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Applying the SWAT Model as a Decision Support Tool for Land Use Concepts in Peripheral Regions in Germany

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ABSTRACT

In the Lahn-Dill- Bergland in the hilly midlands of Hesse, Germany, agriculture is retreating from landscape due to employment alternatives in various branches of industry and marginal conditions for agricultural production. Thus, the amount of fallow land is increasing. To stop this development a collaborative research project (SFB 299) with 19 departments involved was established at Giessen University in 1997 to develop new concepts of land use and assess their economic and ecological impact. The economic model ProLand (Möller et al., 1999A) is optimizing land use by maximizing agricultural income. It proposes spatially distributed land use options which are evaluated in terms of ecology with ELLA (Weber et al., 1999a) and with regard to hydrological changes with the SWAT model (Arnold et al., 1993, 1998). All three models are GIS-based and exchange data via GIS.

The continuous-time, grid cell watershed model SWAT (Arnold et al., 1993; 1998) was tested and adapted to typical conditions in the project region. The Dietzhölze (81.8 km²) and the Aar watershed (59.8 km²) were used to calibrate and validate the model. All relational databases which are implemented into SWAT (Arnold et al., 1993; 1998) e.g. for weather, soil, tillage, and crops were substituted by regional data sets.

Two different land use scenarios were proposed by ProLand (Möller et al., 1999A) for the Aar watershed and the SWAT model was applied to evaluate the effect of these land use changes on the water balance. An output interface was developed to produce spatially distributed maps of water balance components.

INTRODUCTION

In 1997, the joint research center "SFB 299: Land use concepts for peripheral regions" was established at the Giessen University at the faculty of agriculture. Its main objective is the development of sustainable land use concepts and their evaluation with regard to the effect on ecological and economic landscape functions. Due to the complexity and the enormous variety of landscape functions, a multidisciplinary approach is indispensable. The methodology, which should be transferable to other regions and valid for various scales, is developed in the "Lahn-Dill-Bergland" as a first test region. This region is characterized by its peripheral features. Agriculture is retreating from this area due to marginal natural production conditions, such as shallow, poor soils and steep slopes, and good job alternatives in other sectors of the economy. Thus, the percentage of fallow land is increasing and some landscape functions are endangered, like gaining agricultural income, habitat properties for certain species, and a sufficient quantity of groundwater recharge.

One group of the SFB 299 analyzes the prevailing biotic and abiotic site conditions and provides input information, for instance soil and vegetation data or socio-economic boundary conditions, for the group responsible for modeling. An integrated system of three GIS-linked, raster-based models (Fohrer et al., 1999A; Weber et al., 1999B, Möller et al., 1999b) is used to develop and evaluate land use scenarios in terms of ecology, hydrology, and economy. The economic model ProLand (Möller et al., 1999a) has two main tasks. It provides economic key indicators like agricultural income or labor input. On the other hand it is able to predict spatially distributed land use changes, resulting from a particular framework of natural, economic and political characteristics and is therefore used to generate land use scenarios, which serve as input maps for the other two models. The ecological model ELLA (Weber et al., 1999A) is a cellular automaton, which is investigating the distribution of key species due to land use changes based on habitat preferences. It is providing information on biodiversity as a function of land use patterns. Finally the hydrological model SWAT (Arnold et al., 1993; 1998) is employed to observe the behavior of water balance components for different land use concepts provided by ProLand (Möller et al., 1999A). Every land use scenario is evaluated by all three models. Ecological, hydrological and economic indicators are provided to a decision making group, which consists of scientists (SFB 299), land owners, politicians and citizens of the project region. In a round table discussion, competing aims are weighted and compared with the model outputs for different concepts. If the results are not satisfactory, a new set of socio-economic measures (subsidies, support programs) is proposed to ProLand and new scenarios are developed and evaluated.

APPLICATION OF THE SWAT MODEL FOR DECISION SUPPORT

The SWAT model (Arnold et al., 1993; 1998) was applied in two test watersheds in the Lahn- Dill- Bergland, which is situated north of Giessen, in the state of Hesse, Germany. The Aar catchment (59.8 km²) and the Dietzhölze (81.8 km²) were used to calibrate and validate the model for the utilization under the specific conditions of the region.

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Then two ProLand scenarios for the Aar catchment were evaluated in terms of water balance effects due to land use changes.

