

Dynamic and modelling of sediment associated nutrients in a low mountain environment

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Abstract The characterization of the temporal variability and the spatial heterogeneity of particulate phosphorus transport is important for mitigating nonpoint sources of pollution. Investigations were conducted in the 1.44 km² Schaefertal catchment, which is located in the lower Harz Mountains, Germany. Continuous measurement of discharge and event-based automatic sampling were carried out for sediments and phosphorus (P) at the catchment discharge gauge station. The modelling tool WASIM/AGNPS/SMEM/ANIMO was used to analyse the spatial heterogeneity of runoff and to identify phosphorus source areas, especially in the winter. The complex catchment response to runoff generation and sediment and P transport is shown in hysteresis curves that are both clockwise and anti-clockwise. There is also evidence for the depletion of sediment availability during some events. An event specific sediment/P relationship can be identified as a result of source area characteristics and the characteristics of runoff connectivity to the channel. The sediment/P ratio is significantly higher in the case of long transport distances in the catchment compared to short transport distances, with source areas near the gauge station. Phosphorus export coefficients, or similar empirical tools, do not seem applicable in the Schaefertal catchment since the hydrological characteristics lead to event-based differentiated P enrichment in suspended sediment. The proposed modelling approach is mainly process-oriented, and can be used to identify management options in small-sized catchments.

Key words AGNPS; erosion; Germany; modelling; phosphorus; WASIM; winter condition

INTRODUCTION

Agriculture is one of the dominant sources of phosphorus (P) losses to surface waters. Frequently, the displacement of P is sediment-associated. Therefore, a thorough knowledge of runoff-generating mechanisms and erosion processes is essential to identify spatially heterogeneous and temporally variable “hot spots” that act as P sources. The objective of this paper is to: (a) investigate the dynamic behaviour of sediment-associated P transport in a small headwater catchment, especially for winter conditions; and (b) introduce modifications of an erosion and phosphorus transport modelling system (Ollesch *et al.*, 2004).

MATERIALS AND METHODS

Study area

The 1.44 km² experimental catchment “Schäfertal” is located in the Harz Mountains, northeast Germany, approximately 150 km southwest of Berlin. The outlet of the catchment is at an elevation of 392 m a.s.l. (Fig. 1). Average annual rainfall is approximately 640 mm; the average annual temperature is 6.8°C, ranging from –1.8°C in January to 15.5°C in July. The evident seasonality in discharge is mainly caused by variations in evapotranspiration and modifications of baseflow, caused by attendant mining activities in the region that were ongoing until 1990. Discharge varies from less than 10 l s⁻¹ in summer to above 200 l s⁻¹ during winter.

The predominant soil units are Luvisols and Cambisols; these have developed on loess sediments on slopes, and are used intensively for agriculture (Altermann, 1985). Major crops are winter cereal and rape in a rotation of various lengths. Triticale and peas have become more important in the last three years. The Gleysols at the valley bottom are utilized for pasture, or represent set-aside areas.

The hydrological and meteorological observations and measurements in the catchment started in the early 1960s. A monitoring programme for erosion as well as sediment and nutrient loads was established in 1998. The regular biweekly runoff sampling scheme for major nutrients and suspended sediments at the catchment outlet is supplemented by an automatic sampler (ISCO 6700 Series). The starting water level for sampling, and the time interval for sampling, is seasonally adjusted (2 h during

