Characterisation and Modelling of Winter (Snow Melt) Soil Erosion Processes

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Abstract: Soil erosion processes as well as sediment and nutrient transport in winter caused by snowmelt runoff generation is often neglected or ignored. Recently, studies have focused on the dimension of erosion in winter times and pointed out that erosion modelling tools do not take this phenomenon into account so far. This paper presents data from one Russian and one German catchment, which demonstrate the complexity of snowmelt runoff generation and the related erosion and transfer processes. Interannual variability is typical for regions with cold continental climate. Soil frost depth is identified as major factor of influence. Examples for intraannual variability are given for a low mountain area of Germany in a temperate climate.

A model system that links the water balance model WaSim ETH and the sediment and nutrient load AgNPS, was used to simulate the snowmelt runoff generation and erosion. Although the first results are satisfactory further model development is necessary to characterise soil frost. Also, a better parameterisation of soil erodibility in winter is required.
Keywords: winter soil erosion, snow melt, phosphorus, erosion modelling, Russia, Germany

1 Introduction

Traditionally, soil erosion is considered as the loss of topsoil material from agricultural areas, which surpass the natural background denudation rate or that is perceived to be detrimental to a community or region and leads to loss of physical, chemical and biological functionality on the related field (Boardman *et al*., 1990). Nowadays, new methodological approaches, i.e. tracer technology or modelling, allow a broader and a more holistic view of erosion. Furthermore, numerous studies characterised the processes of particle detachment, surface crusting, runoff shear stress or soil shear strength on the basis of input of kinetic energy from natural or artificial storms.

Consequently, the measures for soil conservation, which were developed from the 1940s and onwards mainly focus on soil properties to increase infiltration characteristics and soil aggregate stability or to reduce the detaching impact of rainfall and surface runoff. The application of empirical or deterministic models has become a strong tool in planning for soil erosion protection. However, most of these models, especially the more physically based ones, have some limitations through data requirements or the dimensions of the scale. Moreover, in all models snow melt erosion and related processes of snow accumulation, snow melt dynamic or soil frost are not described in an appropriate way. Results of erosion studies in northern, central or eastern Europe indicate that the erosion rate during snow melt events can reach or even surpass the rainfall erosion rate (Lundekvam, 2001; Zglobicki *et al*., 2001; Burney, 1994). Relevant for the characteristics of snow melt erosion is the variable combination of snow depth, soil frost, antecedent soil moisture or "rain-on-snow" situations, which are, at the same time, all factors that influence soil aggregate stability (Lehrsch, 1998; Van Klaveren *et al*., 1998). Understanding the nature of snow melt erosion processes is essential for solving the on-site and off-site problems and to deduce recommendations for management practices. Predictive modelling is an important tool in evaluating alternative technologies. This paper presents data and modelling results from research catchments in Russia and Germany which are characterised by erosion and sediment output during the winter season.

2 Study areas and methods

The research catchment "Schäfertal" is located in the Harz mountains, NE-Germany approximately 150 km south-west of Berlin. The outlet of the 1.44 km^2 catchment is at an elevation of 392 m a.s.l. and the catchment ranges within 83 m. The orthic Luvisols and Cambisols, which have developed on the loess sediments on the slopes are used intensively for agriculture. The eutric Gleysols and Fluvisols at the valley bottom are utilised for pasture or meadow. The instrumentation station is located at the catchment outlet. In addition to the registration of meteorological standard parameters several temperature sensors at different above-ground heights and soil depths are installed. Manual measurements of snow cover height and water equivalence are conducted in four transects to characterise the spatial heterogeneity of the snow cover. The water balance is measured with automatic rainfall gages, "watermark" soil moisture sensors, TDR measurements and tensiometers that are distributed over a slope. Continuous measurements of discharge, ground water table, hydrograph separation with ^{18}O, estimation of water quality parameters and also manual and automatic water sampling for sediment yield and phosphorus load encompass the measurement program (Ollesch and Wenck, 2001). If required, a mapping of erosion may be conducted.

