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Soil erosion in the Upper Ouémé Catchment (Benin) considering land use and climate change – a modelling approach

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Abstract

Soil degradation is a severe problem in Africa. The resulting decline of crop yields threatens food security and forces poverty, migration and land use conflicts. Therefore effective measures against soil degradation are crucial for the achievement of the UN Millennium goals. Prior intervention areas with especially high risks should be identified.
In this study, which is part of the German integrated water resource management project IMPETUS, soil erosion by water has been studied in the Upper Ouémé catchment (15.000 km^2) in sub-humid Northern Benin. Field studies in 2001/02, performed by Junge (2004), revealed that soil loss rates on agricultural fields were 10 times higher on fields than on savannah land. Cotton and yam fields were the main contributors. The quantification of soil erosion at the regional scale for longer periods requires a modelling approach. Therefore, the semi-distributed continuous erosion model SWAT (Soil Water Assessment Tool) has been chosen. For the years 1998 to 2004 the model was successfully calibrated and validated against daily measurements of discharge at various outlets in the catchment. Subsequently, the model was applied for different scenarios of climate and land use change until 2025 using spatially distributed results from the regional climate model REMO and the land use/land cover change model CLUE-S, produced by other IMPETUS members. Land use changes lead to a strong increase in soil erosion rates, whereas lower mean precipitation reduces water and sediment yield in most parts of the catchment. Regions with actual and future high erosion risk were identified. In future, recommendations for a sustainable soil management will be given considering field observations and farmer interviews.

Introduction

One of the main questions of the 21st century is the topic food security. According to Lal (2000) in 2010 one third of the population in sub-saharan Africa could be malnourished if there is no significant increase in productivity. However, crop productivity is severely threatened by soil degradation. Soil erosion contributes one fourth to the productivity loss in Africa (Oldemann, 1998). Despite the flat relief in Benin soil erosion is a considerable problem caused by high precipitation intensities and unsustainable cultivation methods. The effects of soil erosion cannot be neglected because soil depths are often low and farmers can rarely afford fertilizers to compensate fertility decline due to topsoil loss. To improve the effectiveness of soil management measures prior intervention areas with current and future high risks of soil degradation need to be identified.
This study is embedded in the IMPETUS framework, an integrated water resource management project funded mainly by the German Ministry of Research and Education (Speth et al., 2005).

The project design covers three 3-year periods with a focus on process understanding (2000-2003), modelling and scenario analysis (2003-2006) and the development of decision support systems (2006-2009). The research areas of the project are the Ouémé catchment in Benin and the Wadi Draa in Morocco.

Research Area

Figure 1: The Upper Ouémé catchment in Benin

The Upper Ouémé catchment (14.325km^2) is situated in Northern Benin (Figure 1). The research area is part of the sub-humid climate zone with one rainy season between May and October. The annual means for rainfall and total discharge are 1100 mm and 150 mm, respectively. The vegetation is dominated by wet savannah types, which are severely degraded in the north-western part of the catchment. Farmers depend mostly on subsistence farming based on crops like yam, cassava and maize, besides cotton and cashew as cash crops. The catchment can be characterized as an undulating pediplain relief overlying a pre-cambrian crystalline basement. Fersialitic and ferralitic soils are dominant and have often gravelly or plinthic horizons. The agricultural area is rapidly expanding due to population growth, migration and an improved accessibility.

Methodology

Former field studies in the first phase of the project showed that the amount of soil erosion depends significantly on the land use system and the rainfall intensity. Soil loss rates on agricultural land were 10 times higher than on savannah land, with a maximum on cotton and yam fields. The quantification of soil erosion at the regional scale until 2025 requires a modelling approach. The free available, time continuous, semi-distributed SWAT model (soil water assessment tool, www.brc.tamus.edu/swat) was chosen due to its capability to simulate large catchments with a manageable demand of input parameters. For African conditions a comparatively well database was available from previous IMPETUS work and counterparts in Benin. Own field studies were required to obtain soil properties for the application of the French soil map (Faure 1977) and time-continuous suspended sediment concentrations at four river outlets. Hydrological model calibration and