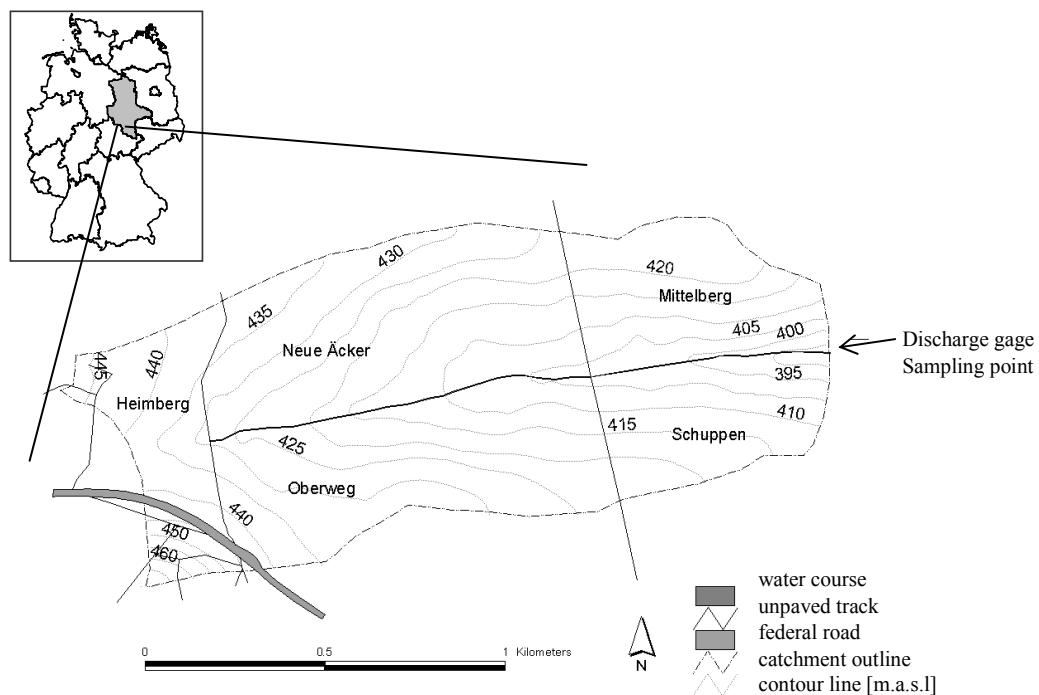


Fig. 1 Characteristics of the Schäfertal, and division into fields, by name, along with an accompanying map that locates the catchment within Germany.

winter). In addition to water temperature and specific conductivity, the relevant parameters are suspended sediment concentration (SSC), total P, dissolved P, reactive P, nitrate, ammonium and dissolved organic carbon. The treatment of the samples and laboratory analyses follow standard procedures (Flynn, *et al.*, 2002). Special attention is paid to measurements of winter runoff and erosion, since the autumn of 2000. Erosion is mapped after relevant events.

Model description

For this investigation important model requirements are: (a) a capacity to represent the spatial heterogeneity of runoff and P availability; and (b) to simulate soil detachment during snowmelt, under frozen soil conditions. Therefore, a system of loosely coupled models was developed, that consist of four independent modules and several pre- and post-processing procedures. The core of the modelling system is represented by the hydrological model WASIM-ETH version 2, that has been amended with a soil temperature module (Schulla, 1999; Ollesch *et al.*, 2004). Results of the soil/water balance from WASIM are utilized to calculate the P turnover with ANIMO 3.5 (Groenendijk & Kroes, 1999). The WASIM-AGNPS model coupling was enhanced with the addition of a new snowmelt erosion model (SMEM) that is based on an estimate of overland runoff from WASIM (Sukhanovski *et al.*, 2004). A first application of this model, at the plot scale, was satisfactory (Ollesch *et al.*, 2003). AGNPS 5.0 is a distributed, raster-oriented, event-based model that calculates erosion, suspended sediment, and nutrient transport at the catchment scale (Young *et al.*, 1995). The internal calculations for erosion and P availability are replaced and augmented with the results from ANIMO and SMEM.

