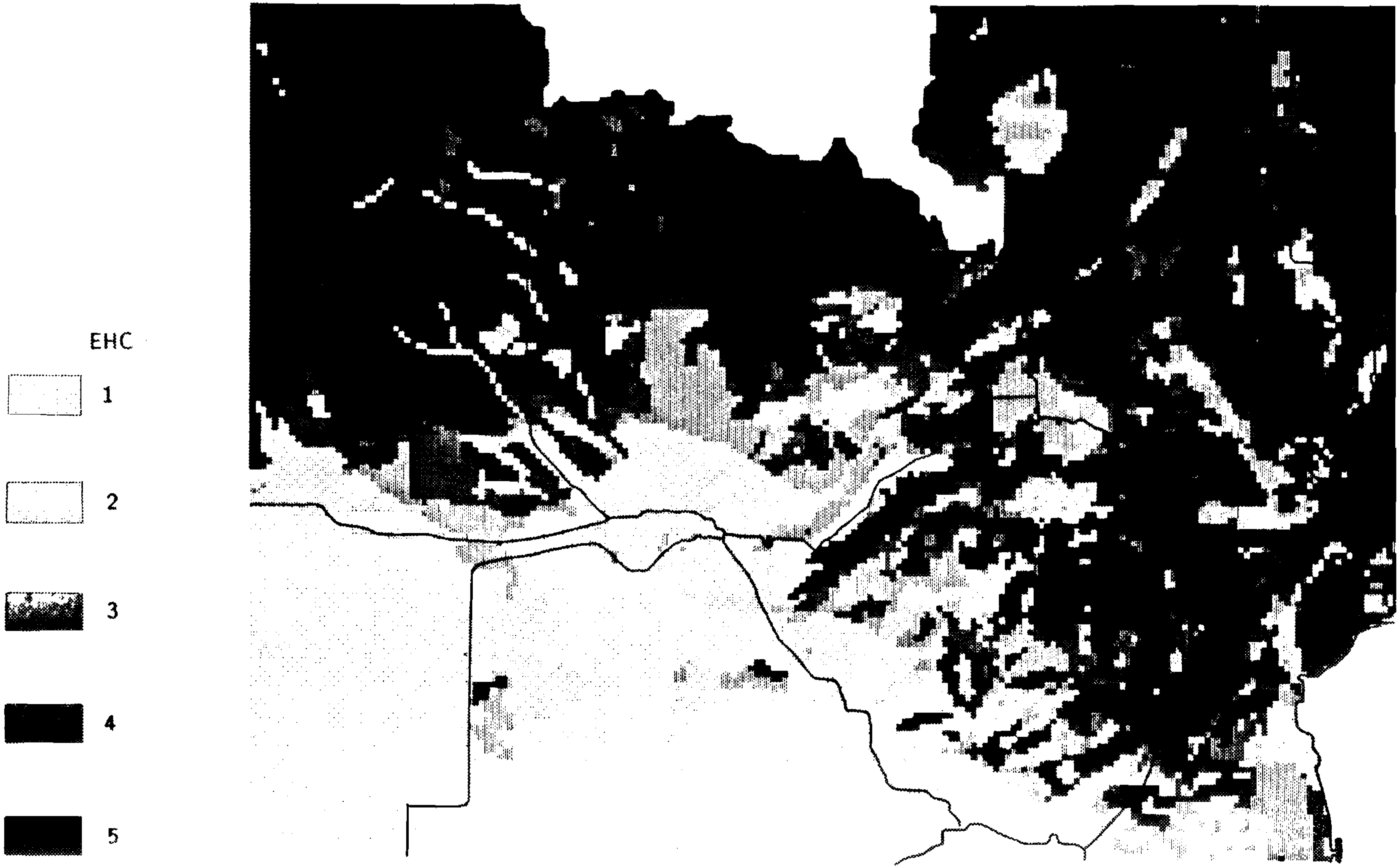

Figure 6e. Soil erosion hazard in the Zambezi river basin – bare soil.

7. RECOMMENDATIONS FOR FURTHER RESEARCH

The work presented in this paper is regarded as one step in the development of a flexible tool for assessing the environmental impact of land use changes on soil erosion and sediment transport. The benefits of this research can be greatly improved by linking the GIS-based erosion hazard model to: 1) the coupled Water Balance Model-Water Transport Model (WBM/WTM) that was constructed for the Amazone River (Vorosmarty et al., 1989) and is currently applied to the Zambezi River, and 2) the Simulation Model for Determination of Surface Runoff and Prediction of Erosion Processes (SMODERP) that operates at the field scale (Holy *et al.*, 1982). In addition to erosion hazard assessment possibilities, one would then have the tools to predict the impact of land use change on the discharge regime and the sediment routing in the Zambezi River basin. Furthermore, given a set of defined aims (such as maximizing food production, maximizing soil conservation or minimizing reservoir siltation) this scientific setup would provide the capability to find an optimal solution in terms of landuse (which areas should be used as cropland, which crops should be grown, what is the impact of different farming practices/ soil conservation measures ?, etc.)

The raster data have recently been transferred to a Unix-based minicomputer running the GRASS (Geographic Resource Analysis Support System) GiS software package. A CSO trainee is programming SLEMSA in the "C" language to create a GRASS – application that will allow flexible spatial selection through a mouse-driven user interface. After selecting an area within the basin, the user may define its own land use scenario and rerun SLEMSA. The graphical facilities of GRASS will help to examine the results on the screen or to generate hardcopy output.

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