Linking hydrology to erosion modelling in a river basin decision support and management system

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Abstract This paper focuses on the integration of basin sediment transport with a physically-based hydrological model that links the water budget model WaSiM (Water Simulation Model) to the erosion model AGNPS_5. The results of the water budget simulation are then incorporated into the AGNPS_5 model to calculate sediment transport. The surface runoff calculated in WaSiM replaces the SCS curve number runoff calculation in AGNPS_5 to obtain a more accurate and physically-based sediment transport simulation of the basin. Data from a mesoscale river basin in Germany is used to compare two different simulations: (a) WaSiM (TopModel) + AGNPS_5 (sediment only); and (b) only AGNPS_5 (both SCS curve number runoff and sediment). The results and the advantages/disadvantages of each simulation method are discussed in light of integrated computerized management systems for river basin planning.

Key words parameter elasticity; river catchment; sediment transport; soil erosion; water balance

INTRODUCTION

A description of the hydrological processes and sediment transport is an essential requirement for a river basin management system and will be the focus of this paper. Due to the advancement of wastewater treatment (e.g. biological phosphorus removal) and expansion of treatment plants, there has been a shift from point to nonpoint sources as the major contributor of pollution loading into rivers. Hence, the transport of sediments and nutrients via erosion from land surfaces is a key element for the management of river water quality. Management of the river must include management of land in the basin.

Hydrological and sediment transport models have become essential tools for simulating the nonpoint loading from land surfaces to the river and out of the basin. We are using the AGNPS_5 sediment transport model for this purpose. However, surface runoff calculations based on the empirically-based Soil Conservation Service (SCS)-curve number method are replaced with runoff simulations from WaSiM, a physically-based hydrological model. Data acquired from the Lumda River basin in Germany are used to investigate the coupling of the models.

WATER BALANCE SIMULATION MODEL (WaSiM)

WaSiM (Schulla & Jasper, 1999) simulates the hydrology of river basins. Spatial dimensioning is represented in the model using a grid system with equal-sized
orthogonal cells discretized over the surface of the basin. The basin is subdivided into sub-basins, for which the runoff generation and soil water balance are calculated separately using the TopModel algorithm (Beven & Kirby, 1979), which accounts for both Horton and saturated runoff. Both translation (based on the Manning-Strickler equation) and diffusion (using a linear storage reservoir) water transport concentrate the runoff to the sub-basin outlet. The spatial data required include digital elevation, land use and soil type. At least precipitation and temperature meteorological data are required. More accuracy is attained if global radiation, sunshine hours, wind velocity, relative humidity and vapour pressure are also included in the database.

Some of the most sensitive parameters in the TopModel algorithm (Beven & Kirby, 1979) are (Fig. 1): (a) $m$ [m] a recession parameter for base flow; (b) $T_{corr}$ [-] a correction factor for the transmissivity of the soil (these parameters stem from the spatial distribution of saturated areas and are especially important in determining the baseflow $Q_B$ [mm per time step] for each sub-basin); (c) $P_{thresh}$ [mm h$^{-1}$] a precipitation intensity threshold for generating preferential flow into the saturated zone; (d) $K_{corr}$ [-] a correction factor of the saturated conductivity for vertical percolation taking in to consideration both unsaturated and preferential flow paths; (e) $SH_{max}$ [mm] a maximum storage capacity for the interflow storage; (f) $k_H$ [h] a single reservoir recession constant for interflow; (g) $r_k$ [-] a scaling of the capillary rise/refilling of soil storage from interflow [0...1] (this parameter is used to quantify the flow $Q_{buc}$ [mm] back from the interflow storage into the soil storage); and (h) $c_{melt}$ [-] a fraction of snowmelt which is surface runoff [0...1].

![Diagram](image-url)  

Fig. 1 Soil model with parameters used for the sensitivity analysis in parentheses (modified from Schulla & Jasper, 1999).
AGRICULTURAL NONPOINT SOURCE MODEL (AGNPS_5)

AGNPS was originally developed to calculate the surface runoff and sediment and nutrient transport from large predominantly agricultural catchments (Young et al., 1989). It is a distributed model in which a mass balance for each cell is carried out followed by a sequential algorithm where transport of water, sediment and nutrients is routed through the cells and channelled to the basin outlet. Empirical formulations are used to describe the components of the model, which include hydrology, erosion and the transport of sediment and chemicals. Erosion is calculated using a modified Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978). The transport formulations for nitrogen, phosphorus and chemical oxygen demand were adopted from the CREAMS model (Smith & Williams, 1980). The Soil Conservation Service (SCS) curve number method was used to calculate runoff volume $Q$ (mm) from the precipitation $P$ (mm) but modified for German conditions according to Lutz (1984):

$$Q = (P - la) \times C + \frac{C}{a} (e^{-a(P-la)} - 1)$$

where $la$ [mm$^{-1}$] is the initial abstraction depending on the land use and consisting mainly of interception and surface storage, $C$ [-] is the maximum runoff coefficient, and $a$ [mm$^{-1}$] is a proportionality factor. AGNPS overestimates the peak flow rate $Q_p$ for German conditions, hence a modified $Q_p$ [m$^3$s$^{-1}$] is used (Rode & Frede, 1997):

$$Q_p = 0.159 A^{0.856} Q^{0.700}$$

where $A$ (km$^2$) is the total basin surface area.

