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ScienceDirect
Catena 68 (2006) 161 – 176
CATENA
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Modelling of snowmelt erosion and sediment yield in a small low-mountain catchment in Germany

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Abstract

Temporal variability and spatial heterogeneity of surface runoff generation triggers the dynamics of source areas of sediment and sediment-associated nutrient transport. Reliable modelling of hydrological special situations i.e. snowmelt is of high importance for the quality of erosion and sediment yield modelling. Data from the research catchment Schäfertal demonstrate the individuality of snowmelt events in terms of runoff coefficient and delivery ratio. This 1.44 km^2 low mountain catchment is characterised by a high portion of arable land with a winter grain/winter rape crop rotation. The integrated winter erosion and nutrient load model (IWAN) considers these dynamic aspects by coupling a hydrological model with a sediment load model. Cell size of this raster-based approach is 10×10 m^2. Additionally, snowmelt rill erosion is simulated with a newly developed physically based model that is firstly applied on a catchment scale. A sensitivity analysis of this model system component demonstrates the plausibility of the model approach and the overall robustness of the model system IWAN. The results of the long-term hydrological modelling from 1991 to 2003 are reliable and form the basis for the simulation of six snowmelt events which were observed in the Schäfertal catchment. The estimated total runoff volumes for these events match the observations well. The modelled overland runoff coefficients vary from 0.001 to 0.72. The mean values of cell erosion, which were modelled with one set of parameters for all six events range from 0.0006 to 0.96 t ha^{-1}. The total modelled erosion for the events with unfrozen soil and low amount of surface runoff is of a factor 50 below those with partly frozen soil. In addition to these distinctions, the major differences are caused by flow accumulation in shallow depressions in variable parts of the catchment. However, the validation of these results on the single event scale is restricted due to limited spatial data. Total simulated sediment yield at the catchment outlet was as high as 13.84 t which underestimates the observed values, with the exception of one event. Oversimplification of the modelled channel processes may be a reason. The temporal variability and spatial heterogeneity of the surface roughness parameter, which was identified to be sensitive, also causes uncertainty in the parameter estimation. Despite these findings, the model system IWAN was applied successfully on the catchment scale and the simulated results are reliable.

Keywords: Integrated modelling; Snowmelt erosion; Sediment yield; Low mountain catchment; IWAN; Germany

1. Introduction

The hydrological regime is of importance for the specification of transport pathways in a catchment which may vary with event preconditions. Thus, the sediment and nutrient loads of storm events often have an individual character. A detailed knowledge about runoff-generating processes is essential to understand the runoff sediment load relationship. In general, erosion and sediment load models are composed of a hydrological and a sediment component. One significant difference between models is the complexity of the characterisation of the rainfall–runoff processes. Basic models of erosion research such as USLE or RUSLE (Renard et al., 1997) do not describe the hydrology of a catchment. These models utilise empirical relationships and are often applied on the event level. Models such as AGNPS

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doi:10.1016/j.catena.2006.04.005

(Young et al., 1994), WEPP (Laflen et al., 1991) or E3D (Schmidt, 1996) include established approaches, i.e. Green–Ampt approach, for rainfall–runoff calculations into their structure.

Grayson et al. (2002) emphasise a need for further research with regard to the patterns and spatial heterogeneity of runoff generation. The influence of spatial heterogeneity of selected parameters on runoff generation is examined by Rustomji and Prosser (2001) in a study about the effect slope hydrology and sediment transport capacity have on sediment inputs into surface waters. The authors conclude that only few field data exist to support the selection of an appropriate hydrological model. They find that this problem forms a high uncertainty in defining sediment source areas which opens questions regarding sediment transport processes. The quality of sediment or nutrient modelling is also dependent on adequate estimation of hydrology since it cannot become better than the underlying hydrological model, in particular for hydrological extreme situations such as snowmelt. Detailed model approaches for runoff generation from snowmelt and frozen soil conditions exist; however, their data demand is high and their application in a heterogeneous catchment is difficult (Ollesch et al., 2005a).

Eight years of erosion plot experiments in Russia with path lengths of 100 m reveal the dominance of rill erosion over inter-rill erosion during snowmelt (Demidov et al., 1995). The range of erosion varies from 0.34 to 2.2 t ha^{-1} for frozen soils and tends to zero for unfrozen conditions and low amount of surface runoff. The results also show the effective protection of perennial grass and winter grain against soil detachment by concentrated flow due to their dense root system and large water stable aggregates. Most of the erosion models do not cover these problems of winter conditions in a suitable way. Unsatisfying modelling results are due to an inadequate process description of winter runoff generation during soil frost occurrence or soil detachment processes during snowmelt flow (Grønsten and Lundekvam, 2006). Hence, Sukhanovski et al. (2004) have developed a snowmelt rill erosion model on a physically basis that combines process description and low parameter demands (see Section 2.2). The first application of this model was conducted with data from a runoff plot at the Niznedevitsk water-balance station in Russia. The accuracy of the model result is reliable and increases for longer simulation periods of the model application.

There is an increasing tendency to apply models of higher complexity and to develop model systems through coupling of single models. The studies of Sophocleous et al. (1999), Arheimer and Lidén (2000), Verstaeten et al. (2002) and Hebel (2003) are examples of this trend. However, there is still a demand to simulate and evaluate well-known processes in their spatial dimension and functionality. Viney et al. (2000) exemplify this by calculating the sensitivity of complex models through the application of a nutrient model that is coupled to the hydrological model LASCAM for the Avon catchment in southwest Australia. The results of the modelling document the sensitivity of the nutrient model in dependency of water and sediment balance. They develop a modelling strategy, which firstly calibrates the hydrological model to apply the sediment module with this calibrated set of parameters. The optimised version of both the hydrological and sediment module serves as a basis for the nutrient calculations. Uncertainties in the results of the hydrological modelling lead to corresponding errors in the sediment balance, which are propagated and even accentuated in the nutrient model.

This paper describes the application of the recently developed snowmelt rill erosion model within the model system IWAN on the catchment scale The model system is calibrated and verified with snowmelt single event data from a small low-mountain research watershed. The focus of the study is the sensitivity of the model chain and the spatial plausibility of the results.

2. Material and method

2.1. Study area

The Schäfertal research site is located in the lower Harz mountains, approximately 150 km southwest of Berlin, Germany (Fig. 1). The climate of the 1.44 km^2 catchment shows a distinct continentality with an average annual temperature of 6.8 °C, ranging from −1.8 °C in January to 15.5 °C in July. The leeward position of the region results in an average annual rainfall of 640 mm which is low in comparison to other low-mountain areas of Germany. The evident seasonality in discharge is caused mainly by variations in evapotranspiration and snowmelt events in winter. Additionally, a modification in base flow is caused by mining activities in the region that were ongoing until 1990. Variations in discharge range from less than 10 l s^{-1} in pre-event situations to above 200 l s^{-1} during winter snowmelt periods. Discharge regularly intermits during summer from July until autumn.

The Gleysols (according to World Reference Base for Soil Resources) at the valley bottom are utilized for pasture, meadow or represent set-aside areas. In contrast, the Luvisols and Cambisols on the loess covered slopes are used intensively for agriculture (Altermann, 1985). The entire catchment is divided into five fields that are managed by one agricultural cooperative society that provides information such as fertilization or crop yield. Ploughing and harrowing is conducted in autumn. Major crops are winter cereal and winter rapeseed. 3% of the catchment area is forested.

Hydrological measurements, which began in the sixties, complement the meteorological data. In addition to water level measurement in a flume, groundwater level observations and soil moisture measurements are conducted in the catchment. A network of seven rainfall gauges and rainfall

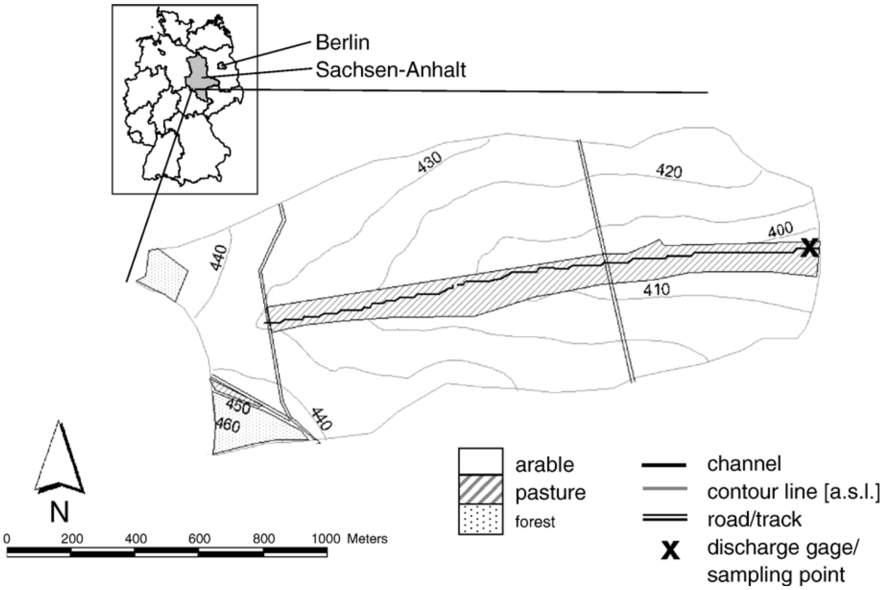

Fig. 1. Characteristics and land use of the 1.44 km^2 Schäfertal catchment, along with an accompanying map that locates the catchment within Germany.

and wind speed measurement at different elevations above ground complete the standard meteorological parameters which are collected at the gauging station at the catchment outlet (for more details see Ollesch et al., 2005b).