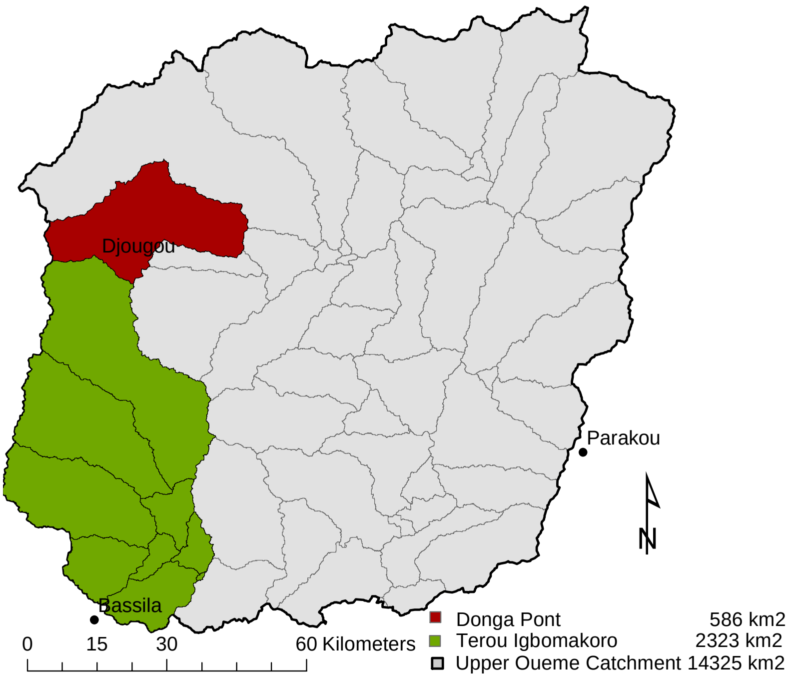


Figure 2: Subcatchments Donga Pont and Terou-Igbomakoro

validation were performed for the years 1998-2004 using daily discharge data provided by IRD and Diréction General de l'Hydraulique (Benin). Calibration was conducted simultaneously at two outlets: the Terou Igbomakoro catchment (agricultural land about 10%) and the intensively agriculturally used Donga Pont catchment (agricultural land about 37%) (cf. Figure 2). Subsequently, the model was applied to compute scenarios of climate and land use change until 2025 using spatially distributed results from other IMPETUS members. As input for the land use scenario land use maps were generated for each year between 2000 and 2025 in a 250 m resolution by the land use/land cover change model CLUE-S (Thamm et al., 2006). This model considered several driving forces like population density, topography and distance from roads and rivers. In order to reduce the error in the representation of farmland due to the coarse resolution of the land use map a simple disaggregation algorithm was applied: The 250 m-grid cells were disaggregated into 25 m cells according to the mean fractions of land use types represented in a 250 m – grid cell of the original, not aggregated land use map derived from a satellite image of the year 2000. The input parameters for the climate scenarios were provided by the regional climate model REMO (Paeth 2004) driven by the IPCC SRES scenarios A1B and B1. For a correct representation of daily rainfall in the SWAT model, including the frequency distribution of site-specific events and the magnitude of extreme events, daily REMO output in a 0.5° grid resolution was attributed to the rain gauge sites considering the rainfall distributions of the rain gauges.

Results

<u>a) Model calibration and validation</u>

Model calibration was successfully performed for the period 1998 to 2001 at two subcatchment outlets. Weekly model efficiencies of 0.73 and 0.81 were obtained for the Terou-Igbomakoro