PARAMETER SENSITIVITY ANALYSIS

Figure 2 shows the elasticity $e$ (a term borrowed from economics) of each parameter $P$ on the outlet runoff $Q$, $e = (\partial Q/\partial P)(P/Q)$, which is both normalized and non-dimensional. After a runoff $Q_0$ was calculated using a base parameter set, a parameter value was increased by 10% from which a new runoff $Q_1$ was calculated for each time step. The elasticity then becomes:

$$e \approx \frac{\Delta Q}{\Delta P} \times \frac{P}{Q} = \frac{Q_0 - Q_1}{Q_0} \times \frac{P}{Q_0} = \frac{Q_0 - Q_1}{Q_0 - 0.1Q_0}$$

As indicated in Fig. 2, the most sensitive parameters (parameters with the highest elasticity on outlet runoff) are $m$, $S_{max}$ and $k_H$. Hence, only these parameters were used to calibrate the model. The elasticity of $m$ is 1 ($Q$ changes by the same percentage as the change in $P$) for the spring, summer and autumn but becomes negative and drops towards $-1$ in the winter months. There is an upward trend from $\approx -\frac{1}{2}$ to 0 in the elasticity of $S_{max}$ from early spring until late autumn. Then, heavy rains cause an abrupt jump to $\approx \frac{1}{2}$, after which successive rains force the elasticity to $\approx -\frac{1}{2}$. This pattern reflects the increased soil moisture content during the winter compared to the summer conditions. No pattern is evident in the $k_H$ elasticity, which sways erratically between $-\frac{1}{2} < e < \frac{1}{2}$ in the winter months with a narrow range of $-\frac{1}{4} < e < \frac{1}{4}$ in the summer period.
Fig. 2 Parameter elasticities on basin outflow of the most sensitive parameters $m$, $S_{max}$, and $k_d$.

Fig. 3 Hourly summation of precipitation and simulated and measured hydrographs of hourly basin outlet runoff for the rainfall event 20–22 June 1992.
RESULTS AND DISCUSSION

The soil parameters were first calibrated using a one year data set (1 June 1991–31 May 1992) from which the parameters $m$, $S_{\text{max}}$, and $k_f$ were set at 0.055 m, 24 mm and 95, respectively. A simulation was then carried out for the entire four-year period 1990–1993 using daily meteorological input values. Except for 1991, a water balance from the simulations for each year (not shown) showed very good agreement between the calculated and measured runoffs. The change in storage also varied somewhat due to the high variation in the total precipitation per year.

To test the sediment transport, the rainfall-runoff event of 20–22 June 1992 was chosen. The comparison of simulated and measured hourly runoff in Fig. 3 shows a close match between the two curves. The AGNPS runoff volume, peak flow rate and total sediment yield are given in Table 1 using three different runoff volumes calculated using: (a) a modified curve number; (b) surface runoff simulated from WaSiM; and (c) total runoff (surface runoff and interflow) calculated from WaSiM. The field measurements are also included for comparison. Both methods (a) and (c) gave similar results with runoff volume and peak flow rates matching very closely to field measurements. Both overestimate the total sediment yield.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Comparison of results obtained with AGNPS only and WaSiM-AGNPS coupling.</th>
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<tbody>
<tr>
<td></td>
<td>AGNPS only</td>
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<tr>
<td>Runoff volume (mm)</td>
<td>3.6</td>
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<tr>
<td>Peak flow rate (m$^3$s$^{-1}$)</td>
<td>7.9</td>
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<td>Sediment yield (tonnes)</td>
<td>319</td>
</tr>
</tbody>
</table>

$Q_s$ cell surface runoff; $Q_i$ cell interflow; $Q_o$ gauged outflow.

CONCLUDING REMARKS

Linking a physically-based hydrological model with a sediment transport model gives a more realistic description of the erosion in river basins. This is especially important for basins located in humid climate zones, which is the case for the Lumda River, where saturated runoff plays a more important role. Hence, erosion hot-spots are more accurately identified and landscape changes to reduce sediment transport can be made more confidently. Only one precipitation-rainfall event has been analysed in great depth and further research is required to investigate more events. The elasticity parameter on basin outflow served to make quick and easy comparisons and more in-depth interpretation of parameter sensitivities. It was found that parameters directly affecting soil moisture caused the greatest elasticities and variations to the basin runoff throughout the year.

REFERENCES


Karl-Erich Lindenschmidt & Michael Rode