A monitoring program for erosion, sediment and nutrient loads was established in 1998. The regular biweekly runoff sampling scheme for major nutrients and suspended sediment at the catchment outlet was supplemented by an automatic sampler (ISCO 6700 Series) for high flow event sampling. The triggering water level for sampling and time interval was seasonally adjusted. Since the fall of 2000, special attention is given to winter runoff and erosion, spatial distribution of snow water equivalent and soil temperature (Ollesch et al., 2005b). Erosion was mapped after relevant events. The location of the erosion feature was mapped and the rill extension was documented qualitatively photographically during or immediately after each event. No sheet erosion was observed and gullies did not form during the period of observation.

2.2. Model description

Snowmelt erosion and sediment yield from the Schäfertal was modelled using an integrated winter erosion and nutrient load model (IWAN). The model system comprises four stand-alone models which are coupled in a Java-based frame:

(a) WaSim-ETH (Water balance Simulation Model ETH; Schulla, 1997) simulates the hydrology of catchments spatially on a cell base and temporally with time steps from minutes to day intervals. Although runoff generation from both excess infiltration and saturated areas can be model with a TOPMODEL approach (Beven and Kirkby, 1979), only the version which estimates water flux in layered soils with the Richards equation was used. The Richards equation formulates water flow through the unsaturated soil as a function of hydraulic conductivity and soil water potential in dependency of soil water content. WaSim-ETH was applied in various environments and studies regarding climate-change or runoff-generating mechanisms (Jasper et al., 2002). With respect to data availability in river basins, the model offers submodules with different data requirements. In this study the model is applied with the minimum amount of input data which are precipitation, temperature and 10×10 m^2 grid-based information about topography soil characteristics and land use. Due to specific requirements, the model was complemented with a module that estimates the soil surface temperature and modifies the soil water flux during frozen soil conditions (Ollesch et al., 2005a). The module estimates the soil surface temperature of each grid cell in relation to daily average air temperature, land use and exposition. In case of a modelled snow water equivalent of more than 5 mm, the soil surface temperature from the previous day is adjusted. The saturated hydraulic conductivity of grid cells with temperatures below the freezing point is set to zero, thus water infiltration is limited to a filling of the free soil pore volume. These changes in snowmelt runoff generation allow a spatially plausible differentiation of surface runoff for relevant events.

(b) SMEM (Snowmelt erosion model; Sukhanovski et al., 2004) is a new cell-based model to estimate soil detachment by concentrated flow in rills during snowmelt. Basic assumptions are that one rill is formed per cell (10×10 m^2 in this study) and that soil detachment takes place for unfrozen and saturated

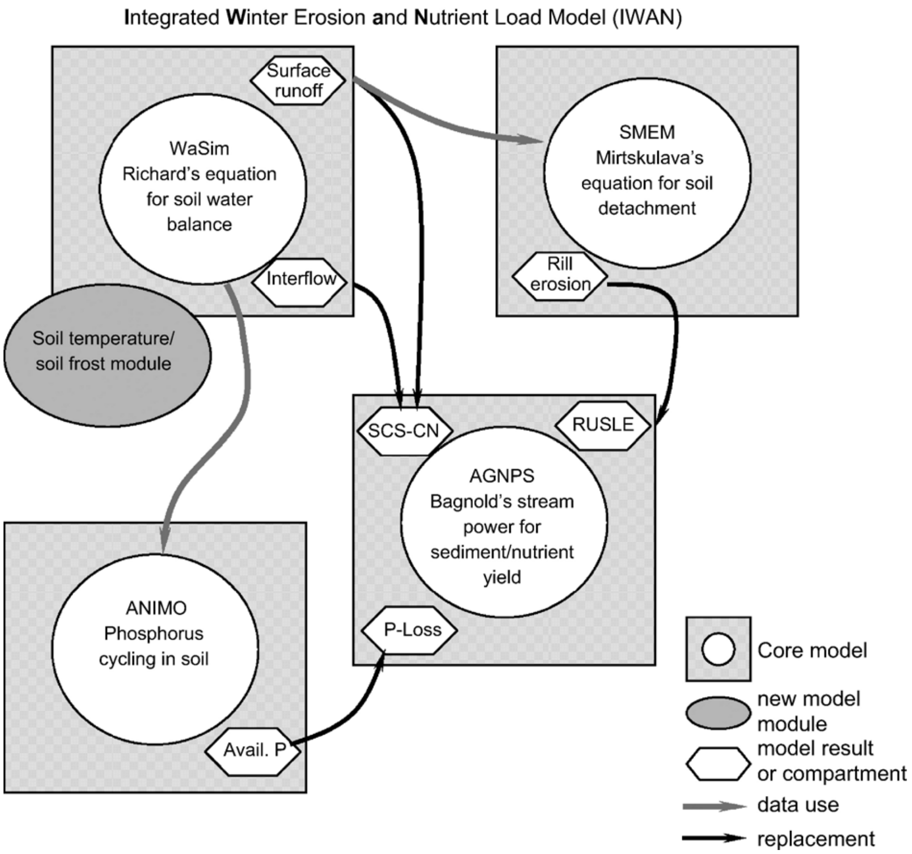

Fig. 2. Schematic overview of IWAN model structure and data flows.

soil conditions which are characterised by a minimum of coalescent force between soil particles. Whereas the first assumption is needed for model technical purposes, the second assumption was derived from field experiments during snowmelt events in Russia. These results show in general a triangular form of the rill with an incision that was not limited by a frost layer. The approach of Mirtskhulava (2000) was used to estimate the erosion rate. This approach utilises the frequency of pulsation of water to calculate the detachment of water stable aggregates. Soil resistance against detachment is influenced by parameters that reflect the root density and water stability of aggregates. These parameters depend on tillage operations and crop rotation or plant growth conditions. Basic information about parameter values are deduced from laboratory experiments (Kusnetsov, 1981). Parameter sensitivity is presented in Section 3.3.

(c) AGNPS (Agricultural Non-Point Source Model) is an event-based raster-oriented model to simulate surface runoff, non-point source pollution and pollutant load in river basins (Young et al., 1994). The general approach for runoff and erosion is empirical, since the SSC curve number and the revised universal soil loss equation (RUSLE) is utilised. However, these two estimations are replaced in the IWAN system (see below). The computation of effective transport capacity follows Bagnold's stream power equation.

(d) Extended ANIMO (Agricultural Nitrogen Model; Groenendijk and Kroes, 1999) with a phosphate module. The present version computes the transformation processes and pool size of nitrogen phosphorus and organic cycle in a one-dimensional soil column. Because this paper focuses on erosion and sediment yield, the coupling of ANIMO to the model system IWAN is not referred to henceforth.