Description of the study area and model setup

SWAT (Arnold et al., 1993; 1998) is a spatially distributed, physically based hydrological model, which can operate on a daily time step as well as in annual steps for long-term simulations up to 100 years. Three different types of input data are required. Spatially distributed information is necessary for elevation, soil, and land use data. Relational databases such as soil, weather and crop data are provided for the use within the US. An input interface (SWATGRASS, Srinivasan and Arnold, 1994) links these data bases with the spatially distributed raster maps, which are stored in the GIS system GRASS (U.S. Army, 1988). Optionally time series of rainfall and temperature data are needed for each model run. They can be generated also by the implemented weather generator. For validation purposes the catchment should be gauged.

For the use in the SFB 299 the SWAT model was modified and the SWATGRASS interface (Srinivasan and Arnold, 1994) was adapted to the regional data bases formats. All US databases where substituted by regional data sets (Fohrer et al., 1999b). A management database for typical regional cropping systems was also implemented into the model.

Spatial information for the model runs was provided in a 25 m by 25 m grid. Actual land use information was derived from Landsat TM5 satellite images for the years 1987 and 1994. In the Dietzhölze catchment, peripheral features are more pronounced than in the Aar catchment (Fig. 1).

More than 58% of the Dietzhölze catchment are covered by forest and 36% are grassland. Cropland exists only on 0.2% of the area. The Aar catchment is also characterized by a high percentage of forest (42%), but 25% of the area is still under tillage. The grassland portion is 20%. For both catchments, a digital elevation model in a 40m*40m grid was obtained by the German Land Survey. The software package TOPAZ (Version 1.2, Gabrecht u. Martz, 1998) was used to delineate sub-basins for the spatial aggregation. The concept of virtual sub-basins was employed, as recommended by Mamillapalli et al. (1996), to increase the level of discretization. The virtual sub-basins were derived with the SWATGRASS interface (Srinivasan and Arnold, 1994). In total, the Dietzhölze watershed was subdivided into 58 sub-basins and 256 virtual sub-basins and the Aar into 21 sub-basins and 125 virtual sub-basins, respectively. The soil information was based on the soil map of Hesse 1:50.000 (Hessisches Landesamt für Bodenforschung, 1998). Measured daily rainfall and temperature data were obtained by the German Weather service. For the Dietzhölze four rainfall stations in and around the catchment were available, while for the Aar there were two rainfall gages within the watershed. For each catchment, one climate station was employed. For flow calibration and validation the stream gauges Dillenburg II (Dietzhölze) and Bischoffen (Aar) were used. For the Dietzhölze stream flow data were available for the hydrological years 1985-1995, for the Aar 1979-1987, respectively.

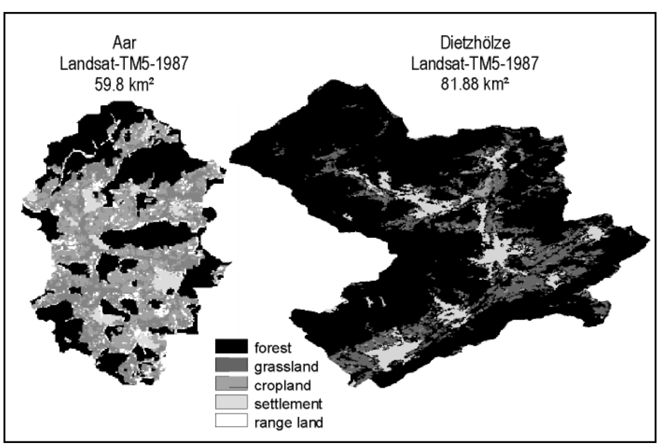

Figure 1. Actual land use for the Aar (1987) and the Dietzhölze (1994) catchments derived from satellite images.

Calibration and validation of the model

The Aar catchment. Figure 2 shows the time series of observed and simulated monthly stream flow for the Aar catchment during the period of 1983-1987. For calibration the hydrological years 1986/87 were analyzed in a daily resolution.

A base flow separation (Arnold et al., 1995) was carried out to gain more information for calibration purposes. The input variables used for calibration were soil properties and curve number. The curve number (USDA Soil Conservation Service, 1972) was allowed to vary within the range of the categories for good and fair hydrologic conditions. The available water capacity was set within the range of its natural uncertainty for the study region. Statistical results for the comparison of measured and predicted stream flow can be found in Table 1. The correlation coefficient for observed vs. predicted monthly stream flow is 0.92. The model efficiency (Nash and Sutcliffe, 1970) is 0.74. For model validation in the period of 1983-1985, the correlation coefficient is 0.85 and the Nash Sutcliffe index 0.53, respectively. In general, the model is able to predict the temporal dynamics of total stream flow rather well (Fig.

