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Modelling runoff and erosion in agricultural soil: application of ICECREAM model to a field site in southern Finland

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Abstract

The hydrological submodel of ICECREAM, which is the Finnish version of CREAMS/ GLEAMS model, was calibrated and validated against surface runoff and snow water equivalent data from a sloping clayey field under small grain crop cultivation. The field data indicated pronounced short-term and seasonal variation of surface runoff and erosion. Soil loss was modelled using either simulated or measured surface runoff as an input data. The calibrated model performed moderately in simulating surface runoff in an annual time scale, but prediction of short-term surface runoff dynamics was rather weak. The erosion submodel with measured runoff underestimated high soil losses observed in the field in wet autumns. Recalibration of the erosion model is needed to improve prediction of sediment concentrations in surface runoff. This is important because the measured concentrations showed obvious seasonal variation. Furthermore, several cultivation practices and agri-environmental measures have been observed to clearly influence concentrations.

1. Introduction

Mathematical models are widely used in studies on non-point source pollution from cultivated fields. The ICECREAM model, which is similar to the CREAMS and GLEAMS models, is used to analyse impacts of different agri-environmental measures and agricultural policies on nutrient losses to surface waters in Finland (e.g. Rekolainen *et al*.1999; Rankinen *et al*. 2000, Bärlund *et al*. 2005). Earlier testing of ICECREAM in experimental sites in Finland have revealed a need for further evaluation of the model for different soil types, slopes and crops (Rekolainen and Posch 1993; Tattari *et al*. 2001).

The aim was to test the hydrological and erosion submodels of ICECREAM against field-scale monitoring data from southern Finland. The field data indicated that surface runoff and erosion exhibited a pronounced short-term and seasonal variation. The idea was to explore how well the model simulates temporal behaviour of runoff and erosion in a daily time scale.

2. Materials and methods

ICECREAM model is based on CREAMS/GLEAMS models developed in the USA (Knisel 1980, 1993). The hydrological and crop growth computation schemes have been modified for Nordic conditions by Rekolainen and Posch (1993). The model consists of submodels simulating runoff generation and soil water processes, erosion, and transport and transformations of nutrients in the unsaturated soil. The model operates in field scale using a daily computational time step.

In this study, data for testing ICECREAM were available from Sjökulla experimental site located in southern Finland (60º15’ N, 24º27’ E). The field was subsurface drained in 1951. The clay content of the soil is 38–90%. In the model application a field section of 2.2 ha with a slope of 2–4% was studied. Values of the soil properties for four horizontal layers in the model were according to measurements from the field (Alakukku *et al*. 2006).

Surface runoff and subsurface drainage outflow were measured in the field using a v-notch weir and a pressure sensor. Water samples were manually collected at irregular intervals. The concentration of total suspended solids (TSS) was determined by using filtration (1μm fibreglass filter) during 1993–1996 and by weighing the evaporation residue during 1997–1999. Daily values of meteorological variables were measured at the site. Missing measurements were replaced by data from nearby weather stations.

The model was calibrated against data from December 1997 to April 1999 and the rest of the data was left for validation. Model parameters were optimised by minimising the criterion (*CR*):

$$CR = 5.0 - NS_{SWE} - 3\ NS_{SR} - NS_{P}$$

where NS_{SWE} is the efficiency (Nash and Sutcliffe 1970) describing the goodness of fit between measured and computed snow water equivalent, NS_{SR} is the efficiency between measured and computed surface runoff, and NS_{P} is the efficiency between measured drain flow and computed percolation. Optimisation was carried out with the shuffled complex evolution method (SCE-UA) of Duan *et al*. (1992).

The calibrated snow model parameters were the degree-day factor, threshold temperature for snowmelt, and liquid water retention capacity of snow. The rest of the calibrated parameters were saturated hydraulic conductivity, the difference between porosity and field capacity, and the wilting point in the four soil layers, and SCS curve numbers for sowing and tillage.

3. Results and Discussion

The snow model showed a much better performance in terms of efficiency for the calibration period (NS_{SWE} = 0.86) than for the validation (NS_{SWE} =0.41, see Fig. 1). It is worth noting that optimisation against snow and runoff data simultaneously degraded the snow model performance.

Fig. 2 shows that the model reproduced the cumulative surface runoff well for all years except 1995 and 1996. The surface runoff in autumn 1996 was clearly overestimated. In 1995, the total volume of surface runoff was correct, but there was a clear underestimation of surface runoff in springtime, which was compensated by overestimation in autumn. In terms of efficiencies the model performance in daily time scale was rather weak. The efficiencies for calibration and validation periods were 0.35 and 0.27, respectively. Low values of efficiencies are partly explained by measurement problems during wintertime, when freezing and thawing conditions caused technical problems. However, periods with unrealistic or missing measurements were excluded from the analysis by assessing the model results against only those periods when the measurements were deemed reliable.

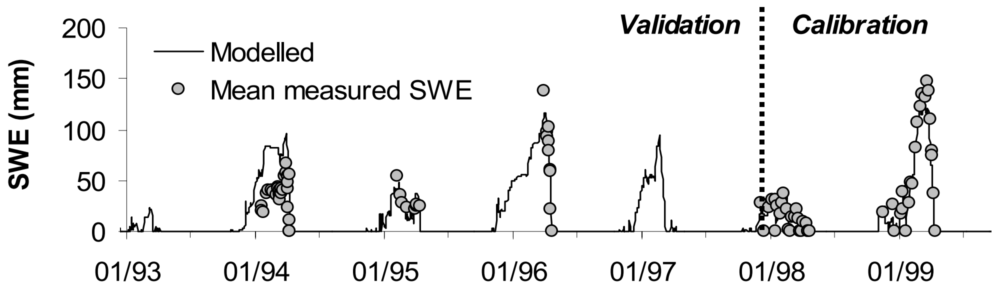

Figure 1. Measured and calculated snow water equivalent (SWE). The calibration and validation periods were December 1997 – April 1999 and June 1993 – December 1996, respectively.