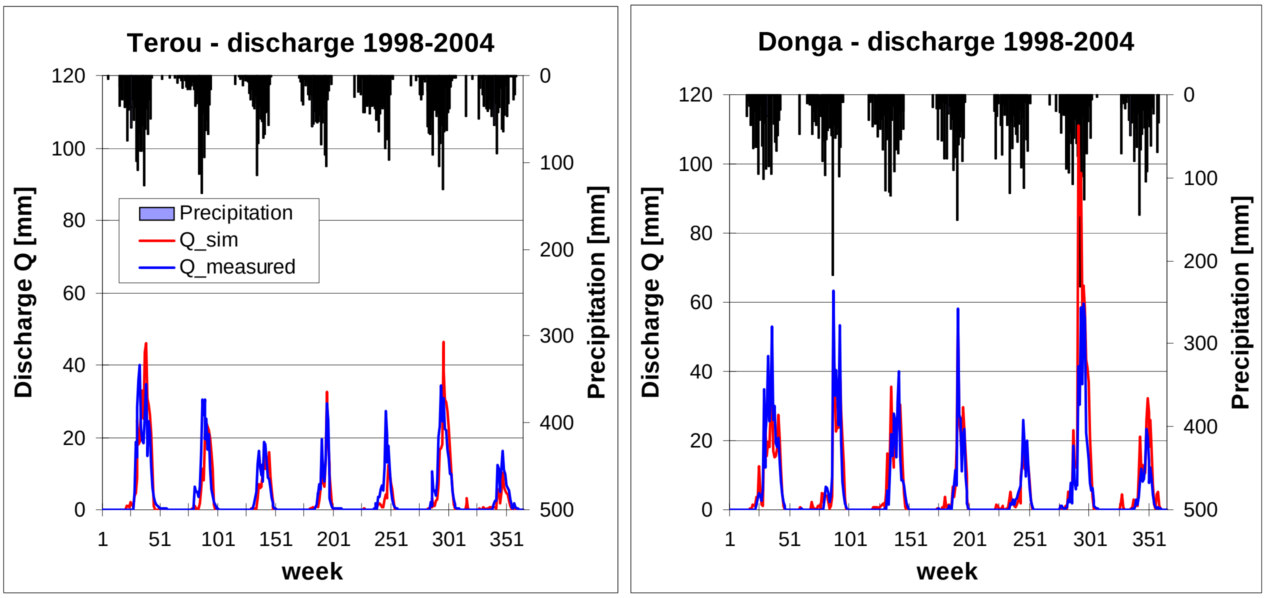


Figure 3: Measured (blue) and simulated (red) discharge curve for the calibration (1998-2001) and the validation period (2002-2004) for the Terou-Igbomakoro and the Donga Pont subcatchments

and the Donga Pont outlets, respectively. During the validation period (2002-2004) model efficiencies were still satisfactory (0.64 and 0.72). In general, the discharge dynamics were well represented in both subcatchments (Figure 3). However, some difficulties in capturing extreme events were observed. The fractions of slow and fast discharge components were correctly simulated.

As expected, absolute and relative surface runoff amounts were much higher in the Donga Pont catchment than in the Terou catchment, due to higher land use intensity, higher rainfall amounts as well as intensities. Mean annual sediment yields for all subcatchments ranged from 0.1 to 4 tons per hectare for the 55 subcatchments. Highest values were obtained around the cities (Parakou and Djougou) and along the roads. The mean annual sediment yield of 2.31 t/ha/yr in the Donga Pont catchment was more than four times higher than for the Terou-Igbomakoro catchment. About 78% of the total sediment load was contributed by cropland, followed by brush savannah with about 17%. The average sediment yield on cropland was 5 t/ha/yr (Figure 4). As a comparison with the measured sediment data has not yet been performed the absolute values for the sediment yield should be considered as preliminary.

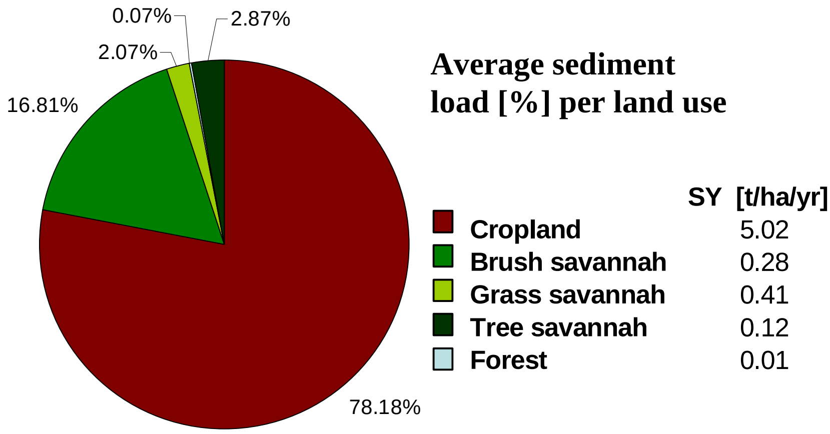
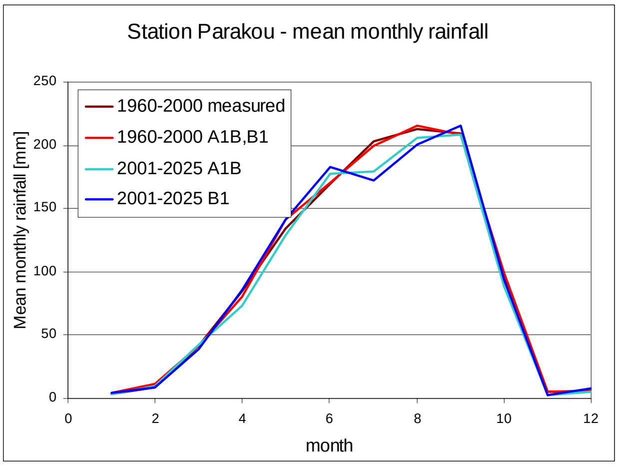


