Modelling Soil Erosion, Sediment Transport and Closely Related Hydrological Processes (Proceedings of a symposium held at Vienna, July 1998). IAHS Publ. no. 249, 1998.

The linkage between hydrological processes and sediment transport at river basin scale

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Abstract The linkage between hydrological processes and sediment transport was analysed by applying the model SWIM to the Mulde River basin, situated in the south of the German part of the Elbe drainage basin (Fig. 1). The model runs with a daily time step. First, sediment yield is computed for each of 62 sub-basins with the Modified Universal Soil Loss Equation (MUSLE) (Williams & Berndt, 1977) as dependent on surface runoff, peak flow rate, and other factors. Then the sediment routing model consisting of two components—deposition and degradation in the streams—is applied. Hydrological processes clearly play a dominating role in controlling sediment yield and transport (the bulk of sediment yield is produced during a few flood events in spring and autumn), while soil erodibility is the second important factor determining spatial patterns of sediment yield.

INTRODUCTION

Progress in coupled hydrological/erosion modelling is more evident at the field scale or in small homogeneous basins, for which a number of models are available: (a) empirical models (USLE, RUSLE), (b) those that are largely based on mathematical descriptions of physical processes (WEPP, EUROSEM), and (c) intermediate models combining some mathematical process description with empirical relationships (GLEAMS, EPIC, ANSWERS, AGNPS) (see the overview in Favis-Mortlock *et al.*, 1996). The availability of GIS tools and more powerful computing facilities makes it possible to overcome many difficulties and limitations and to develop distributed continuous time basin-scale models, based on available regional information. Recent developments provide a few models which allow evaluation of erosion processes at the basin scale, among them SWRRB (Arnold *et al.*, 1990), SWAT (Arnold *et al.*, 1993), and SWIM (Krysanova *et al.*, 1996a,b). Usually, the basin-scale model includes a version of a field-scale model as a module, plus a parameterization of the routing processes. Thus, a simplified version of EPIC (Williams *et al.*, 1984) is included in SWAT and SWIM for simulation of crop growth and sediment yield processes.

This paper demonstrates the ability of the SWIM model to evaluate sediment yield and transport at the basin scale. The model was applied for the Mulde River basin (gauging station Bad Düben, 6171 km^2), situated in the south of the German part of the Elbe drainage basin (about 96 000 km^2) (Fig. 1). The Elbe is one of the most heavily contaminated water courses in Europe, due to ineffective sewage water treatment and lack of nonpoint source pollution control (agricultural areas cover about 56% of the total drainage area). Erosion is more pronounced in the southern and western part of the Elbe basin due to the mountainous or hilly relief and occurrence of loess soils.

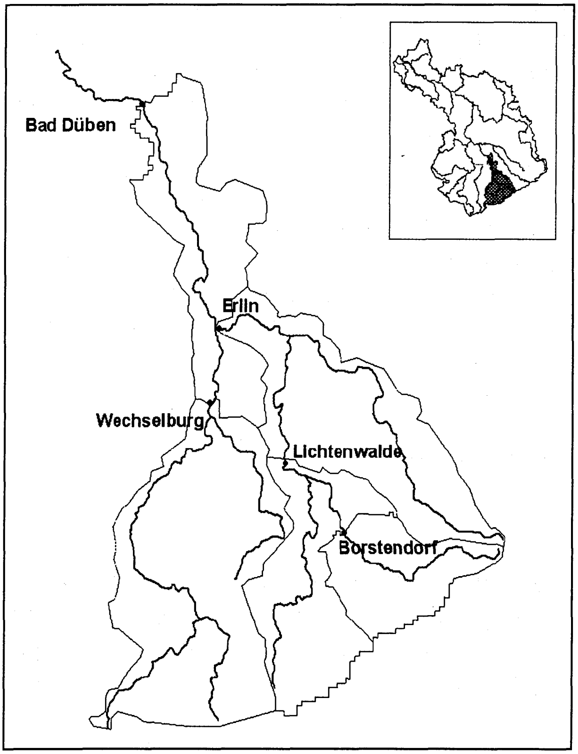

Fig. 1 The Mulde basin located in the south of the German part of the Elbe drainage basin and its subdivision into five sub-basins with the corresponding gauging stations.