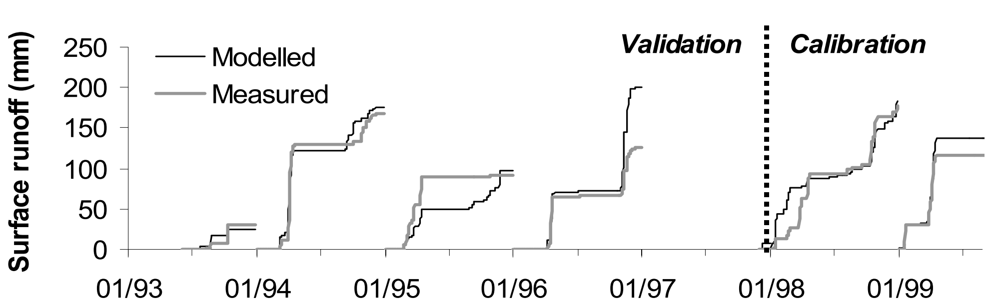

Figure 2. Measured and calculated cumulative surface runoff. Periods with missing measurements were excluded from the graphs.

Soil loss was estimated using three approaches: 1) ICECREAM was run to simulate both surface runoff and erosion for 1993–1999, 2) ICECREAM was run with measured surface runoff as an input to the erosion computation routine for 1993–1999, and 3) soil loss was estimated from hourly runoff and instantaneous TSS concentration measurements for 1996 and 1998.

The total soil loss calculated by ICECREAM with simulated surface runoff was on the average 65% higher than the soil loss calculated by ICECREAM with measured surface runoff. Fig. 3 indicates that there was a large discrepancy in 1994 and in 1996 between the accumulated values of soil loss computed with simulated and measured surface runoff. ICECREAM produced much more erosion when surface runoff was simulated compared to the situation when measured surface runoff was used as an input. In 1996, this difference is mainly explained by the large discrepancy between the simulated and measured surface runoff (see Fig. 2).

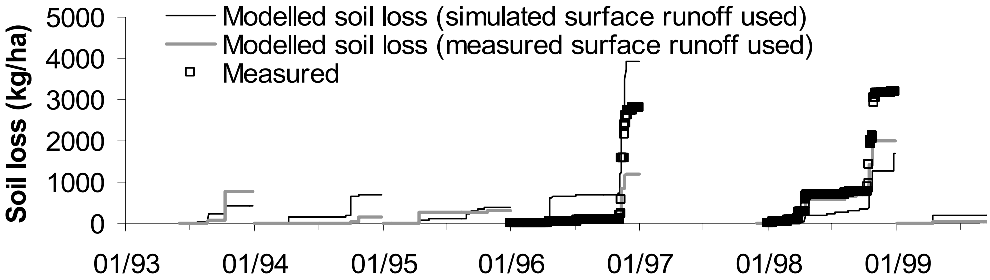

Figure 3. Modelled cumulative soil loss for the period from June 1993 to April 1999. Periods with missing runoff measurements were excluded from the graphs.

Fig. 3 also presents soil loss estimated from surface runoff and TSS concentration measurements for years 1996 and 1998. In January – September 1996 and 1998, ICECREAM with measured surface runoff compared well with the measured soil loss. However, the model failed to simulate high soil loss in late autumn 1996 and 1998. When ICECREAM was run with simulated runoff, the erosion was overestimated in autumn 1996. This was explained by the overestimated surface runoff (see Fig. 2). In spring 1996 and 1998, there was a clear discrepancy between the soil loss calculated by ICECREAM with simulated runoff and the measured soil loss. According to the results, the erosion model underestimated soil loss in wet autumns of 1996 and 1998. This suggests that the simulated sediment concentrations in surface runoff are too low for this season. The measured soil losses included some uncertainty due to the irregular water sampling. However, the measurement procedure covered well the seasonal variation of sediment concentrations and the episodic nature of surface runoff generation.

4. Conclusions

ICECREAM calibrated to the Sjökulla site performed moderately in simulating surface runoff in an annual time scale. The hydrological results were comparable with earlier applications to Finnish experimental sites. In terms of efficiencies that characterise the goodness of fit between daily computed and measured surface runoff, prediction of short-term surface runoff dynamics was rather weak.

The errors in computing surface runoff propagate to the simulation of erosion and form one source of uncertainty in the estimation of soil loss. Another source of uncertainty arises from the parameterisation of the erosion computation scheme that was not calibrated in this study. Recalibration of the erosion submodel is needed to improve prediction of sediment concentrations in surface runoff, and to account for the observed seasonal variability of the concentrations. Accurate computation of concentrations is important, because several cultivation practices and agri-environmental measures have been observed to have a more clear influence on concentrations than on runoff volumes (e.g. Puustinen *et al*. 2005).

Besides surface runoff and snow melt, testing of the model should be extended to other water balance components, such as evapotranspiration and percolation outflux at the bottom of the profile. The model does not include subsurface drainage flow, which is an important flow pathway at the Sjökulla site and in many arable soils in Finland. The transport of sediment and nutrients can be remarkable via subsurface drainage system.

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