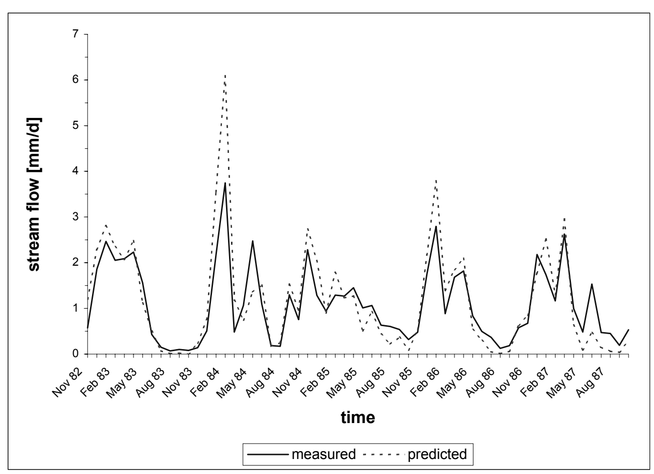

Figure 2. Time series of observed and simulated monthly stream flow for the Aar catchment, gauge Bischoffen, 11/1982-10/1987.

Table 1. Statistical parameters from observed vs. predicted monthly stream flow for the Aar and the Dietzhölze catchment.

	Aar monthly stream flow 1983 –1987 mm d^{-1}	Dietzhölze monthly stream flow 1991 –1994 mm d^{-1}
MEAN	1.17	1.24
standard deviation	1.17	1.36
correlation coefficient r	0.92	0.71
Nash Sutcliff index	0.74	0.79

2).In the summer season it tends to underestimate the measured values, although it has to be taken into account, that the river system is additionally fed through sewage treatment plants. The total amount of these point sources can reach up to 30 % of the total stream flow during the summer months.

The Dietzhölze watershed

The statistical results for the Dietzhölze are also presented in Table 2. The Dietzhölze was given as an example for the transferability of the SWAT model to other regional catchments without further calibration. The model was run in a monthly time step for the hydrological years 1991-1994. The model efficiency for the uncalibrated run was rather high (0.79), but the correlation coefficient was only 0.71. Thus the model predicted the general stream flow trend in a reasonable way, but was less accurate for single peaks. A higher temporal resolution (daily time step) is not feasible without careful calibration and application to land use change studies seems not advisable without calibration.

Land use scenarios provided by ProLand

Two different land use scenarios were proposed by ProLand (Möller et al., 1999) for the Aar watershed (Fig. 3). In the first case (Grassland bonus), a bonus for extensive grassland of 300 DM ha^{-1} was introduced. This is a typical socio-political measure for keeping landscapes open, preventing a stepwise development of shrubs followed by forest. In consequence, the percentage of forest decreased from 42 to 13% of the total area, while grassland now dominates the land use with more than 40%. Cropland is found on 32% of the area.

In the second case (without animal husbandry), the income situation is assumed to improve for jobs outside the agricultural sector. Therefore the opportunity costs for labor increase. Thus all labor intensive branches of farming like most forms of animal husbandry are not favorable any more. Grassland is no longer exploitable as a source of agricultural income and disappears completely from the catchment (Fig. 3). Wherever soil, climate and relief condition allow cropping systems, pasture is transformed into tilled fields (36% of the area). Forested areas expand to nearly 50% of the land use.

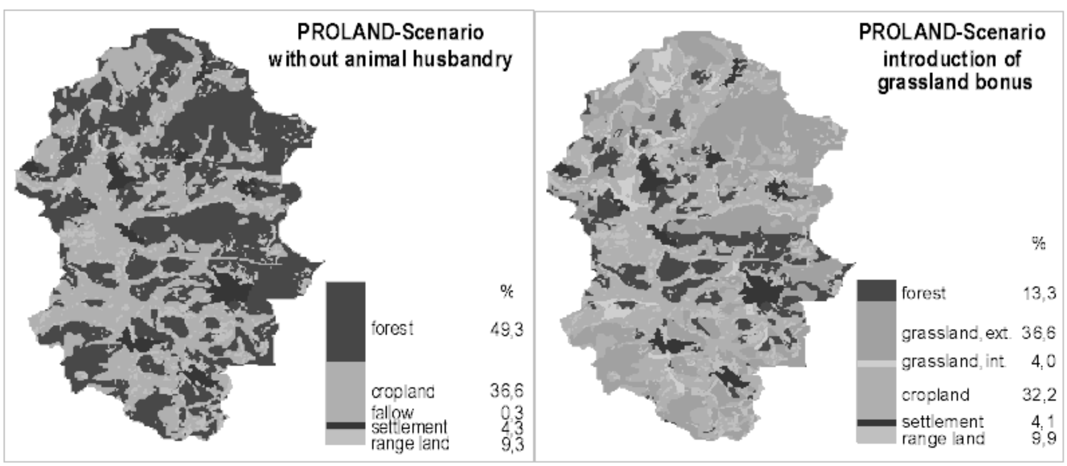

Figure 3. Land use scenarios for the Aar catchment provided by the economic model ProLand.