MODEL DESCRIPTION

SWIM (Soil and Water Integrated Model) is a continuous-time spatially distributed river basin model, based on two previously developed tools: SWAT (Arnold *et al.*, 1993) and MATSALU (Krysanova *et al.*, 1989). The direct application of either of these two models in the Elbe basin has not been possible, mainly due to their connection to specific databases (weather, soil). Hence, the two models were combined with the objective of providing a generic model for mesoscale basins in Europe, which can be initialized using regionally-available data. The model integrates hydrology, erosion, crop/vegetation growth, and nutrients (nitrogen and phosphorus) at the river basin scale. SWIM has an interface to GRASS, which was modified from the SWAT/GRASS interface (Srinivasan & Arnold, 1993). A three-level disaggregation scheme similar to that used in MATSALU is implemented in SWIM: (a) basin, (b) sub-basins, and (c) hydrotopes inside sub-basins. The hydrotope is a set of units within the sub-basin which have the same land-use and soil type. The model can be applied to basins of several hundred to several thousand km^2.

The hydrological module is based on the water balance equation, taking into account precipitation, evapotranspiration, percolation, surface runoff, and subsurface runoff for the soil column subdivided into several layers. The water balance for the shallow aquifer includes groundwater recharge, capillary rise back to the soil profile, lateral flow, and percolation to the deep aquifer. Sediment yield is calculated for each sub-basin with the Modified Universal Soil Loss Equation (MUSLE, Williams & Berndt, 1977), almost the same as in SWAT (see equations in Arnold *et al.*, 1994). The only difference is that the surface runoff, the soil erodibility factor *K* and the crop management factor *C* are estimated for every hydrotope, and then averaged for the sub-basin (weighted areal average). To estimate the daily rainfall energy in the absence of time-distributed rainfall, an assumption about exponential distribution of the rainfall rate is made. This stochastic element is included to allow realistic representation of peak runoff rates, given only daily rainfall and monthly rainfall intensity. Soil erodibility factor is estimated from the texture of the upper soil layer. The slope length and steepness factor is estimated from the Digital Elevation Model of a basin.

SPATIAL AND RELATIONAL DATA

Data requirements

The SWIM/GRASS interface is used to extract spatially distributed parameters of elevation, land use, soil types, and groundwater table. The interface creates a number of input files for the basin and sub-basins, including the hydrotope structure file and the routing structure file. To start the interface, the user must have at least