Table 1
Water balance characteristics of the Schäfertal and month of maximum daily runoff

Hydrological year	Rainfall (mm year^{-1})	Runoff (mm year^{-1})	Month of max. runoff
1993	727	61	January
1994	1036	470	April
1995	763	210	February
1996	562	87	March
1997	593	27	February
1998	856	194	January
1999	622	237	November
2000	696	209	March
2001	691	116	March
2002	798	232	February
1993–2002	• 735	• 184	

Table 2
Characteristics of eight single runoff/erosion events from the Schäfertal

	Winter situation	Snow/rain water equivalent (mm)	Discharge max. (l s^{-1})	Runoff (mm)	Net erosion (t)	SSC max. (mg l^{-1})
06.02.01	Unfrozen soil	20 snow	59	10.2	0.36	35.1
30.03.01	Unfrozen soil	26 snow+29 rain	97	2.2	0.73	40.6
20.01.02	Frozen soil	50 snow+34 rain	175 (85 snowmelt)	50 (25 snowmelt)	4.9	1390
26.02.02	Partly frozen soil	6 snow+32 rain	146	19.3	1.81	171
04.05.02	Unfrozen soil	25 rain	27	1	0.26	682.8
30.11.02	Unfrozen soil	33 rain	63	4.3	10.2	5200
26.12.02	Frozen soil	5 snow+27 rain	91	5.5	8.5	6065
02.01.03	Unfrozen sub-soil	17 snow+20 rain	268	20.0	17.22	2020

The core models of IWAN are loosely coupled in two ways, either utilisation of simulation results of one of the core models or replacement of internal calculations with results from other models (Fig. 2). Runoff calculations in AGNPS are replaced and augmented by those from the WaSim model, optionally only surface runoff or surface runoff and interflow is taken into account as runoff in channels. Also, surface snowmelt runoff from WaSim is utilised as a driving variable in SMEM to estimated rill detachment per cell. For this purpose the daily sum of surface runoff from WaSim is routed on the slopes and disaggregated to hourly time-steps and an artificial hydrograph depending on field measurements is created. The resulting amount of detached soil replaces the AGNPS internals. The empirical approaches of AGNPS are replaced step by step with more physically based calculations. The surface routing routines as well as transport capacity and sedimentation algorithms remain in AGNPS. The model system IWAN is embedded in a Java frame which includes the control files and pre- as well as post-processing options.

3. Results and discussion

3.1. Experimental results

Runoff generation in the Schäfertal is characterised by maximum discharge in winter (Table 1). Initial soil moisture and occurrence of soil frost in combination with snowmelt or rain-on-snow events are the most important factors of runoff generation (Ollesch et al., 2005a). The importance of snowmelt dynamics for runoff generation is also documented for other regions. Helliwell et al. (1998) refer to the high intra- and inter-annual variability of runoff dynamics which is also typical for the Schäfertal catchment. However, the spatial heterogeneity of runoff in their study is caused by temporal dynamics of snowmelt and not through frozen soil like in the Schäfertal. This is in agreement to findings by Hayashi et al. (2003), who observe that soil frost occurrence is of importance for runoff generation in regions with low snow water equivalent.

Ten events with high water levels were recorded automatically since the winter of 2000, when monitoring

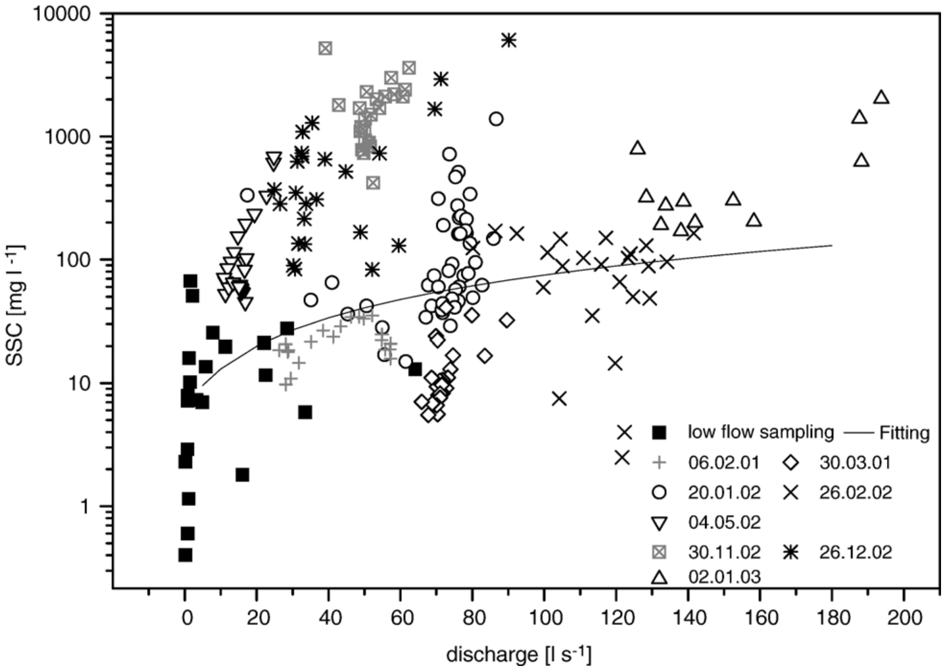

Fig. 3. Plot of the relationship of discharge and suspended sediment concentration (SSC) for events and low flow sampling in the Schäfertal.

of winter runoff and erosion began. Two events with significant runoff and sediment yield had to be excluded from the data set because channel maintenance was carried out at the time of the event. The eight unaffected high water events caused 90% of the total sediment yield. Six of the eight events are related to winter conditions, i.e. snowmelt, rain on snow, or frozen soil, which caused a total sediment yield of 33.52 t at the catchment outlet (Table 2). An additional 10.5 t were transported out of the catchment by two rainfall/runoff events in May 2002 and November 2002. In dependency of soil and weather conditions the runoff varies between 2.2 and 20 mm. With the exception of the event on 30 March 2001 (30.03.01), the resulting runoff coefficients range from 0.5 to 0.6 for winter events. The measured suspended sediment concentrations (SSC) vary from 35.1 to 6065 mg L^{-1}. In general, the maximum and average SSC for events with frozen soils are above those for unfrozen soil conditions. Problems in comparing these values with SSC found in the literature result from differences in catchment conditions such as size slope or portion of arable land. In contrast to common mountain catchments the Schäfertal is characterized by low slope angles and above-average proportions of arable land, two factors with major influence on erosion and sediment yield. However, the SSC of the Schäfertal conform to reported SSC with loess cover or riparian zones and unfrozen soil conditions (i.e. Van Dijk and Kwaad, 1996; McKergow et al., 2003). The pasture area near the brook in the central part of the valley likely acts as a sediment trap.

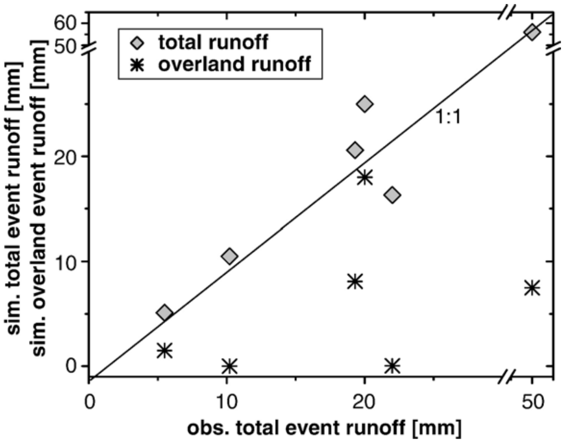

Fig. 5. Comparison of observed total event runoff of the Schäfertal events with simulated total event runoff and simulated overland event runoff.

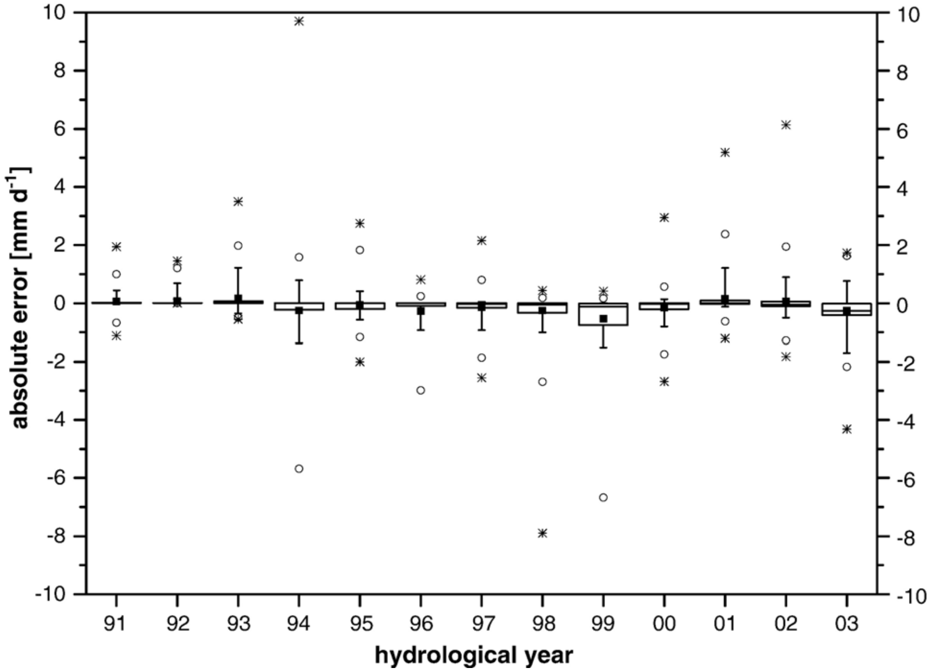

Fig. 4. Box plot diagrams of the absolute modelling error of daily runoff for the hydrological years 1991 to 2003 (central bar: median; hinges = 25 and 75%; open circles = 3 × interquartile range; asterisks: outside values).

