Soil erosion at the mesoscale: comparison of two erosion models for a pre-alpine Austrian basin

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Abstract In an attempt to get detailed information about amounts and spatial extents of soil erosion we conducted a study on sediment and water loads for the Ybbs River basin (1100 km^2), located in the pre-Alpine area of lower Austria. As the spatial validation of soil erosion and sediment yield at the mesoscale is almost impossible, we tried to gain knowledge about probable risk areas by application of completely different erosion models (MUSLE and MMF). We tried to evaluate whether they lead to a different pattern of risk areas and if they are comparable in terms of absolute values of soil loss. Measured flows were used to calibrate the two different erosion models in four sub-basins with markedly different land use. Differences in model results could be attributed to different methods of spatial aggregation. Both models overestimated sediment delivery to the river. Unrealistic parameter values for calculating transport capacity had to be used for calibration of sediment yields.

Key words drainage basin; mesoscale; MMF; soil erosion model; SWAT

INTRODUCTION

Non-point source pollution has become a serious concern in recent years. It is estimated, that 64–89% of the total nitrogen load and 41–80% of the total phosphorus load of the Danube River basin can be attributed to diffuse sources (Schreiber *et al.*, 2003). Phosphorus is a limiting factor for eutrophication in many inland rivers. As the main pathway of phosphorus transport into aquatic ecosystems is by erosion, approaches for better land management policy should include erosion models as a basis for sediment load estimation. To increase the understanding of processes and to improve the quantification of related fluxes at the mesoscale, the project *Nutrients Management in the Black Sea and its Impact on the Black Sea* (daNUbs) was launched.

Modelling of soil erosion for large basins is complicated by the fact that data availability is usually very limited and a spatially distributed validation is practically impossible. Generally, data requirements increase with the size of the drainage basin and on that score the accuracy of the model results decreases. A second difficulty of applying models is the level of uncertainty surrounding the model output. This arises from various sources such as difficulties during parameterization of the model; numerical errors; conceptual errors (Konikow & Bredehoeft, 1992); or simply the fact that modelling approaches are different. Hence, different models used for the same basin may produce different results (Svorin, 2003). Therefore, as a first step in the daNUbs project two soil erosion models with a completely different structure (SWAT and MMF) were compared in order to determine differences in modelling and results. Our major interest was whether they produce similar spatial patterns in terms of soil erosion rates and sediment yield into the river.

Table 1 Comparison of the different approaches of the SWAT and MMF models as used here.

Processes and key factors	SWAT	MMF
Surface runoff	Curve number (Mockus, 1972)	Daily rainfall exceeds soil moisture storage capacity (Kirkby, 1976)
Soil erosion	MUSLE (Williams & Berndt, 1972)	Total soil loss is compared to transport capacity (Meyer & Wischmeier, 1969)
Spatial disaggregation	Sub-basins ~15 km^2	Raster cells a 625 m^2
Connection between spatial units	No connection	Flow method of steepest ascend (Jenson & Domingue, 1988)

MODEL DESCRIPTION

Erosion rates were modelled using two erosion models, the MUSLE (Williams & Berndt, 1977) integrated into the SWAT model (Arnold *et al.*, 1998) and the MMF model (Morgan, 2001), incorporated into PCRaster (Wolkerstorfer, 2002). Because both models are already incorporated into GIS systems and require relatively few data, they seemed suitable for application to large basins. However, they completely differ in terms of their structure. Table 1 gives an overview of how the main processes in the two models are treated. Due to the different treatment of the main processes, it is necessary to use different input parameters. To describe the influence of plant cover on soil erosion, MUSLE for instance, uses the C-factor of the USLE (Wischmeier & Smith, 1978) while MMF requires canopy cover, ground cover, plant height and the USLE C-factor.

In general, there are two main methods of spatial disaggregation for the pre-processing procedure: either the use of a regular grid or the subdivision of a drainage basin into sub-areas or classes of sub-area that are assumed to be homogeneous in their hydrological response. In SWAT, a river basin may be partitioned into a number of sub-basins wherein the dominant land use and soil are used as a unique and homogenous value for the basin leading to a single result per sub-basin. MMF is implemented in a raster GIS wherein input parameter values and soil loss are calculated for each grid. Grid results are routed according to the topographic structure using the method of steepest ascent as described by Jenson & Domingue (1988).

