Simulation of soil erosion by water at the watershed level
A. Pinheiro, B. Caussade*, H. Ayphassorho^* 

aInstitut de Mecanique des Fluides de Toulouse - URA au CNRS, Avenue du Professeur Camille Soula 31400 Toulouse, France 
bCEMAGREF/Bordeaux - 50 avenue de Verdun 33611 Gazinet Cedex, France

Abstract
Agricultural activities have been identified as the largest contributor to nonpoint source pollution of surface water systems. Soil erosion (sediment in the streamflow), nutrients (primarily nitrogen and phosphorus) and pesticides appear to be the major causes for water quality impairments. In this work we propose a distributed conceptual watershed modelling for the soil loss. Application sites of different size are located in the south west in France. Comparison between field measurements and numerical simulations give good results.

1 Introduction

It is well known that agricultural practices play a major role in the deterioration of water quality; the essential elements are: suspended matter linked to the phenomenon of erosion due to runoff, nutrients (nitrogen and phosphorus) in general caused by fertilisers, pesticides, climate, and the site.

Due to the expense and labor intensivity of long term field studies which are required to reliably quantify agricultural nonpoint-source pollution, computer modelling has gained widespread acceptance for developing agricultural management practices that protect water quality. In this case, a model should therefore describe, as realistic as possible, the effects of transfer and transformations of products liable to contribute to the degradation of the concerned environment and of other contributing factors.

Two main type models are available to predict soil erosion: empirically based and process-based. The first type is represented by methods such as the Universal Soil Loss Equation [1]. Several lumped and distributed parameter modelling, including CREAMS [2], EPIC [3] and AGNPS [4] are based on this empirical equation. The second type is the process-based model that computes erosion using mathematical representations of fundamental
hydrologic and erosion processes. Fundamental erosion processes are
detachment by raindrop impact, detachment by flow, transport by raindrop
impact, transport by flow and deposition by flow. In this case, two approaches
are considered: (1) a quasi-steady-state erosion model based on the continuity
equation for sediment transport and the concepts of rill and interrill erosion;
e.g. Foster [5], Sharda and Singh [6] and (2) the fictitious reservoir introduced
by Negev [7]. Coupling between the Negev’s approach and a conceptual
hydrologic model is appropriated.

This paper presents a distributed conceptual model to simulate soil erosion
at the watershed level. The model is built around "CEQUEAU" the
hydrological model developed by the INRS-Eau, Québec, Canada [8]. It takes
into account the Negev’s approach to represent the soil erosion processes.

The CEQUEAU model is based on division of the watershed in a set of
square areas with identical dimensions and with a mean value of the physics
parameter, the so called "whole squares". Each whole square from the first
sub-division is further sub-divided into "partial squares" according to sub-basin
divides. This allows the determination of downstream routing from one partial
square to the next. This second subdivision allows us to follow the formation
and evolution of stream flow in time and space, and also to calculate the
discharge at any point in the drainage network.

2 Erosion model

The model for simulating soil loss was derived from research by Negev [7].
The erosion process of sheet and rill erosion on agricultural land, transport and
deposition in drainage network are considered. Figure 1 shows the scheme of
the erosion model. Raindrop impact is mostly responsible for detachment of
soil particles during the water erosion process on an interrill area. Rate of
rainfall detachment, \( D_i(t) \), is defined as the mass of soil detached by rainfall per
unit area and time that supply sediments reservoir. Rose [9] treats the raindrop
detachment process empirically by the non-linear relationship between rainfall
detachment rate and rainfall rate. Assuming that \( D_i(t) \) is proportional to the
fraction of soil (\( cov(t,kc) \)) exposed to raindrops, we can write:

\[
D_i(t) = cov(t,kc) \alpha_1 P(t)^{\beta_1}
\]

where \( \alpha_1 \) is a measure of the detachability of soil by rainfall rate \( P(t) \) and \( \beta_1 \)
is the exponent (non-dimensional), \( cov(t,kc) \) is the land surface cover, function
of time and type of crop. Monthly covered values are specified as occurring on
the first day of the month. Cover on any day is determined by linear
interpolation between the monthly values for each crop.

The potential sediment load by runoff on sediments stocked in a sediment
reservoir is compared to an overland flow sediment transport capacity \( T_c(t) \),
given by
\[ Tc(t) = \alpha 2(icp)Q(t)^{\beta 2} \]  \hspace{1cm} (2)

where \( \alpha 2(icp) \) is the transport coefficient of a partial square, \( Q(t) \) is the runoff rate per unit plane area and \( \beta 2 \) is the exponent (non-dimensional). The transport coefficient represents the characteristics and slope of surface land. It is specific for each partial square.

\[ Ds(t) = \alpha 3(Q(t) - Q_{cr})^{\beta 3} \]  \hspace{1cm} (3)

where \( \alpha 3 \) is the entrainment coefficient by runoff, \( Q_{cr} \) is the value of runoff which the entrainment process commences and \( \beta 3 \) is the exponent (non-dimensional).