Fig. 3 characterizes the discharge–SSC relationship for the high flow events and extrapolates the values of low flow sampling. In contrast to reports in the general literature no dependency of SSC from discharge is visible, neither for single events nor for the entire data (i.e. Luk et al., 1997; Alexandrov et al., 2003). Furthermore, for single events during the period of observations a clear hysteresis of the discharge–SSC relationship is evident, but this is not a systematic occurrence for all events. Consequently, the dynamics of sediment yield in the Schäfertal can be characterized as a combination of processes including runoff generation, erosion and transport in time and space which have to be reflected in a model system. The extrapolation of the SSC values of the low flow sampling indicates two groups of events with

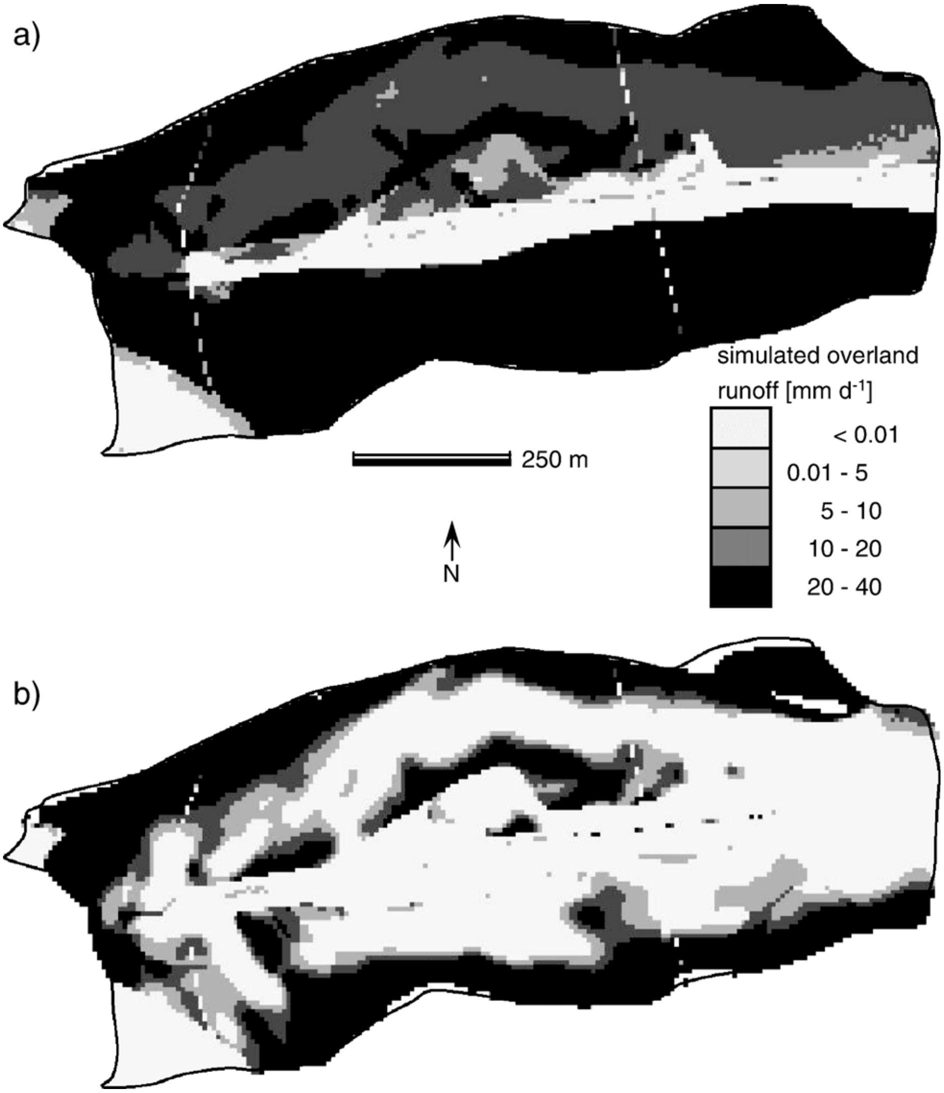

Fig. 6. Maps of simulated overland runoff: a) 20.01.02; b) 26.02.02.

comparable low SSC and those with partially higher SSC. Probably the events with low SSC are restricted to sediment scouring in the channel of the creek. Additional evidence for this source dynamic arises from hysteresis loops rotating in different directions (Ollesch et al., 2005c).

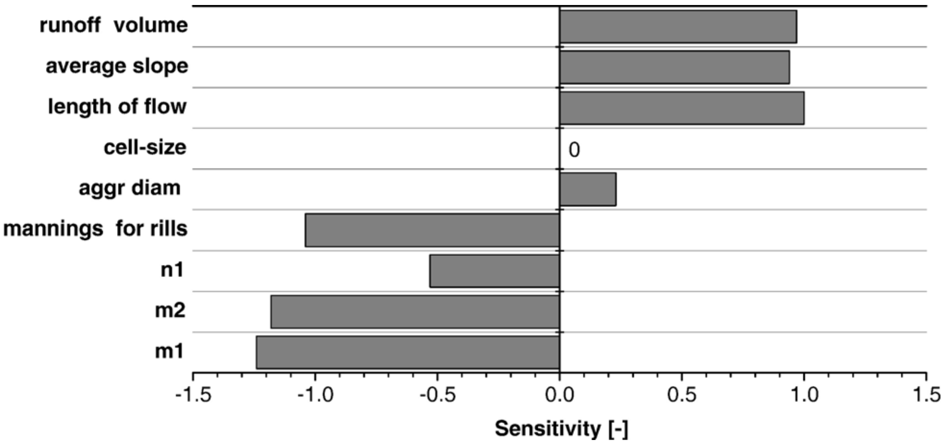

Fig. 7. Average parameter sensitivity of the SMEM model.

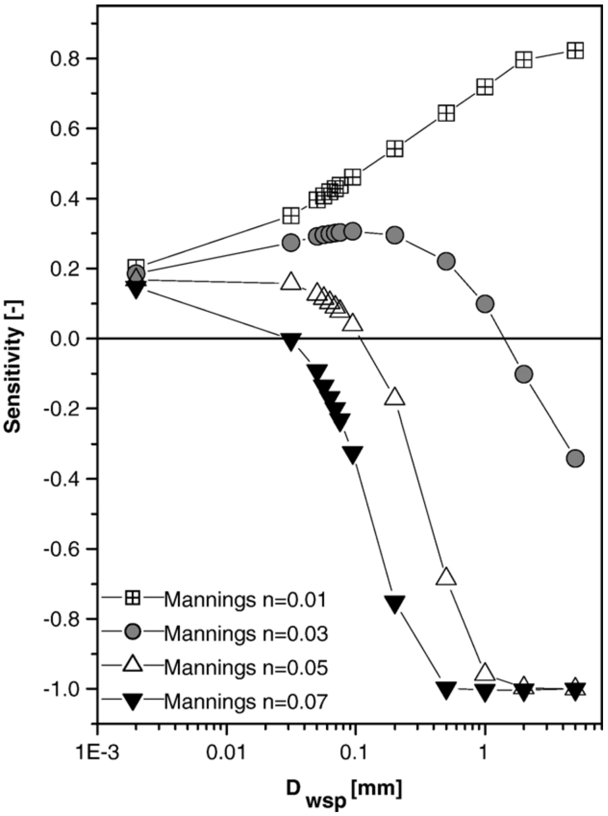

Fig. 8. Sensitivity of the parameter "water stable aggregate diameter" (D_{wsp}) in combination with four Manning coefficients.