Figure 4: Average annual sediment load per land use in % and in t/ha/year

b) Climate scenarios

After post-processing the REMO rainfall, the mean simulated monthly rainfall amounts represent quite well the measured values for the period 1960 to 2000. Mean simulated rainfalls and temperatures between the globally economy-orientated scenario A1B and the global sustainability-orientated scenario B1 did not differ much for the period 2001 to 2025. Compared to the period 1960-2000 mean annual rainfall amounts are slightly lower with higher monthly values at the beginning und lower monthly values in the middle of the rainy season. The comparison was performed for three stations including the station Parakou (Figure 5). Also the distribution of daily rainfall was well represented. For the Parakou station low intensity rainfalls



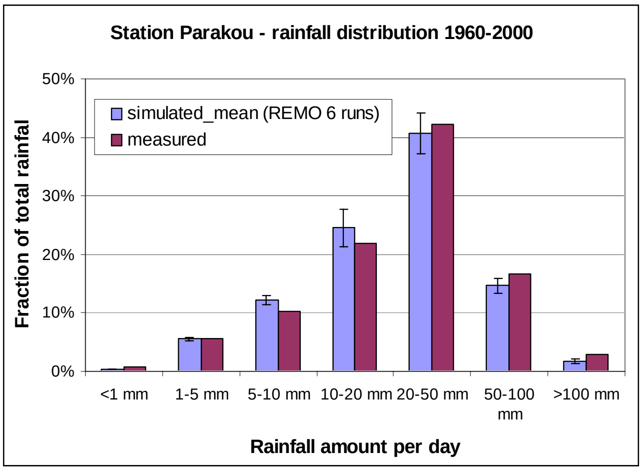


Figure 5: Parakou station –comparison of measured and simulated rainfall data for the period 1960 to 2000

(1-20mm) were slightly overestimated, high intensity rainfalls (20-200mm) slightly underestimated (Figure 5). Calculated values for potential evapotranspiration (ET_{pot}) from REMO climate data for the period 1979-1997 were in the range of values obtained using measured climate data. For the period 2001-2025 annual ET_{pot} values increased by 200-300 mm due to the temperature increase, in particular for scenario A1B.

Table 1 provides an overview of the results of the climate scenarios. The results of each scenario are based on three model runs referring to the three ensemble runs from the climate model REMO. Besides the whole catchment, the table shows also the results for the two previously mentioned subcatchments to point out the regional variation. The reduced mean rainfall amounts for scenario A1B led to a decrease of mean water and sediment yield in the Upper Ouémé and the Donga Pont catchment for all three runs (variation +/- 5%). For the B1 scenario, with a slightly lower reduction of rainfall, effects are not so clear. The variations of the simulated mean water and sediment yield between the three runs are higher (+/- 13%) and indicate positive and negative trends compared to the period 1998-2004. The mean of the three runs showed an increase of water and sediment yield despite the reduced mean rainfall. This effect may be attributed to the changed rainfall pattern with higher rainfall at the beginning of the rainy season where vegetation cover is still low. For all six runs mean rainfall, sediment and water yield increased in the Terou Igbomakoro subcatchment. Looking at the spatial maps, which are not presented here, it becomes obvious that the spatial pattern of sediment yield in the catchment remained quite similar. However, a few subbasins experienced a pronounced decrease (Donga region) or increase (north-eastern edge of the catchment, only for B1 scenario) of sediment yield.

Table 1: Simulated mean annual values of rainfall, sediment yield (SY) and water yield (WY) for the climate scenarios A1B and B1, change in % from the baseline scenario (1998-2004)

	1998-2004			2000-2025 A1B, 3 runs			2000-2025 B1, 3 runs		
	rainfall [mm]	WY [mm]	SY [t/ha/yr]	rainfall	WY	SY	rainfall	WY	SY
HVO	1183	207	0.89	-4%	-9%	-9%	-3%	8%	12%
Donga	1281	268	2.31	-8%	-11%	-32%	-4%	3%	-21%
Terou	1127	189	0.52	5%	14%	17%	9%	28%	31%

c) Land use scenarios

The implementation of a completely different land use map into the SWAT model requires a new HRU delineation and consequently also a re-adjustment of all calibration parameters. Therefore it is not feasible to directly implement all land use maps for the years 2000 to 2025 for the business as usual scenario. In a first approach the model has been run for the period 1998-2004 with the land use map for 2025. The results were then compared to the baseline scenario with the aggregated land use map for 2000.