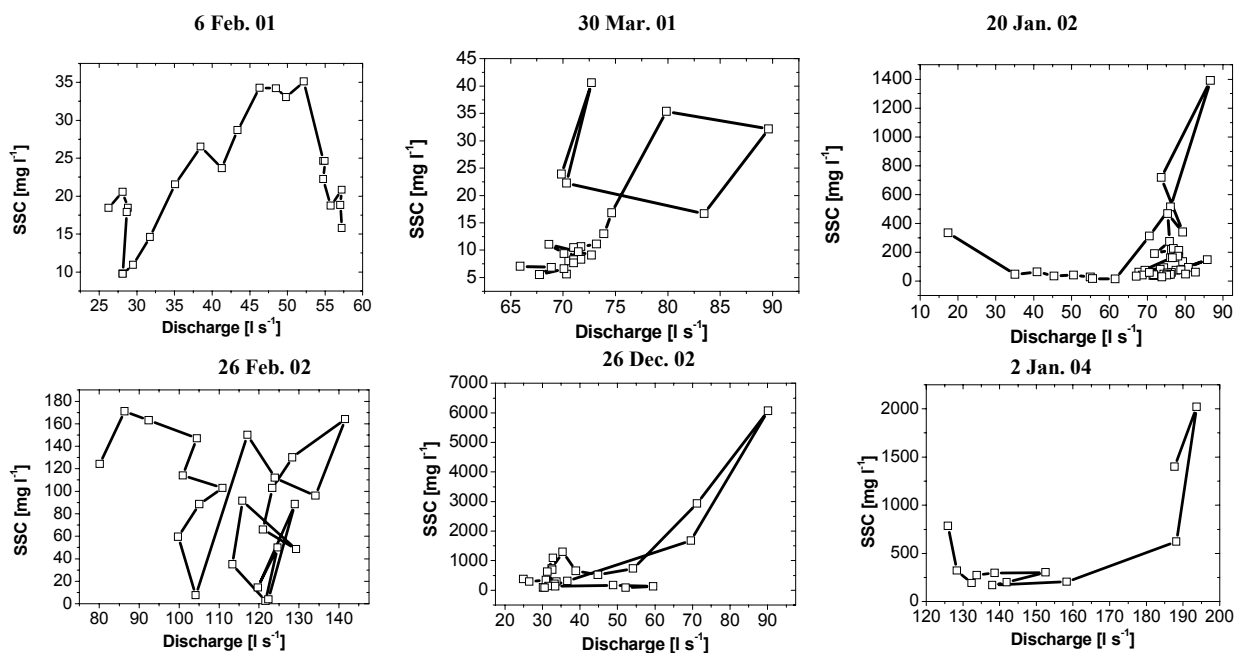
RESULTS AND DISCUSSION OF FIELD EXPERIMENTS

Ten events have been recorded and automatically sampled since the beginning of the experimental work that has focused on winter situations. Two events were excluded from the data pool because channel work was ongoing at the time of the event. The unaffected high water events caused 90% of the total sediment yield, and two-thirds of the total P load. Six of the eight events were related to winter conditions (i.e. snowmelt, rain on snow, or frozen soil), and caused a total sediment yield of 33.52 t at the catchment outlet (Table 1). An additional 10.46 t were transported out of the catchment by two rainfall/runoff events in May 2002 and November 2002, respectively. The hydrological parameters, as well as the sediment and nutrient characteristics, of these events differ due to changes in the dominant runoff processes (Ollesch *et al.*, 2004). The maximum SSC for the events varies from 35.1 to 6065 mg l⁻¹. In comparison with some literature values, this concentration range, and the resulting net erosion are low, although the generation of small rills are frequently observed (i.e. Baade, 1996; Steegen *et al.*, 2000). However, the values are similar to those that have been gathered from catchments with riparian areas (McKergow *et al.*, 2003). Most likely the pasture and meadows in the central part of the Schäfertal, near the channel, act as a buffer strip for sediment.

Table 1 Characteristics of eight single runoff/erosion events from the Schäfertal.