3.2. Hydrological modelling

The hydrological model WaSim, which includes the soil surface temperature module, was first applied for the hydrological years 1993/1994 as the calibration period and 1994/1995 as the verification period in daily time steps. The model efficiency was $r^2 = 0.943$ and 0.912, respectively. These periods are characterised by an above average discharge in spring 1994 and average discharge conditions in 1995. The period 1994–1995 was chosen for training for high flow periods. The fitted parameter set was utilised to model a longer period. Fig. 4 compares the observed and simulated daily values of runoff for the hydrological years 1991 to 2003 as absolute modelling error. For all years the mean and median values of error shown in the box plot diagrams are close to zero which is indicative of reliable modelling results. However, some extreme errors of up to 10 mm day^{-1} do occur, such as those in 1994, 1998 and 2002. This is directly caused by daily time-step simulations that result in a time lag of one day for some snowmelt events. An improvement may be possible by extending the snowmelt modelling, however, this would also augment the data demand of the model. Thus, the outliers do not contradict the generally good performance of WaSim for longer modelling periods. These results are supported by satisfying model outcomes for total water balance and soil moisture (Lindenschmidt et al., 2004).

The total event runoff from the continuous simulation with daily time steps for the six measured snowmelt events from 2000 until 2003 with a duration of 2 to 5 days is close to the observed values (Fig. 5). An overestimate or underestimation of +5 mm and −5.7 mm, respectively, occurs for the events from 30.03.01 and 02.01.03. The modelled overland runoff coefficients that were calculated from the maximum snow water equivalent for these six events range from below 0.001 to 0.72 for one event in January 2003. However, no dependency of total event runoff to overland runoff can be established. The variable portion of overland runoff originates from the long-term modelling of soil moisture patterns and soil frost occurrence that modifies the modelled infiltration characteristics (Ollesch et al., 2005a). An advantage in continuous modelling is that antecedent soil moisture need not be estimated but can be calculated, which is a major challenge in single event modelling of erosion (i.e. Kirkby, 2002; Hessel et al., 2003a). In addition, the distributed modelling approach enables a spatial differentiation of surface runoff generation due to the identification of different runoff generation mechanisms. Lindenschmidt et al. (2004) elucidate the spatial extend of Hortonian runoff and saturated areas for the Schäfertal catchment with a spring event as an example. As a result of the spatially dynamic modelled influence of soil frost on infiltration, the heterogeneity of overland runoff has a high inter-event variability. Fig. 6 exemplifies this spatial differentiation for two events: 20.01.02 with frozen soil on the north facing slope and 26.02.02 with partly frozen soils on the slopes. Overland runoff was 7.5 and 8.1 mm, respectively. Despite the fact that the overland runoff

Table 3
Statistics of the cell erosion modelling with SMEM (1 kg cell^{-1} is equivalent 0.1 t ha^{-1})

	Mean (kg cell^{-1})	Median (kg cell^{-1})	Minimum (kg cell^{-1})	Maximum (kg cell^{-1})	Sum (t)	S.D.[a] (kg cell^{-1})	N[b]
06.02.01	0.00685	0	0	1.46115	0.098	0.06291	14389
30.03.01	0.03074	0	0	5.29131	0.442	0.19828	14389
20.01.02	3.29414	2.40437	0	79.43437	47.399	3.98917	14389
26.02.02	5.60659	2.15442	0	651.05222	80.673	27.40756	14389
26.12.02	1.42095	0.55591	0	167.8422	20.445	6.93914	14389
02.01.03	9.60736	3.7353	0	1257.7147	138.240	51.08657	14389

[a] Standard deviation.

[b] Number of cells.

volume is quite similar, the modelled spatial distribution of runoff contributing areas differs. In the first event, a major portion of overland runoff is generated on the frozen slope with northern exposition which represents a typical condition for the catchment. In contrast, the second event occurred on partly frozen soils with runoff on the flat interfluvial areas of limited infiltration capacities. The hot spots of overland runoff generation on the south facing slope are confirmed by field observations and locally called “spring”. At these positions interflow exfiltrates during conditions of high soil moisture in the catchment due to changes in slope and soil characteristics. The role of topography and event pre-conditions is also emphasised by Western et al. (2004), who concluded that controlling processes of runoff generation change between locations and that these processes may vary as the catchment conditions change.

3.3. Snowmelt erosion modelling

The SMEM has a number of parameters to describe the influence of topography and related flow characteristics as well as surface and soil values. Fig. 7 elaborates the average sensitivity (after McCuen, 1973) of selected parameters for soil detachment. If doubling a parameter value results in a doubling of the output values, the sensitivity becomes 1. As

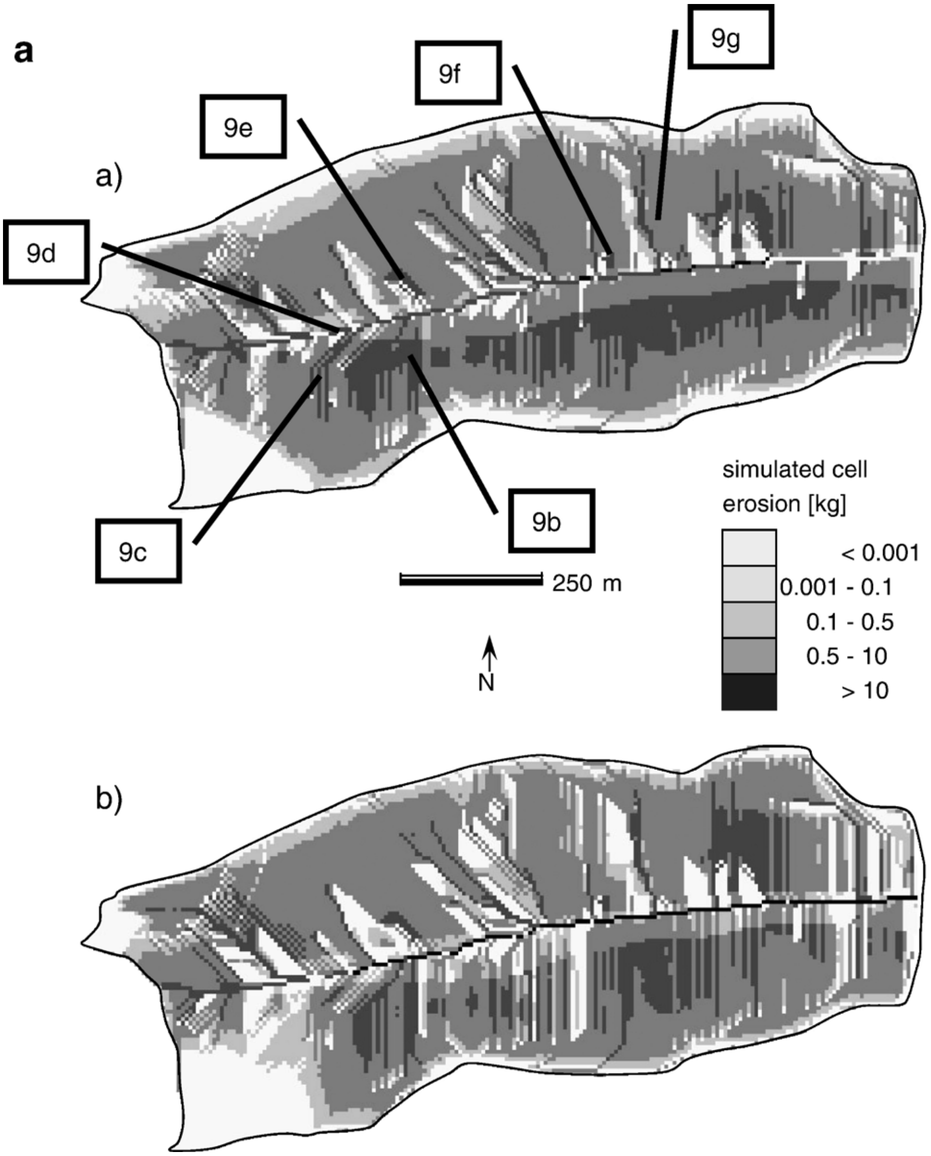

Fig. 9. (a) Maps of simulated cell erosion: a) 20.01.02; b) 26.02.02 and location of photos in panels (b) to (g). (b) Continuation of surface runoff and evidence for sedimentation on a winter grain field after snowmelt at position 1; compare panel (a) (all pictures were selected because of contrast and clarity and are from different snowmelt events). (c) Surface runoff and runoff concentration and micro rill development after snowmelt along tillage direction at position 2; compare panel (a). (d) Bank erosion in the main channel in the upstream area at position 3; compare panel (a). (e) Surface runoff after snowmelt across tillage direction in a winter rape filed and micro rills at position 4; compare panel (a). (f) Surface runoff after snowmelt in a winter rape filed and ponding sedimentation at the boundary to pasture at position 5; compare panel (a). (g) Surface runoff after snowmelt in a winter rape filed without rill incision at position 6; compare panel (a).