The 20 km^2 Lubazhikha catchment lies 100 km south of Moscow in a transition area from southern linden dominated taiga to northern forest steppe. Low precipitation occurs in winter although a snow layer of up to 50 cm depth can form, which normally melts during one short period in March or April. Grey forest soils have developed from loess-like sediments that are eroded in exposed relief positions. The morphology in this catchment is rather contrasting with deeply incised valleys with steep slopes and weakly undulating interfluves. The valleys are characterised by flood-plain soils with large stocks of forest along their steep slopes and the stream banks. The catchment was monitored for seven years in a research campaign on acid rainfall and several studies on soil erosion and soil frost (Demidov, 1995). The dataset was provided by the Russian Academy of Science. A factor analysis was conducted for parameters of the snowmelt runoff of the year 1981 with the statistic program SYSTAT 8.0.

The winter runoff generation and snow melt erosion was modelled with a model system, which combines a continuous water balance model (WaSim ETH) with the nutrient and sediment load model AgNPS (Lindenschmidt and Rode, 2001). WaSim ETH has a modular architecture to simulate the hydrology of a river basin. The model offers components for snow accumulation and snow meltingSoil water balance was calculated on the basis of a Richards equation. The AgNPS model calculates the soil erosion by means of a modified Universal Soil Loss Equation and sediment transport with a Bagnold stream power equation. The peak flow estimation with the SCS curve number approach in AgNPS is replaced by the physically-based overland runoff calculation of WaSim ETH. Although this model combination has some limitations, it was chosen to provide the opportunity to parameterise and model German and Russian catchments.

3 Results and discussion

The Lubazhikha catchment is characterised by a single snow melt period and related runoff generation in March or April. Although the relief energy is low and the catchment is covered 1/3 by forest, the sediment load can reach up to 0.5 t/(ha • y) during spring runoff. Fig. 1 shows the monthly variation of sediment load and amount of rainfall. With the exception of August 1978 (1769 t • month^{-1}) the sediment load during snowmelt events in March and April is the highest during the year. The erosion process and the sediment load in spring runoff is characterised by high interannual variability, which depends on snow depth, melting dynamic and soil frost conditions.

The regime of soluble substances in the discharge at the catchment outlet is characterised by a complex interaction of snow-atmosphere and snow-soil. A factor analysis of 11 parameters measured during the snowmelt period of 1981 demonstrate the atmospheric deposition of chloride, sulphate and nitrate from domestic fuel onto the snow cover and the exposure of snowmelt runoff to the soil nutrients ammonium and potassium (Table 1).

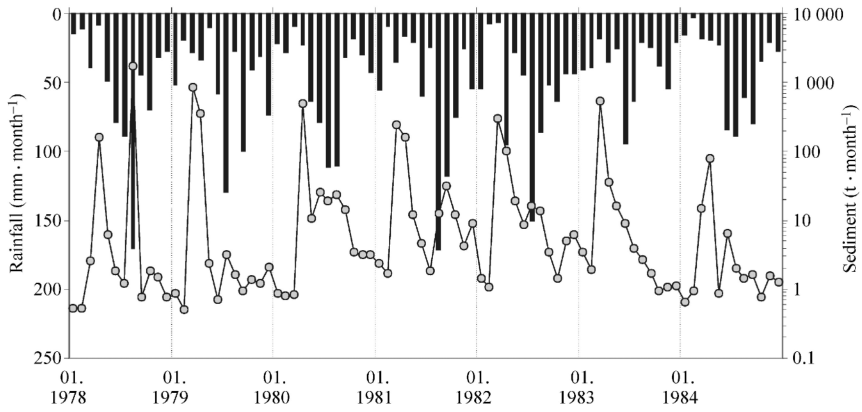

Fig.1 Monthly amount of rainfall and sediment load for the Lubazhikha catchment (rainfall in columns; sediment in dots, log scale!)