	Winter situation	Snow/ rainwater equivalent (mm)	Discharge max. (l s^{-1})	Runoff (mm)	Net erosion (t)	SSC max. (mg l^{-1})	Total P yield (kg)
06 Feb. 2001	Unfrozen soil	20 snow	59	10.2	0.36	35.1	3.1
30 Mar. 2001	Unfrozen soil	26 snow + 29 rain	97	2.2	0.73	40.6	2.3
20 Jan. 2002	Frozen soil	50 snow + 34 rain	175 (85 snowmelt)	50 (25 snowmel t)	4.9	1390	8.1
26 Feb. 2002	Partly frozen soil	6 snow + 32 rain	146	19.3	1.81	171	3.3
04 May. 2002	Unfrozen soil	25 rain	27	1	0.26	682.8	0.28
30 Nov. 2002	Unfrozen soil	33 rain	63	4.3	10.2	5200	3.5
26 Dec. 2002	Frozen soil	5 snow + 27 rain	91	5.5	8.5	6065	2.65
02 Jan. 2003	Unfrozen sub- soil	17 Snow + 20 rain	268	20.0	17.22	2020	2.2

The uniqueness of the six winter events is clearly demonstrated by the differences in the hysteresis curves that result from variations in the time for runoff generation, and from the heterogeneity of SSC source areas (Fig. 2). Clockwise hysteresis, and low SSC appears to indicate a sediment source near the catchment outlet, or in the channel itself (i.e. 6 February 2002). On the other hand, slope processes appear to be characterized by counterclockwise hysteresis curves that frequently follow an irregular pattern, as well as low SSC values (i.e. 20 January 2002). This appears to indicate a lack of sediment availability in the final stages of the event.

**Fig. 2** Hysteresis curves for six winter events measured in the Schäfertal catchment.

Total P concentrations that were measured at the catchment outlet of the Schäfertal vary from 0.05 to 1.7 mg l⁻¹. Total P loads for single events range between 0.0125 and 0.05 kg ha⁻¹. However, the ratio of net phosphorus yield to net erosion declined from 1:100 to 1:900 in the first two years of observation, to 1:3000 to 1:7500 in the third year. Strong positive correlation coefficients exist between SSC and total P for single events. This appears to demonstrate that P transport in the Schäfertal is dominated by suspended sediment, and may be the result of a soil texture that is dominated by silt-sized particles (65–70% of the total) and/or aggregates of similar size (Fig. 3). Thus, a selective detachment, or transport of soil particles with different enrichment ratios, appears to be of minor importance. However, the existing differences in the P enrichment ratio may indicate the existence of variable sources. In the Schäfertal catchment the source areas and transport processes appear to be controlled by agricultural practices. In 2001 and 2002, the application of fertilizer led to a significantly greater availability of phosphorus near the catchment outlet. In contrast, in 2003 fertilizer was deployed on a field that had a low potential for erosion, reduced connectivity to the stream channel, and at a much greater distance from the sampling point. The greater distances between sediment and P sources in 2003 may account for the high sediment loss, and low P yield, during that year. At the same time, the initial source of phosphorus detected in the early part of this study, apparently has been depleted. However, the available data are still insufficient to allow generalizations.

RESULTS AND DISCUSSION OF MODEL APPLICATION

The results from the hydrological model WASIM are in good agreement with actual measurements in the Schäfertal (see Fig. 4, which displays a comparison between simulated daily discharge and actual observations). The model was calibrated with a