Table 2: Effect of land use changes on water balance components in the Aar catchment.

Parameter	Units	Actual land use 1987	Scenarios: Grassland bonus	Scenarios: Without animals
Precipitation	mm/a	875	875	875
Stream flow	mm/a	426	463	436
Actual evaporation	mm/a	436	412	433
Surface runoff	mm/a	115	140	126
Percolation	mm/a	312	322	310

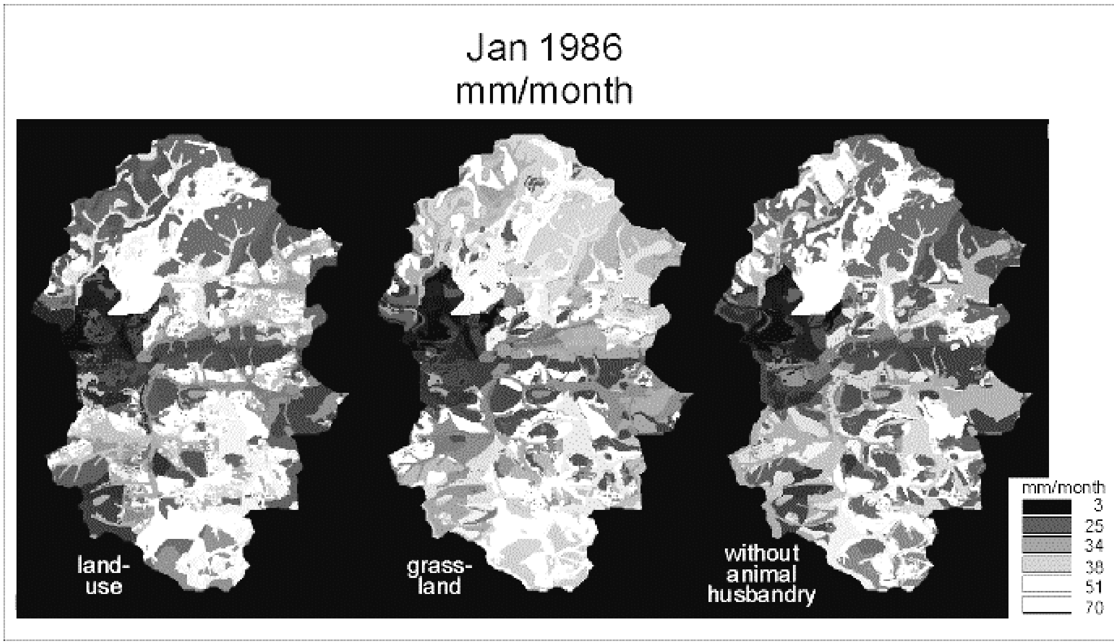

Figure 4. Spatial distribution of surface runoff for three different land use options.