Table 1 Factor analysis of parameters measured during the snowmelt 1981, Lubazhikha catchment

Factor Analysis of 11 parameters during snowmelt 1981
(29 values/7 weeks)
Rotated Loading Matrix (VARIMAX, Gamma = 1.0000)

	1	**2**	**3**
snow/soil interaction	pH-regulation	atmos. deposition in snow	
CL	0.062	0.299	**0.879**
SO4	- 0.102	- 0.442	**0.613**
NH4	**- 0.944**	- 0.076	0.063
FE	- 0.154	- 0.671	0.027
pH	0.273	**0.883**	- 0.013
HCO3	0.368	**0.900**	0.012
NO3	0.258	- 0.674	**0.601**
CA	0.468	**0.807**	0.187
MG	0.426	**0.858**	- 0.146
K	**- 0.828**	- 0.379	- 0.154
NA	- 0.084	**0.906**	- 0.093
"Variance" Explained by Rotated Components			
	1	2	3
	2.300	5.136	1.603
Percent of Total Variance Explained			
	1	2	3
	20.907	46.693	14.574

In contrast, the low mountain catchment Schäfertal in Germany is characterised by intranannual variability, which is defined by numerous snow periods during winter from November to April, diurnal occurrence of soil frost and rain on snow events. In particular, the rain-on-snow events are of high erosivity because of a rapid generation of overland runoff and flash flood development that causes river bank erosion. As an example of a diurnal cycle of soil frost and snowmelt the runoff, sediment and total phosphorus concentration from the event on 6th to 8th February is shown in Fig.2. The minimum in sediment and phosphorus concentration during the late afternoon and night is most likely caused by a decrease in snowmelt runoff generation and lowered soil erodibility through frost. Soil temperatures during the night below freezing point and ^{18}O hydrograph separation also support this interpretation.

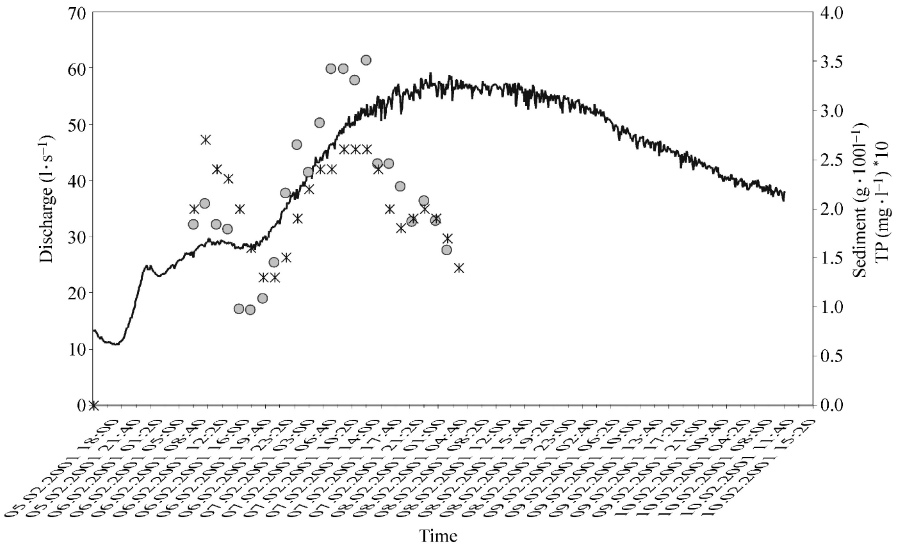

Fig.2 Discharge, sediment and total phosphorus concentration from the research catchment Schäfertal as an example for a diurnal cycle (discharge in line; sediment in dots; total phosphorus in asterisks)

A typical rain-on-flow induced flood event is depicted diagram in Fig. 3. Rainfall occurred in the middle phase of the melting period and caused the maximum runoff, but the maximum sediment concentration appeared during overland runoff generation from snowmelt six hours before the peak discharge. A change in the relationship of phosphorus species (TP, DP, SRP) and dissolved organic carbon during the event provides an indication of differentiation in the sediment and phosphorus sources, transport mechanism and pathways.