We consider that all partial squares are linked to drainage network. The sediments transported by runoff supply the sediment river-reservoir. The entrainment at the level this reservoir is controlled by the transport capacity of streamflow. In this case, the transport capacity of the streamflow is given by:

\[ Tce = \alpha 4 Qe(t)^{\beta 4} \]  \hspace{1cm} (4)

where \( \alpha 4 \) is the transport coefficient of the streamflow, \( Qe \) is the rate of streamflow and \( \beta 4 \) is the exponent (non-dimensional).
3 Results and discussions

Two watersheds of different size were chosen as application sites for the erosion model. They are located in the south-west in France: Ruiné and Save watersheds (fig. 2). The first watershed with 547 ha in area, has been sampled by the Service of Water Quality of the Centre National du Machinisme Agricole du Génie Rural des Eaux et des Forêts (Bordeaux - France). The Ruiné watershed belongs to the BVRE network (representative and experimental basins) in France. The second watershed, with 1130 km² in area, is supplied for Neste Systems in upstream during the drought season. The characteristics of each watershed are given in table 1.

Concerning Save watershed, two periods were chosen: the period 1985/88 for calibration of model parameters and the period 1989/92 for verification of the model performance with calibrated parameters. We observe in this calibration period that the model fits reasonably the measured values of suspended matter concentration at the Grenade station (fig. 3c). Therefore, at the Lombez station (fig. 3a) the model reproduces the measured suspended
Figure 3: Measured and simulated values at Lombez a) calibrated and b) verification; at Grenade c) calibrated and d) verification; and e) Ruine calibrated and verification
matter concentration reasonably. In this case, the model sometimes underestimates the measured values. However, the annual balance of soil loss is: 1.16 ton/km²/year at Lombez station and 1.00 ton/km²/year at Grenade station. Concerning the verification period (fig 3b and 3d), the model produces results which are similar those in the calibration period. The annual balance results are 6% and 2.5% higher than those obtained during the first period at the Lombez station and at the Grenade station, respectively.

### Table 1: Characteristics of watersheds

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Ruine watershed</th>
<th>Save watershed</th>
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</thead>
<tbody>
<tr>
<td>Station of sampling</td>
<td>outlet (547 ha)</td>
<td>Lombez (400 km²) and Grenade (1130 km²)</td>
</tr>
<tr>
<td>Sample frequency</td>
<td>weekly</td>
<td>eight per year</td>
</tr>
<tr>
<td>Average rainfall</td>
<td>795.6 mm</td>
<td>682 mm</td>
</tr>
<tr>
<td>Soil Use and occupation</td>
<td>clay-loam</td>
<td>clay generally chalky</td>
</tr>
<tr>
<td></td>
<td>maize (26.2%); vine (24.0%); wheat (21.9%); sunflower (13.4%); wood (8.5%); clam (5.6%)</td>
<td>wheat (18.6%); maize (12.6%); sunflower (11.4%); wood (12.1%); forage (11.4%); clam (10.8%)</td>
</tr>
</tbody>
</table>

The years 1991-1992 were chosen as a calibration period for the Ruine watershed, and the year 1993 was chosen as a verification period. The results (fig. 3e) show an acceptable reproduction of the measured values the concentration of suspended matter. The annual balance presents a soil loss of 2.96 ton/km²/year. This value is about three times more important than at the Save watershed. Two reasons can explain this fact. The first one is related to the sample frequency. For Save watershed the 8 samples per year underestimate the maximum discharge value. In this case, the parameters of the Save watershed are weaker than those of the Ruine watershed. However if we simulate the Save watershed with the Ruine watershed parameters, the results of soil loss is 3.64 ton/km²/year at the Grenade station. The second one is explained by the slope length which contributes to the deposition process. In this case, the Save watershed is more important than the Ruine watershed.

### 4 Conclusions

The proposed model relates the usage of land to the suspended matter enrichment of the surface water for a given watershed. The soil loss was simulated at two watersheds. The results of erosion at the Ruine watershed showed that a good approximation of suspended matter concentration can be predicted. With respect to the Save watershed an increase in the sampling frequency would be necessary to obtain better observed and simulated values.

Considering that the model satisfactorily predicts the suspended matter concentration, it is possible to draw several lessons, mainly in the interest of numerical simulation, even at the cost of greatly simplifying certain processes.
5 Acknowledgements

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6 References