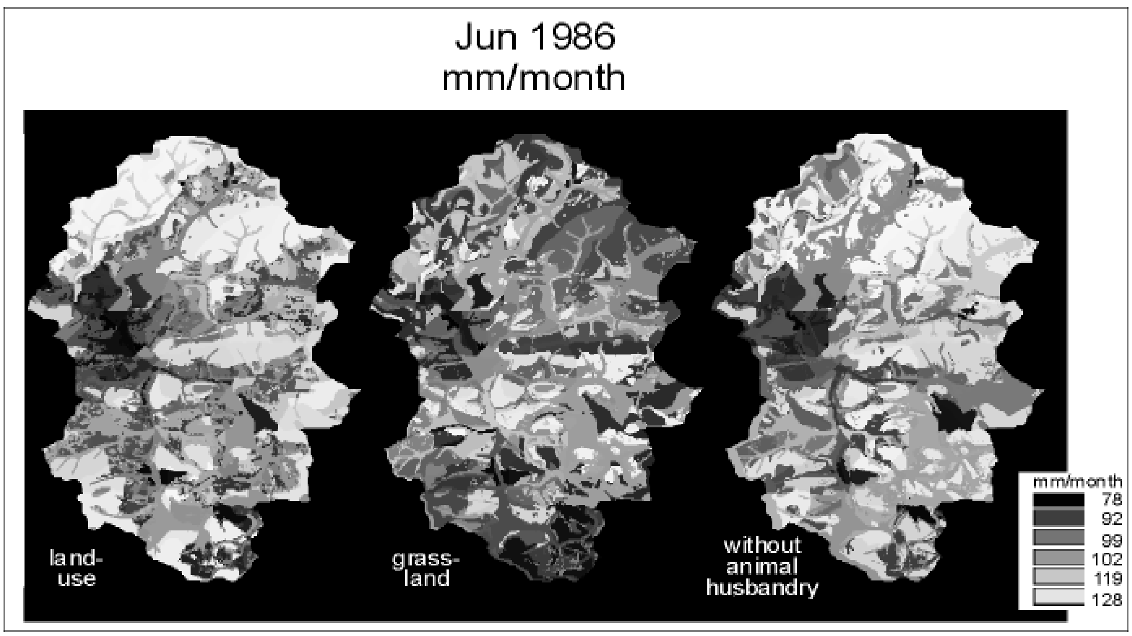

Figure 5. Spatial distribution of actual evapotranspiration for three different land use options

The effect of land use changes on water balance components

The actual land use of the Aar catchment and both ProLand scenarios were analyzed with SWAT to demonstrate their effect on water balance components. For all model runs the meteorological input data were the same. Table 2 shows a comparison of the annual water budgets.

Compared to the land use in 1987, total stream flow increased due to an increasing percentage of cropland in both scenarios. The scenario 'grassland bonus' showed the highest amount of total stream flow. The decrease of forested areas accompanied by a decline in evapotranspiration explains this result. Due to a higher susceptibility for surface runoff, the increasing percentage of grassland areas combined with deforestation measures results in the maximum value for surface runoff for this scenario.

It can be stated that the SWAT model shows the effect of land use scenarios on water balance in the case of two extreme land use options (land use 1987 vs. grassland bonus) in a satisfactory way. Whereas in the case of smaller land use changes (land use 1987 vs. without animal husbandry) the annual output is not appropriate for comparison purposes. Therefore, an algorithm was developed to reallocate the virtual sub-basins within the sub-basins and spatially distributed output maps of water balance components were produced (Fig. 4; Fig. 5).

Figure 4 shows the spatial distribution of surface runoff under the climatic conditions of January 1986 for all three land use options. The implementation of a grassland bonus has the strongest impact on the potential risk for surface runoff. Due to the deforestation, especially in the steep northern and southern parts of the catchment, runoff increases from 3-25 mm/month to over 50 mm/month for the weather conditions of January 1986. In the shallow midwestern part of the catchment, at the outlet of the basin, no land use effect on surface runoff can be observed. Even the scenario 'without animal husbandry', where the annual mean value showed only a small increase in runoff (Tab. 2) in comparison to 'land use 1987', gives a differentiated image of the potential runoff risk (Fig. 4). In the northwestern part of the catchment, forested area was transformed into cropland. Thus increasing the runoff formation in this region. On the other hand, the eastern part was afforested and the risk of runoff declined. Even though grassland was transformed into cropland in the midwest, runoff did not change due to the plane character of this zone.

The spatial distribution of actual evapotranspiration (ETA) is given in Figure 5 for June 1986. The highest absolute values (>128 mm/month) are found in the forested regions, followed by grassland (99-119 mm) and cropland with the lowest evapotranspiration (78-92 mm). The 'grassland bonus scenario' shows in this respect the strongest effect among all considered land use options. The deforestation leads to decreasing rates of evapotranspiration in the north and the south of the watershed. The changes of evapotranspiration in the scenario 'without animal husbandry' compared to 'land use 1987' are explained through the transformation of grassland into cropland, which leads to a slight decrease of ETA in these zones and afforestation, resulting in a increase of ETA in those parts. Thus the absolute difference for the mean annual values (Tab. 2) is insignificant, caused by the contrary effects of these land use changes.

CONCLUSIONS

The SWAT model (Arnold et al., 1993, 1998) was successfully adapted for the application in a peripheral region in Germany. The model efficiency reached, measured by the Nash Sutcliffe index reached values between 0.74 and 0.79, the same order of magnitude as reported for model runs with regions in the US (Srinivasan et al., 1998; King et al., 1998).

For land use change studies, the total annual water budget showed only a significant effect for changes, which affected more than 20 % of the basin area. For smaller shifts in land use a spatially distributed approach is indispensable.

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