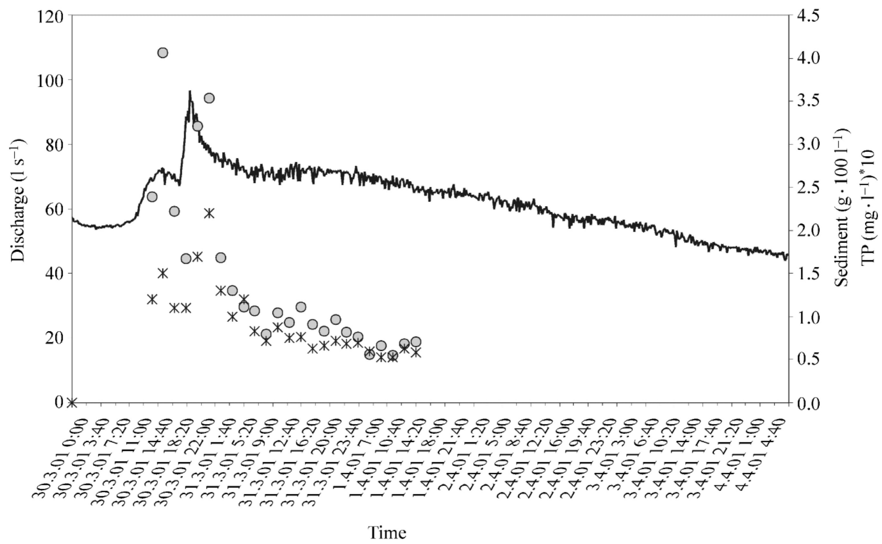

Fig.3 Discharge, sediment and total phosphorus concentration from the research catchment Schäfertal as an example for a rain-on-snow event (discharge in line; sediment in dots; total phosphorus in asterisks)

The application of the modelling system WaSim ETH / AgNPS for the Schäfertal research catchment shows the plausibility of the calculation of runoff generation in time and space. Runoff occurs on the flat interfluves and the valley bottom whereas the steeper slopes generate interflow due to higher infiltration rates (Fig. 4). The related erosion and sediment transport is estimated satisfactorily (Fig. 5).

Overland runoff is concentrated in shallow depressions on the slopes with southern exposition and also locations where runoff and sediment from the slope flow into channel. These positions are visible and checkable in the catchment after major erosion events. Although the slopes are steeper on average on the northern exposition slopes no concentration of runoff and passover into the channel occurs. A significant factor for the decrease of sediment yield is the extensive meadow in the valley bottom. The modelled increase of sediment yield along a line in the south west of the catchment is caused by a change in land use from forest to winter grain.

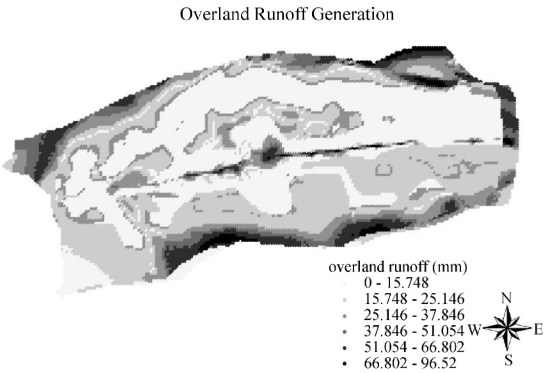

Fig.4 Cell related generation of overland runoff From WaSim ETH

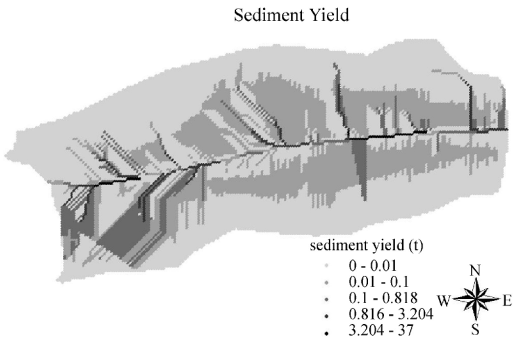

Fig.5 Sediment yield from AgNPS after coupling with WaSim ETH

4 Conclusions and perspective

Runoff generation as well as sediment and nutrient transport through snowmelt is a complex and dynamic process, which can dominate the annual ecological cycle in cold and continental climates. The dimension and risk of erosion events and related nutrient transfer is almost unknown in regions with temperate climate. The intraannual variability of snowmelt events and the differentiation of erosion processes and pathway was demonstrated for the Schäfertal research catchment. Further investigation are necessary and being carried out.

The results of the modelling system presented are satisfactory for some aspects of erosion during winter. Problems occur in the parameterisation of soil erodibility, as well as the reproduction of spatial heterogeneity of soil frost occurrence. Furthermore, modification and development of the model system is required to enhance the modelling results for snow melt erosion events.

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