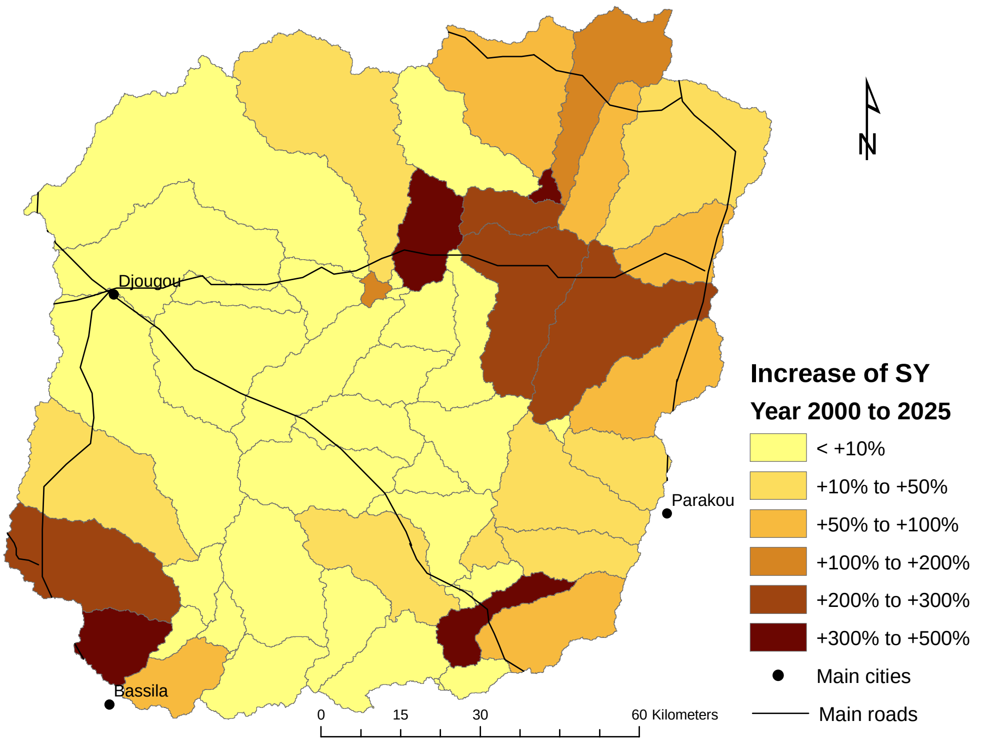


Figure 6: Land use scenario “Business as usual” - Relative increase of sediment yield per subcatchment; comparison of model runs (1998-2004) with land use maps 2000 and 2025

Figure 6 illustrates the calculated relative change of the sediment yield. It can be seen that the highest relative increase took place in the south-western and north-eastern western part of the catchment were land resources are still abundant. In the most degraded region of the catchment around Djougou sediment yield remains almost constant because agricultural expansion was not further possible. Highest absolute changes occurred in the eastern part of the catchment around Parakou. Overall, for the whole Upper Ouémé catchment the increase of 50% of cropland area led to a mean increase of 10% in surface runoff and 25% in sediment yield.

Conclusions and Outlook

This study has shown that the SWAT model is applicable to a sub-humid catchment and delivers reasonable results for current and future time periods. Current hotspots of soil erosion were identified in the north-western and south-eastern part of the catchment. Land use change caused higher surface runoff and sediment yield, especially around Parakou. For the climate scenario A1B lower rainfall, in particular in the period 2015-2025, resulted in decreased water and sediment yield. For the climate scenario B1 effects were not following a clear trend. Two runs of the scenario B1 led to a new hotspot of soil erosion in the north-eastern part of the catchment. As a next step combined climate and land use change scenarios will be calculated. From the separate scenarios and previous results from Busche (2005) and Sintondji (2005) it is expected that land use change will have a much stronger impact on the sediment yield than climate change.
In future, the underlying SWAT modelling will be improved by sediment calibration, automatic calibration and uncertainty analysis. Further land use scenarios until 2025 and extended climate scenarios until 2050 will be calculated. The SWAT results will be integrated in the EPIC model to study the effect of soil erosion on crop yield. Furthermore, agrarian management scenarios could be performed with the SWAT model. Modelling results will be visualized in a decision support system (DSS) for various stakeholders in Benin.

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