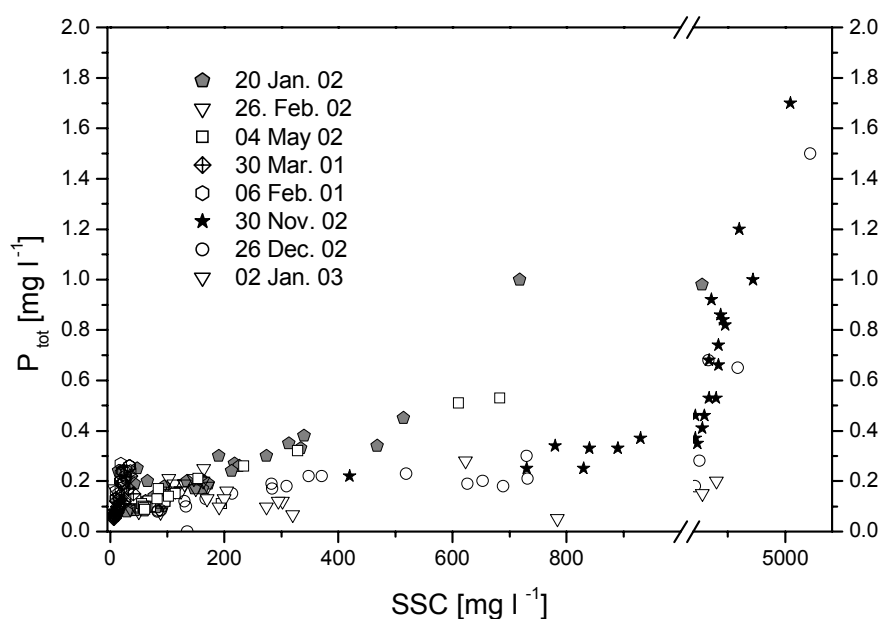


Fig. 3 Relationship between suspended sediment concentration (SSC) and total phosphorus concentration (P_{tot}) for eight measured events in the Schäfertal.

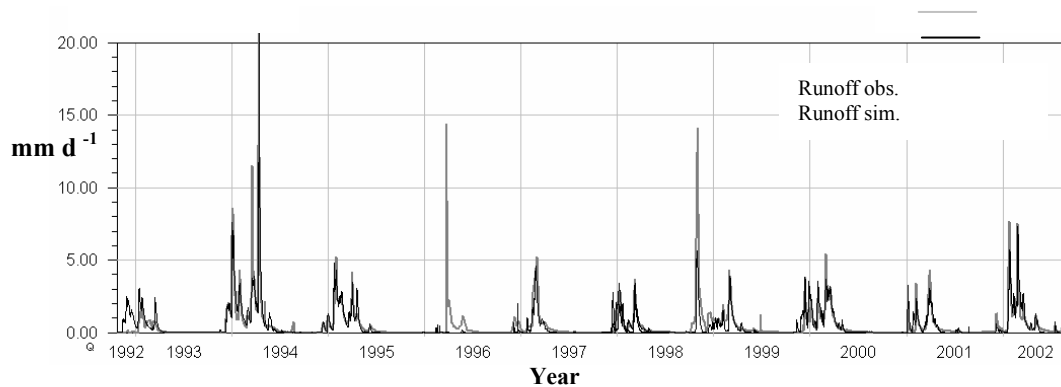


Fig. 4 Observed and simulated total runoff (WASIM) for the Schäfertal catchment.

dataset from the 1993/94 hydrological year, and the selected parameters give reliable results for the ensuing periods. The simulation of the beginning of the runoff period in the autumn, as well as the occurrence of snowmelt floods, and the diminution of discharge in the spring due to high evapotranspiration, reliably matches actual observations. Thus, measures of performance criteria are quite good, and vary between $r^2 = 0.88$ and 0.95 . The only exception is 1996, when the depth of the soil-frost layer exceeded 1 m; this led to the generation of extreme runoff.

The model was also applied to the six winter events that were described previously. There was good agreement between the simulated and observed hydrological characteristics for single events (Table 2). The mean deviation between observed and simulated runoff was 2.3%. However, for single events, differences could reach $\pm 25\%$. The simulated overland runoff coefficient is below 0.001 for events that occurred when the soil was not frozen. However a higher portion of overland runoff is generated for events that occur when the soil is frozen (0.13–0.72). Due to the low amount of overland runoff, and the lack of an algorithm to deal with channel erosion processes, the model tends to underestimate net erosion when the soil is not frozen. Despite these potential shortcomings, model results appear reliable, with the exception of the 26 December 02 event. However, channel modifications were made just before the event, and sediment flushing might have occurred. The variable delivery ratios indicate that the model system appears capable of simulating the uniqueness of events.

Table 2 Summary of observations and model simulations.