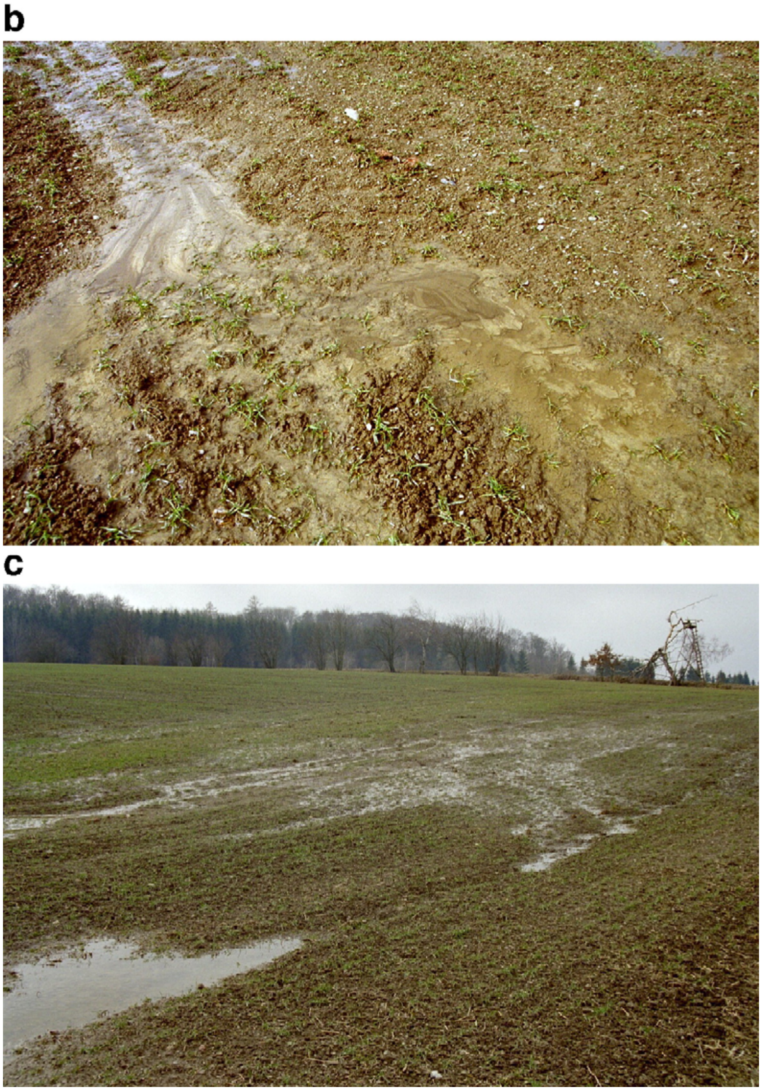

Fig. 9 (*continued*).

to be expected the parameters total runoff volume, average slope and length of flow have a positive sensitivity which is approximately 1. In contrast, the parameters that determine the shear resistance of the soil (Manning coefficient for rills and root density variables n_1, m_1, m_2) have a negative sensitivity ranging from -0.5 to -1.2. In general, the sensitivity is well balanced because no parameter has a remarkable high or low value. The unobtrusive sensitivity of runoff volume for the estimation of erosion is, in combination with realistic model estimates for runoff, of high importance for the trustworthiness of the results, since modelling errors may increase linearly or even exponentially in a chain of models. However, the non-linearity of the algorithms or combinations of variable values may cause a partly higher sensitivity in the possible range for the parameter settings. Although the average sensitivity of the diameter of water stable aggregates (D_{wsp}) is 0.23 mm, these can vary from approximately -1.1 to 0.6 for a D_{wsp} of 1 mm for different Manning coefficients for rill surfaces (Fig. 8). Related to the given Manning coefficient, the largest increment occurs for the diameter range of coarse silt to sand which is also the most common range for water stable aggregates. Thus, a change in one parameter value may not consequently lead to a unidirectional modification of model output.

The application of the SMEM for the six snowmelt events in the Schäfertal was conducted with one set of parameters. These values were determined from the literature (i.e. Manning coefficient for rills) or from laboratory experiments with similar soils (Kusnetsov et al., 1999). The mean values of cell erosion vary between 0.006 kg (0.0006 t ha^{-1}) for the event on 06.02.01 and 9.6 kg (0.96 t ha^{-1}) on 02.01.03 (Table 3). The maximum values range from 0.14 t ha^{-1} to 125.7 t ha^{-1} and a low mean that is within an order of magnitude also found in the literature; e.g. Hebel (2003) for experiments in Switzerland or Basic et al. (2004) on comparable soils and land use in Croatia with rainfall-driven erosion. Furthermore, the median and high standard devia-

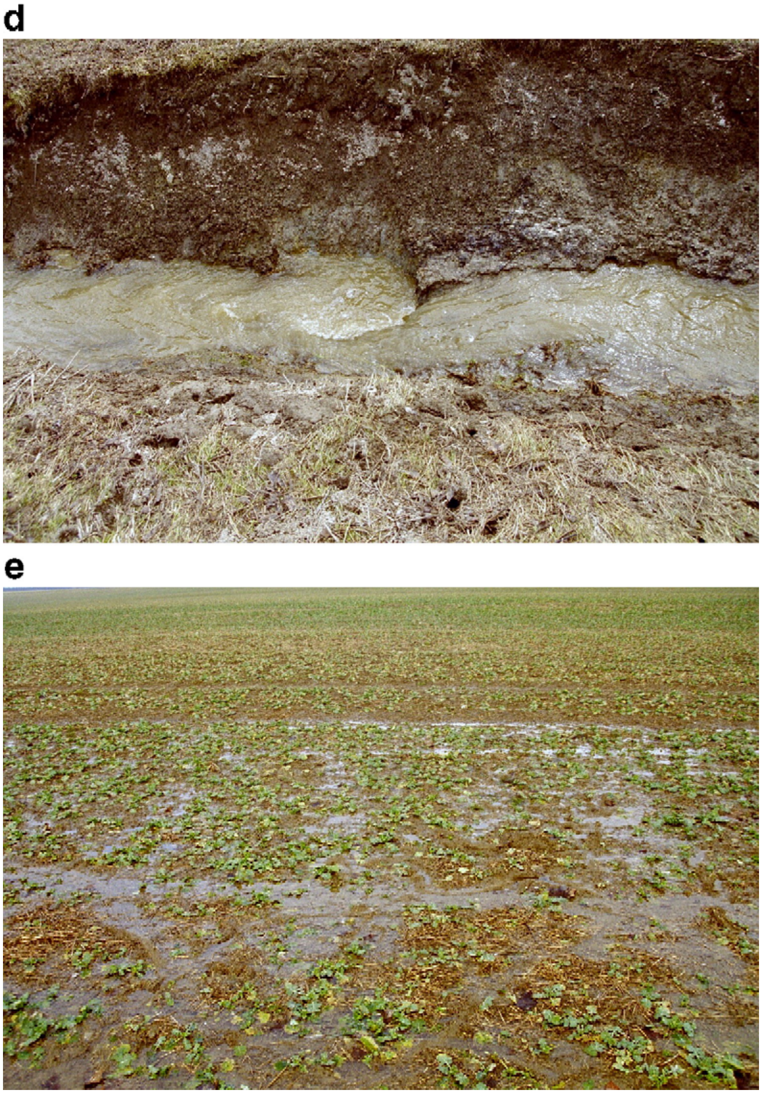

Fig. 9 (*continued*).

tions for the single events indicate a dominance of low values of cell erosion. The sum of erosion for the events with unfrozen soil and low amount of overland runoff is of a factor 50 below those with frozen or partly frozen soil. However, the results are more comparable for a unit discharge of 1 mm overland runoff, for which the erosion varies from 6.3 t mm^{-1} to 13.6 t mm^{-1} for the catchment with an average of 10.1 t mm^{-1}. Fig. 9a compares the spatial heterogeneity of cell erosion for the events on 20.01.02 and 26.02.02 both with similar amounts of overland runoff but differences in the sum of erosion, which is 47.4 t and 80.7 t, respectively. The cause originates not in the average values but in the extremes that are caused by differences in runoff generation and flow concentration in shallow depressions on the south facing slope. Runoff accumulation and runoff concentration downslope is a major factor which influences rill incision. However, compared to the spatial differences in runoff-generating areas, these are diminished for erosion because of the runoff routing process that is conducted before the calculation of soil detachment.