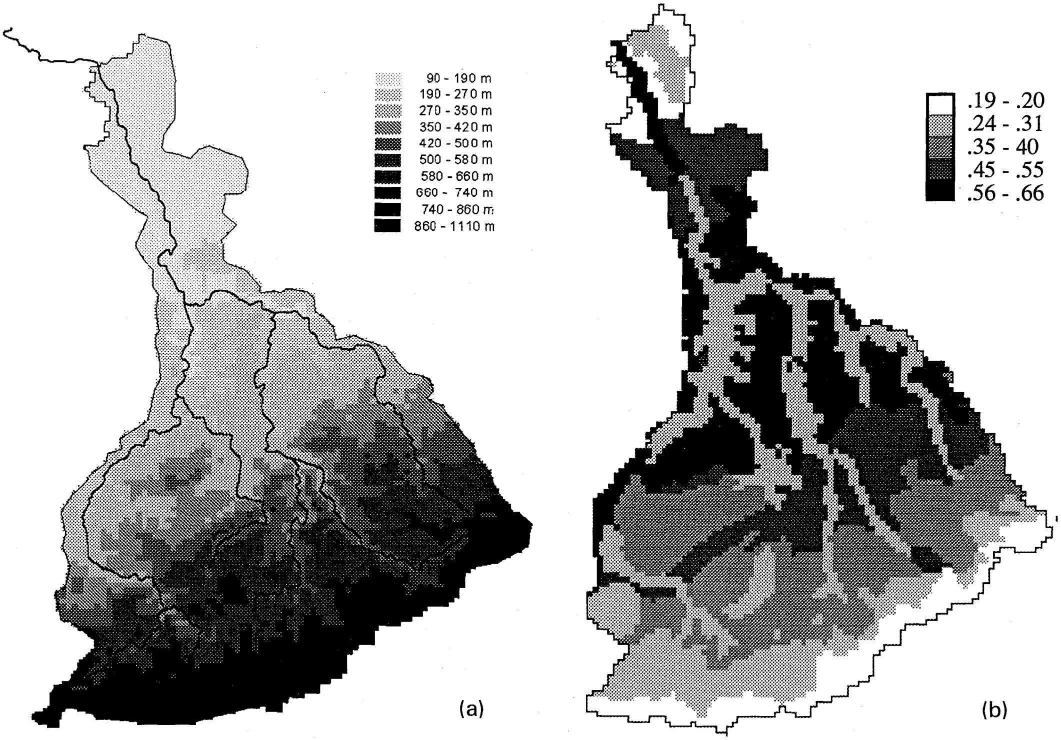

Fig. 2 The Digital Elevation Model (a), and the soil erodibility factor *K* (b) derived from the soil texture for the Mulde basin.

four map layers for a basin: the elevation map (Digital Elevation Model, DEM), the land-use map, and the soil map. The fourth, the sub-basin map should be created in advance either using the *r.watershed* program of GRASS or by subdividing the basin in any other way.

The weather parameters necessary to drive the model are daily precipitation, air temperature (average, minimum and maximum), and solar radiation. Weather data can be taken from meteorological stations or produced using a weather generator based on monthly statistical data. One set of weather parameters may be used for the entire basin, or they can be specified for each sub-basin separately. In addition, a soil database and a crop management database have to be provided. River discharge, concentrations of nutrients and suspended solids (SS) at the basin outlet are needed for model validation.

Data used for the modelling

We used a DEM with 1000 m resolution provided by the "Institut für Angewandte Geodäsie IFAG, Frankfurt-am-Main". The land-use map with 500 × 500 m

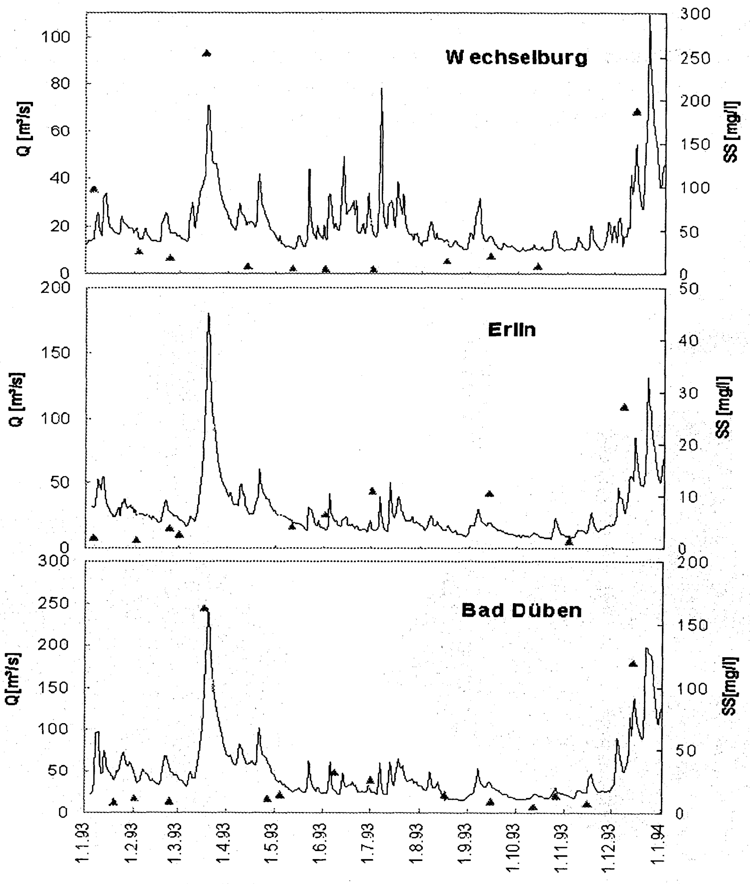

Fig. 3 The daily discharge (—) and suspended solids (▲) in the River Mulde at stations Wechselburg, Erlln, and Bad Düben in 1993.