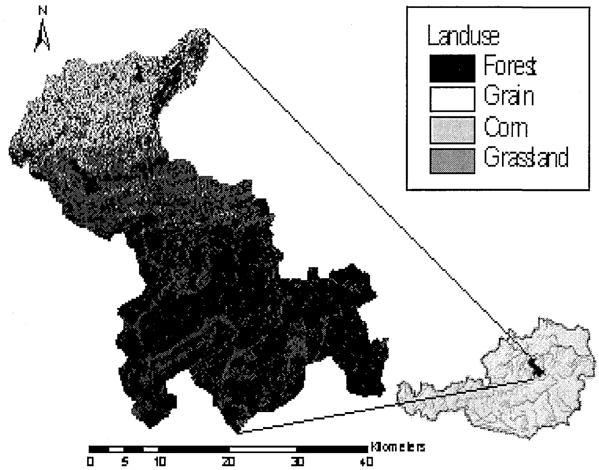
THE CASE STUDY REGION

The River Ybbs is a tributary of the River Danube. The investigated area belongs to the northern limestone pre-Alpine area of Austria. Elevation ranges from 250 m to 1800 m a.s.l. Due to these differences in elevation climatic conditions are highly variable with mean annual precipitation between 650 mm and 2000 mm in the north and south of the region, respectively. Land use follows the pattern of precipitation with almost only forested land in the alpine area to intensively used agricultural land in the northern part of the Ybbs River basin (Fig. 1).

The databases used in this study consist of pre-existing maps and remote sensing data with a resolution of 25 m, field measurements and already existing data (Table 2).

CALIBRATION AND VALIDATION

As a basis for calculation and calibration of surface runoff the knowledge of the regional water balance is essential. Water balance calculations for the Ybbs River basin have been carried out by IHGW (2003) using the water balance model Difga2000 (Schwarze, 2001).



Characteristics of the study area*		
Basin area	km^2	1117
Precipitation	$mm\ a^{-1}$	1377
Slope	°	17
River discharge	$mm\ a^{-1}$	851
Share of arable land	%	16
Overland flow	%	36
Sediment load	$kg\ ha^{-1}a^{-1}$	610

* given values are long term means for the whole basin

Fig. 1 Land use in the Ybbs River basin.

Table 2 Origin and quality of data used for this study.

Data	Resolution	Source
Digital elevation model	25 m	Federal Office of Metrology and Surveying
Land use	30 m	Landsat-7 ETM+
Soil	1 : 25 000 m	Strauss & Wolkerstorfer (2004)
Climatic data	16 gauging stations (daily)	Hydrological Service NÖ
River measurements—flow	5 gauging stations (daily)	Hydrological Service NÖ
River measurements—sediment	3 gauging stations for flow proportional sampling	

This enabled separation of the total flow into slow groundwater flow, fast groundwater flow and direct flow. Direct flow is the surface or subsurface flow in the unsaturated zone. Direct flow rates were then used for the calibration of runoff for both soil erosion models. The drainage basin of the River Ybbs was divided into four sub-basins representing different land-use management areas. These monitoring points were used for calibration. In addition, river basin outlet data were used to validate calibrated results. An automatic calibration tool (van Griensven, 2002) could be applied to the SWAT model. Further details of the calibration for SWAT are described in IHGW (2003). Table 3 gives the calibration results for SWAT and MMF. The SWAT model overpredicted the mean flow conditions for most of the sub-basins. The reason for this is insufficient modelling of runoff events caused mainly by the lateral flow of the faster groundwater runoff (Schilling, 2003). Compared to mean flow conditions, low flow and high flow conditions are reproduced better.

The main parameter for calibrating the MMF model was the parameter "effective hydrological depth". The correlation coefficient between measured and predicted data for MMF is 0.93 which indicates that the model predicts values for surface runoff reasonably well. The different land-use management in the sub-areas is represented especially well. However, mean surface flow at the Ybbs basin outlet is overpredicted. Table 4 shows a comparison of values proposed in the original paper and those obtained after calibration. These values differ hugely. The Ybbs River basin is characterized by a strong gradient in

Table 3 Runoff calibration results for the different sub-basins (north to south) and the main outlet of the River Ybbs, percentage of total river discharge; simulation period 1991–1997.

Surface runoff (%)	River Ybbs Main outlet	Sub-basins Krenstetten Arable	Ybbsitz Grassland	Opponitz Forested area	Lunzois Forested area
Baseflow separation Difga	28.6	32.5	22.9	29.4	31.2
Soil erosion model MMF	32.0	32.5	22.4	29.4	31.5
Soil erosion model SWAT	37.0	56.0	39.0	37.0	23.0

Table 4 Calibration parameter "effective hydrological depth".

Vegetation	Values given by Morgan (2000) (m)	Calibrated Values (m)
Row crops	0.12	0.45
Mature forest	0.20	0.02
Cultivated grass	0.12	0.024

climate, land use, slope and geomorphology from south to north. Water flow follows this pattern. Therefore, the southern parts of the basin, which may be characterized as alpine areas, exhibit high water flow rates but the land is almost exclusively covered with forest or grassland. Direct flow rates given by Difga (2000) also include the quick subsurface flow in the unsaturated zone and this flow path is of particular importance for alpine areas with steep slopes and shallow soils. On the other hand, MMF deals only with surface runoff leading to an incompatibility between model structures. However, the consequences of these high "surface" flow rates for erosion estimation are less than expected due to the dense ground cover of these areas.