The importance of spatial evaluation of distributed erosion models is underlined by Takken et al. (1999) by examination of the behaviour of the LISEM model. They emphasise that an “outlet” validation is insufficient. However, detailed data on the spatial variations of erosion in a catchment on a single event level are sparse. More often the model is validated for single events on a descriptive level that compares observations of erosion features with model results (i.e. Schmidt et al., 1999; Hessel et al., 2003a). Rills were observed for a number of events in the areas of flow concentration of the slopes in the Schäfertal but due to the temporary character of small rills, which rapidly disintegrate or are destroyed by consecutive rainfalls, the observations are incomplete (Fig. 9b–g). Forested areas, gravel roads and pasture are in reality characterised by low values of erosion and are reflected in the model results. However, due to the large size of the arable fields in the

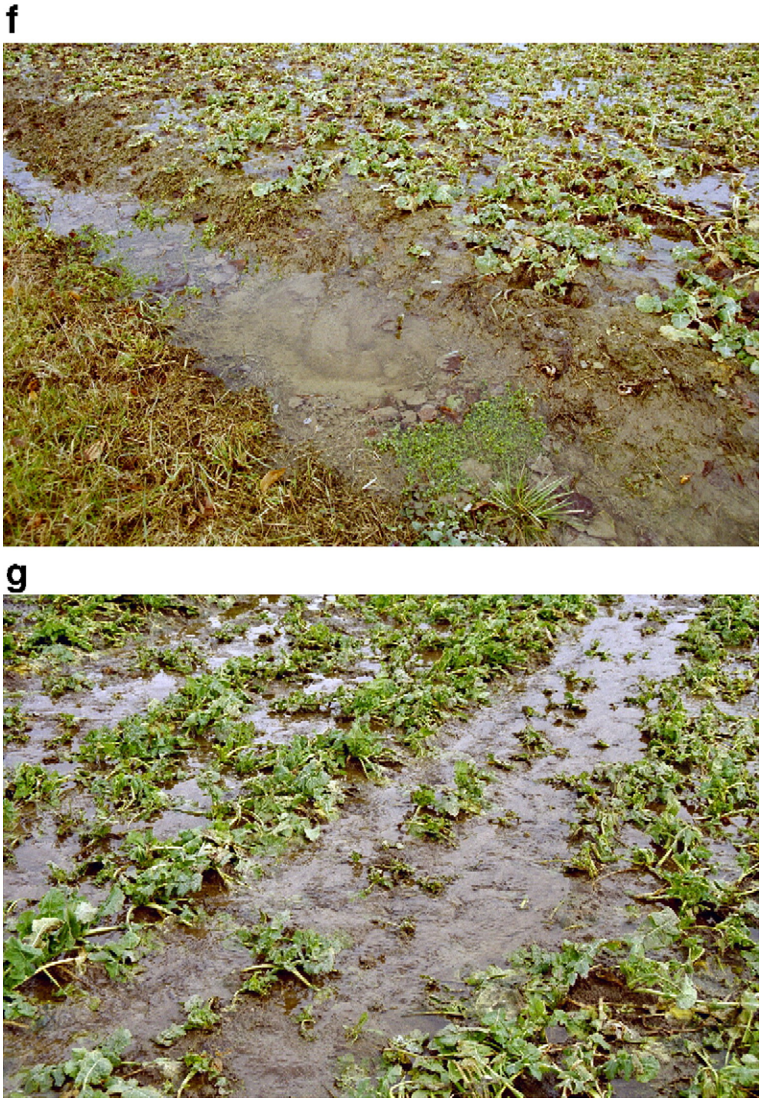

Fig. 9 (*continued*).

catchment and homogenous agricultural practice land use can not be the explanation for small-scale differences. A confirmed agreement between observations and model results can be found for the application of the SMEM in the Schäfertal catchment although no quantitative verification of the model results is possible.

3.4. Sediment yield modelling

Using the overland runoff estimation from WaSim and the cell erosion from SMEM, which respectively replace the SSC-curve number runoff and the RUSLE calculation in AGNPS, the sediment yield was modelled with recursive routing routines. The transport capacity was calculated with a modified Bagnold's approach. A calibration of the sediment yield of the 20.01.02 event was conducted by varying the Manning coefficient, which is known to be a sensitive parameter in AGNPS (Ollesch et al., 2003). All other snowmelt events were modelled with these calibrated parameter values. Table 4 demonstrates the high variability between the events through comparison of means which range from 0.0 to 0.200 t and maximum values from 0.014 to 28.256 t cell-based yield. Evidently, high sediment yield is concentrated in only a few areas or flow lines. However, processes of deposition lead to a simulation of sediment yield at the catchment outlet which varied from 0.0 to 13.84 t. In general, the sediment yield is underestimated with the exception of the 26.02.02 event which sums to a total error of approximately 11 t for the three winter seasons. This is caused by oversimplifications of the channel processes in AGNPS in which parameter estimations for channel characteristics may result in deposition, whereas transport or even sediment scouring should occur. The discrepancy between modelled and observed net erosion is greatest for the event of 26.12.02 which occurred after a storm in November and channel maintenance in mid-December. Hence, it is probable that a sediment flushing out of the catchment took place which

Table 4
Statistics of the sediment yield modelling with IWAN and comparison with observed values

	Mean (t)	S.D.[a] (t)	Maximum (t)	Simulation total yield (t)	Observed yield (t)	Error (t)
06.02.01	0.000	0.001	0.014	0.000	0.360	−0.360
30.03.01	0.000	0.003	0.112	0.030	0.730	−0.700
20.01.02	0.200	0.976	22.956	4.260	4.900	−0.640
26.02.02	0.087	0.535	15.497	3.740	1.810	1.930
26.12.02	0.015	0.110	3.364	0.580	8.500	−7.920
02.01.03	0.184	1.170	28.256	13.840	17.220	−3.380
Average	0.081	0.466	11.700			
Sum				22.450	33.520	−11.070

[a] Standard deviation.

transported material that was made available through previous storms.

Ambiguity in the simulation also results from temporal variability in the Manning's roughness coefficient, which is difficult to estimate (i.e. Li and Zhang, 2001; Sepaskhah and Bondar, 2002). The sediment yield at the catchment outlet is overestimated only for the event on 26.02.02 with almost double amounts of sediments simulated compared to observed values. By increasing the value of n to 0.08 (straw on the surface), which was originally calibrated at 0.03 (bare smooth soil or rills, Young et al., 1994), the model simulates 1.98 t which is much closer to the