horizontal resolution, provided by the "Statistische Bundesamt, Wiesbaden", was reclassified to create a new map with the following categories: (a) water, (b) settlement, (c) industry, (d) road, (e) cropland, (f) perennial grass, (g) pasture, (h) fallow, (i) forest, (j) sand, (k) bare soil, and (l) wetland. The digital soil map of Germany, "Bodenübersichtskarte der Bundesrepublik Deutschland" 1:1 000 000, BÜK-1000, generated by the "Bundesanstalt für Geowissenschaften und Rohstoffe, Hanover" was used. It provides parameters for 72 soil types, characterized through a "leading profile". For each horizon of every soil profile, eight attributes are specified: depth, texture class, clay content, humus content, carbon content, nitrogen content, field capacity, and available field capacity.

Elevation in the Mulde basin increases southward from 87 to 1110 m a.s.l. (Fig. 2(a)). Dominant soil types are spodic and dystric cambisols (54%) and loess (22 %). The soil erodibility factor *K* was estimated from the texture of the upper soil layer, and varies from 0.19 to 0.66 (Fig. 2(b)). The area is dominated by cropland (58%) and forest (26%). Forested areas are located predominantly in the mountainous southern part of the basin.

Actual weather data obtained from the German Weather Service were used for simulation runs: daily temperature and radiation from four climate stations (Oschatz, altitude 150 m; Chemnitz, 263 m; Zinnwald, 877 m; and Fichtelberg, 1213 m), and daily precipitation from 72 precipitation stations. An altitude-correction coefficient was used to estimate temperatures in the sub-basins. Data on water discharge are available for five gauging station indicated on Fig. 1 for the period 1981–1995, while measurements of suspended solids in the river are only available for the period from

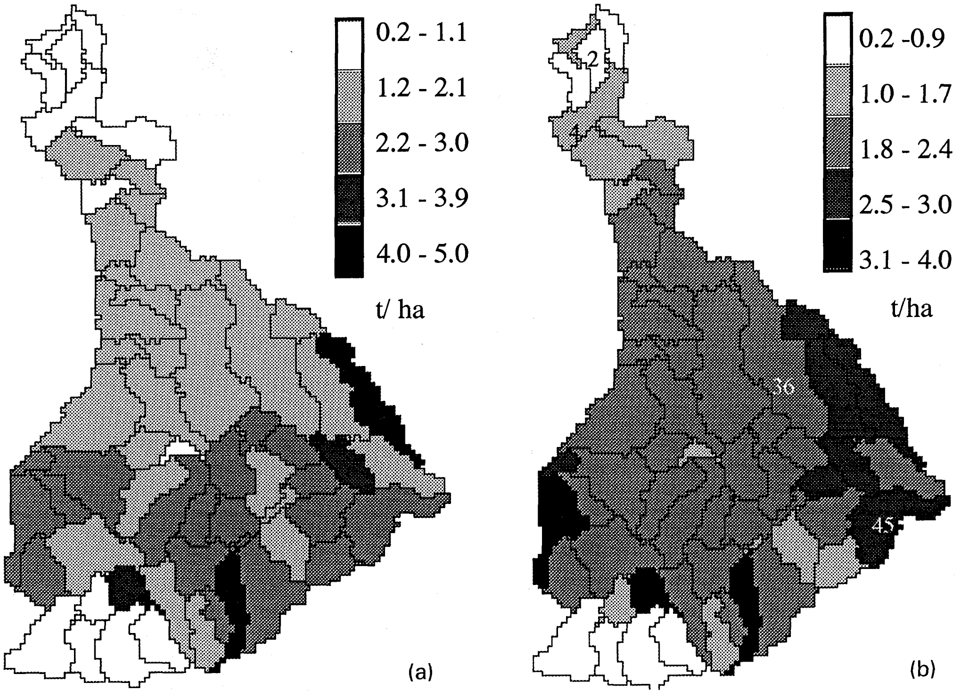

Fig. 4 Spatial patterns of the total annual sediment yield for 62 sub-basins of the Mulde in 1993 (a) and 1994 (b).