MODEL COMPARISON

After calibration of surface runoff we calculated soil erosion rates using both models. Best guess estimates for the different parameters were used, based on different sources of information (model proposals, measured values, literature). To make the models comparable, the results of MMF were averaged on the same sub-basin level (73 sub-basins based on the geomorphological characteristics of the study area) as used by SWAT. The results of this comparison of MMF and MUSLE for the period 1991–1997 (Fig. 2) indicate a general agreement on soil loss risk estimation. The results of both models reflect the land-use pattern with low erosion rates in the alpine areas and higher erosion rates in areas with more intense agricultural land use. However, SWAT exhibits a tendency to estimate higher soil losses compared to MMF for those sub-basins with a higher soil loss risk. This can be confirmed by the slope value of the linear regression between the results of both models which is 0.6 (1 indicates perfect agreement). This compares well with results for the USLE that demonstrate a general overestimation of model predictions at higher soil loss risks (Risse *et al.*, 1993; Strauss & Klaghofer, 2004). For particular sub-basins, considerable variation in results between the models occurs. For areas with low erosion rates calculated by SWAT and higher erosion rates calculated by MMF, this may be explained by the fact that SWAT calculates single input values for each sub-basin. In heterogeneous areas with very different land use intensities, SWAT uses those land-use parameters with the greatest spatial extension. Therefore, small areas with a high erosion risk may be neglected, whereas MMF uses all grid values of a sub-basin for calculation of average soil loss.

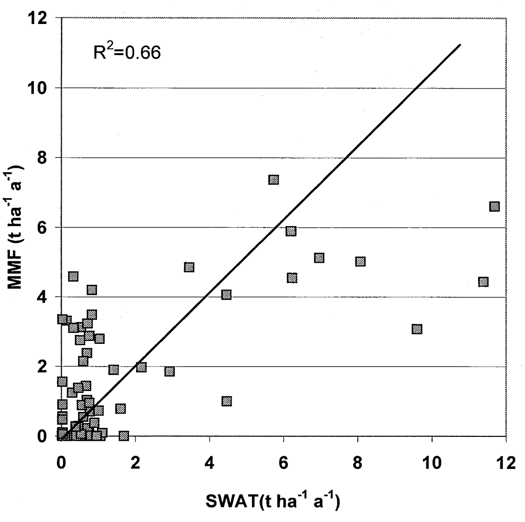


Fig. 2 Comparison of calculated soil loss (t ha^{-1} year^{-1}) using SWAT and MMF for 73 sub-basins of the Ybbs River basin.

A further model comparison was to calculate sediment concentrations by dividing soil loss of the different sub-basins by surface runoff. This resulted in a better correlation between both models (R^2 = 0.71). In addition, the slope value of the regression between MMF and SWAT was not different from 1.

In a second evaluation step we compared calculated soil loss rates to sediment loads measured at the outlet of three sub-basins. Table 5 demonstrates major differences between results calculated with erosion models and measured sediment yields especially in sub-basins with dominantly agricultural land use. Usually, the differences between *on land* erosion rates and *in river* sediment loads are taken into consideration by using sediment delivery ratios. In the case of SWAT, it is stated that due to the inclusion of an explicit runoff term into the erosion equations, delivery ratios are not required and calculated soil losses are equal to sediment input into the river (Arnold *et al.*, 1998). The huge differences therefore could only be explained by retention in the river itself. However, field investigation in the Ybbs River basin did not confirm such large amounts of retention. We therefore conclude that redistribution of soil inside the sub-basins constitutes the majority of soil erosion. This is confirmed by work of Martínez-Casanovas *et al.* (2001) who found soil loss retention of more than 50% already at the field scale, and Strauss & Peinsitt (2002) who mapped soil redistribution rates of a small basin of more than 800 t compared to sediment losses of about 20 t leaving the same basin.

Table 5 Comparison of sediment yields at three river gauging points representing different land use, measured and calculated in t ha^{-1} year^{-1}.

	Measured sediment yield	SWAT predicted	MMF predicted
Opponitz (mainly forested)	0.4	0.5	0.5
Krenstetten (arable land)	0.4	6.2	5.0
Greimpersdorf (river outlet)	0.7	2.7	1.8

To take the retention in the field and in the river into account, different ways of modelling exist: a first attempt was to calibrate MMF for sediment yield of the Ybbs River at the three sub-basins with measured sediment concentrations. Evaluation of the input parameters which are responsible for the soil loss calculation has shown that the transport capacity equation is the limiting process in the soil loss calculation. Transport capacity in MMF is determined by slope angle, surface runoff and land-use cover (C-factor in the USLE). The transport capacity equation appears to be most sensitive to slope angle. Due to this, sediment yields were too high from gentle slopes. As surface runoff has already been calibrated and slope angle cannot be changed, the only parameter to calibrate transport capacity is land-use cover. Calibrating MMF resulted in modelled sediment yields which were similar to measured values. However, the necessary changes of the land-use cover lead to unrealistic values for the C-factor. It was for instance necessary to change the C-factor values for corn from 0.43 to 0.01. Similarly, values for cereals had to be changed from 0.1 to 0.005.

A second possible way of taking the difference between measured sediment yield in the river and predicted soil erosion into account is to develop empirical sediment enrichment ratios. This will be the next step of evaluation.

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