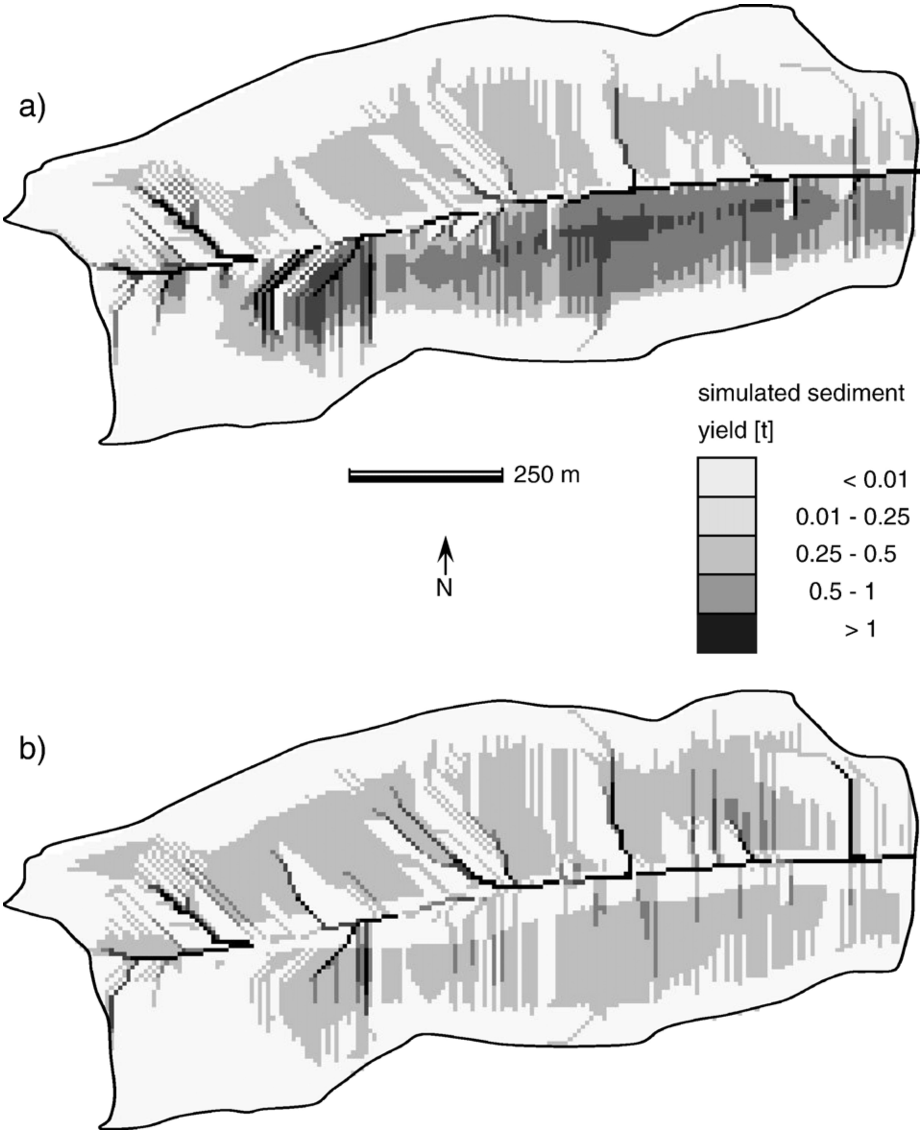

Fig. 10. Maps of simulated sediment yield: a) 20.01.02; b) 26.02.02.

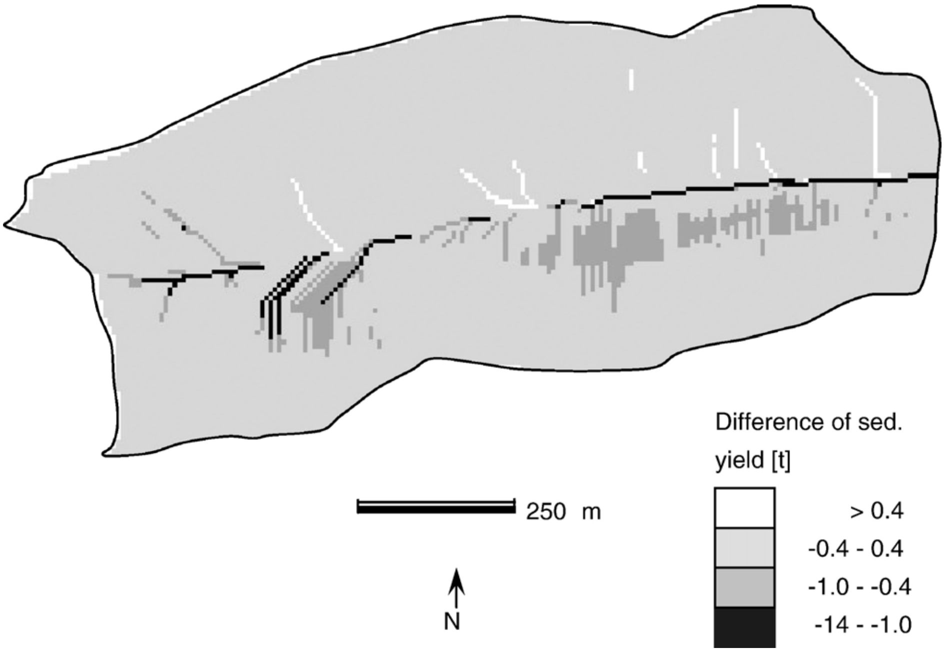

Fig. 11. Map of calculated differences in sediment yield (26.02.02–20.01.02).

observed sediment yield. The estimated value for *n* remains in a realistic range. High sensitivities of Manning *n* for soil loss on a single event level is also discussed by Folly et al. (1999) for the EUROSEM model. They found that calibrated parameter values do not necessarily agree with field measurements or estimations. In addition, Hessel et al. (2003b) describes a dependency of Manning *n* with slope. Thus, in a catchment with a concave–convex differentiation of slopes like the Schaefertal, a spatial heterogeneity of surface roughness may also exist. Additionally, the surface roughness underlies a complex temporal variability, which is especially extreme during frozen soil conditions and subsequent storm events. Temporal variability and spatially differentiated overland runoff generation and soil detachment results when using different Manning coefficients.

Fig. 10 characterises the simulated sediment yield for the two events from 20.01.02 and 26.02.02, respectively. Major differences occur on the southern slope which has higher simulated sediment yield for 20.01.02 and the related sedimentation in the pasture or set-aside area in the central part of the valley. This slope shows low values of simulated yield for 26.02.02. Decrease of sediment yield by sedimentation is indicated by a downstream change from dark grey to light grey. Theses differences in yield, defined as downslope accumulation of sediment, may be induced by changes in slope or surface roughness. Thus, the borderline of the arable land to the pasture or set-aside area with high roughness is reproducible through lowered yield values (compare Fig. 1 for land use).

High sediment yield is also modelled on the northern slope due to the topography which causes a concentration

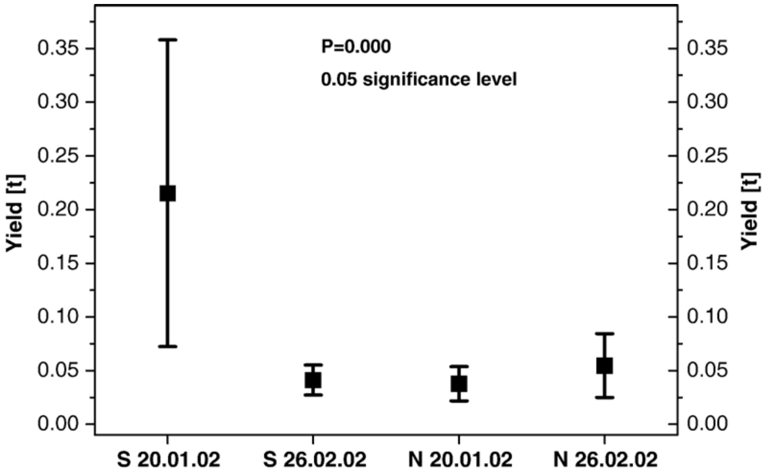

Fig. 12. Comparison of sediment yield per cell for two events and different exposition with one-way ANOVA (S – southern slope; N – northern slope).

of overland runoff, although lower erosion originates in most of the cells on the northern slope. Despite similar overland runoff volume the spatial distribution of runoff-generating areas results in higher yield in these shallow depressions for the event on 26.02.02, whereas for 20.01.02 the channel itself yields high sediment load and the locations of high yield is concentrated on the south-west portion of the catchment (Fig. 11). One-way analysis of variance (SYSTA 8.0) shows that the southern slope not only has a significantly higher average yield on 20.01.02 (Fig. 12), but the connectivity of the source area to the channel in the south-western part of the catchment (yield up to 5.8 t) leads to an overall higher simulated yield for this event. The general distribution of source areas coincides with field observations. However, the quantitative precisions of spatially distributed results are not verified for the Schäfertal catchment on a single event level.

4. Conclusions

The field measurements and observations in the Schäfertal clarify the individual character of runoff generation and related erosion as well as sediment yield during single snowmelt events. This is not only the case for averaged values at the catchment outlet but also for spatially heterogeneous processes. The benefit of continuous hydrological modelling within the model system IWAN gives a reliable estimation of temporal and spatial differentiation of soil moisture in the catchment. This is the basis for characterisation of runoff-generating processes and estimation of erosion. The sensitivity analysis of significant parameters of the SMEM, which was firstly applied at the catchment scale, shows a plausible reaction of the model and no outstanding sensitivity of a single parameter. Although the spatial heterogeneity and the dimension of simulated erosion are realistic, a verification on the single event level is difficult. In any event, the SMEM does create an opportunity to model snowmelt erosion on a physical basis. The good agreement of observed and modelled sediment yield supports the quantity and quality of SMEM results. Uncertainty in the results of sediment yield estimations is acceptable due to the difficulties in determining the Manning surface roughness coefficients during winter and snowmelt periods. However, a characterisation of the Manning parameter was not the scope of this study and a calibration procedure for n was conducted only for one event. Thus, a more flexible parameterisation is desirable and a model version with a temporally variable set of parameters is in preparation. The model system IWAN is robust and no cumulative addition of error and sensitivity has been detected. Moreover, the results reflect the individuality of events. Further tests and improvements are planned for catchments in Russia and China.

Acknowledgement

This work was financed by the German Federal Ministry of Education and Research (BMBF) and is part of the joint German–Russian Project “Volga-Rhine”. Contract nos.: 02WT0099 and 02WT0482.

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