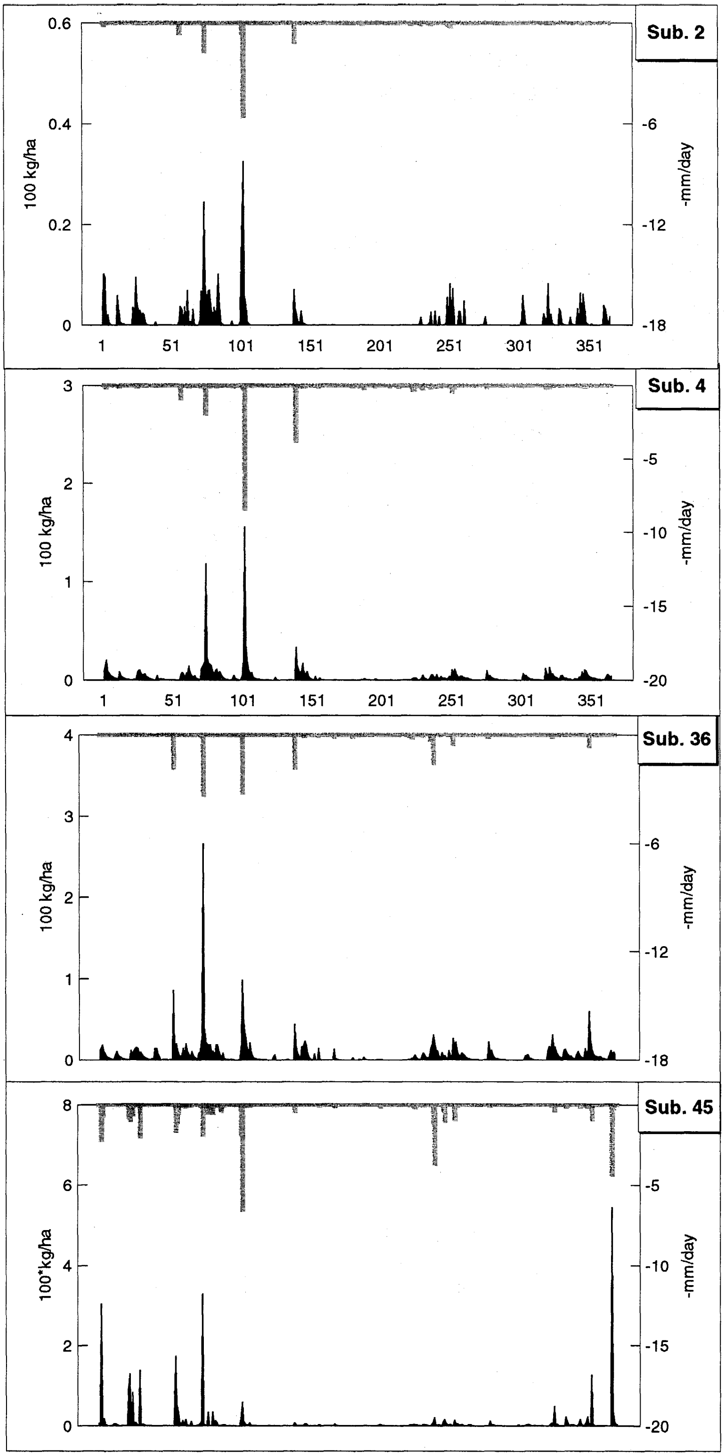

Fig. 5 Time series of surface runoff (grey, negative *Y* axis) and sediment yield (black, positive *Y* axis) for sub-basins 2, 4, 36 and 45 of the Mulde basin in 1994.

1993 (14–15 measurements a year). As we can see (Fig. 3), the SS peaks usually occur during flood events in spring and autumn. Also, it is clear that the frequency of measurements is not sufficient, and there is a high probability that one peak at the station Erlln was "missed" during the spring flood.

RESULTS

Firstly, the simulation results for hydrology were compared with measurement data for the periods 1981–1983 and 1993–1995. The flood events are represented quite satisfactorily, and the Nash & Sutcliffe (1970) efficiency of runoff simulation is about 0.68–0.72. After that, the erosion processes were modelled for the subsequent three years 1993–1995, for which the measured SS data were available. Spatial patterns of sediment yield are shown in Fig. 4 for two years. The maximum values reach 4–5 t ha^{-1}, corresponding to a moderate level of erosion. While the highest surface runoff rates are in the south of the basin due to a mountainous landscape and higher precipitation, sub-basins with the highest sediment yield rates are located in the lower middle part of the basin. This is probably the result of several contributing factors—hydrological processes, soil erodibility, and land use.

Figure 5 shows time series of runoff and sediment yield for sub-basins 2, 4, 36, and 45, which belong to classes I, II, III, and IV as regards their sedimentation rates in 1994 (see also Fig. 4(b), where the location of these sub-basins is indicated). As we can see, there are 2–3 peaks of the SS in spring in sub-basins belonging to classes I–III, and there are five spring and two autumn peaks in sub-basin 45 (class IV). All

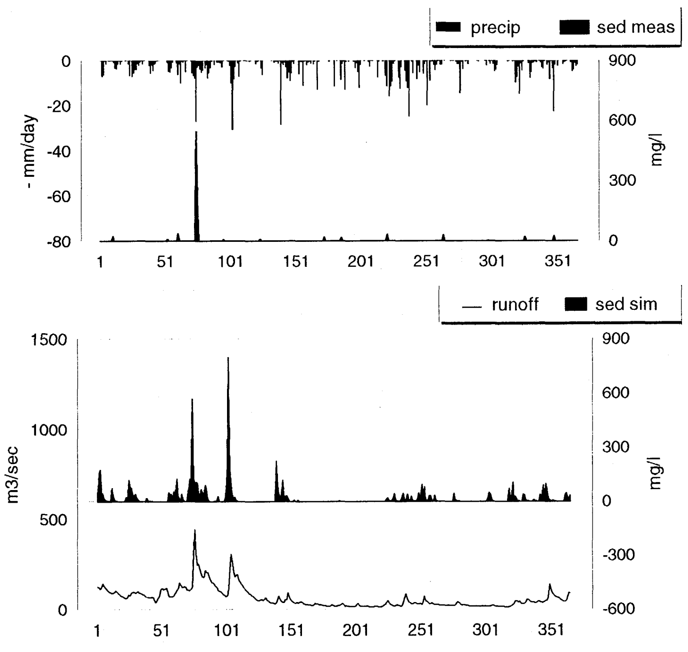

Fig. 6 An example of model validation: time series of precipitation (precip), water discharge (runoff), measured (sed meas), and simulated (sed sim) suspended solids in the Mulde, station Bad Düben in 1994.

the SS peaks correspond to the runoff peaks, except in the summer time, probably due to very low *C* factor. The maximum level of the sediment yield increases clearly from class I to class IV.

And finally, an example of model validation is demonstrated in Fig. 6, where the measured and simulated SS can be compared. As we can see, there are two flood events in spring, and two corresponding peaks in the simulated SS. Only the first peak (day 76) is represented in the measured SS curve. Unfortunately, there were no measurements of suspended solids during the second flood event (days 103–106).

In general, the first test of the erosion module demonstrated the ability of SWIM to simulate sediment yield and transport in mesoscale basins. It was shown that hydrological processes play a dominating role in controlling sediment yield and transport, because most of the sediment yield is produced during a few high flow events in spring and autumn. Also, the soil erodibility is an important factor determining spatial patterns of sediment yield. However, it is clear that the low frequency of observations makes the validation of the model quite difficult. As the next step, it is planned to apply the model simultaneously for a basin and several "nested" sub-basins. Also, the scaling effects have to be studied, comparing results based on finer and lower resolutions of input data.

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