	Winter situation	Total runoff:		Surface runoff sim. (mm)	Sum erosion (t)	Net erosion	
		Obs. (mm)	Sim. (mm)			Obs. (t)	Sim. (t)
06 Feb. 2001	Unfrozen soil	10.2	10.5	0.008	0.1	0.36	0.0
30 Mar. 2001	Unfrozen soil	22	16.3	0.04	0.4	0.73	0.03
20 Jan. 2002	Frozen soil	50 (25 for snowmelt)	56/29	7.5	47.4	4.9	4.26
26 Feb. 2002	Partly frozen soil	19.3	20.6	8.1	80.7	1.81	3.74
26 Dec. 2002	Frozen soil	5.5	5.1	1.5	20.5	8.5	0.58
02 Jan. 2003	Unfrozen sub-soil	20.0	25	18	138.2	17.22	13.84

The benefits of having a complex hydrological nonpoint-source pollution model for the identification of nutrient sources is presented by Lindenschmidt *et al.* (2004). In addition, to process identification, and the estimation of suspended sediment and nutrient budgets, the model allows the evaluation of specific management recommendations. The current model appears to accurately simulate spatially distributed runoff, soil detachment, suspended sediment and P transport, and sedimentation processes. The occurrence of soil frost in the Schäfertal is a significant factor in controlling runoff, and can be simulated by the modelling system. For example, on 20 January 2002, the slope with a northern exposure was frozen, and a high proportion of overland runoff was generated from this location (Fig. 5). Consequently, an overwhelming proportion of erosion and deposition took place on this slope. In contrast, on 3 January 2003, the entire catchment, with the exception of the pasture and forest areas, was modelled with frozen soil, and the overland runoff coefficient was much higher than for the northern exposure slope event mentioned above. Due to the better topographic connectivity of the northern slope, the eroded soil particles reached the watercourse more readily, and resulted in a much higher sediment yield from that source area. The modelling results appear to be supported by actual field observations. On the basis of the dynamic spatial approach incorporated into all parts of the model, the simulated results appear to be reliable.

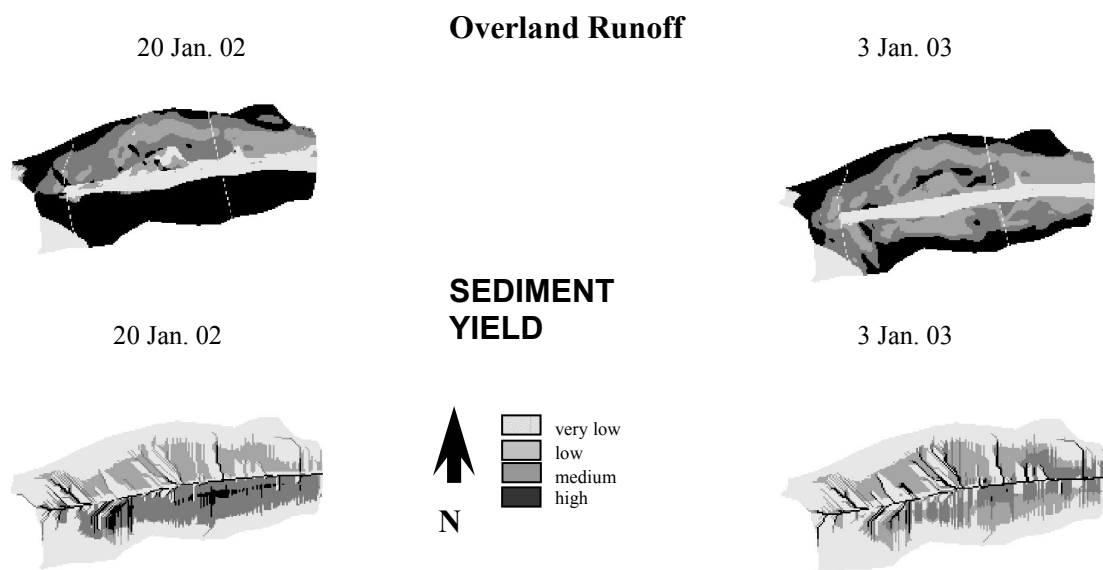


Fig. 5 Sketch-maps of the spatial distribution of overland runoff and sediment yield simulated with the model.

CONCLUSIONS

The results from the Schäfertal catchment demonstrate the dominance of winter runoff and related sediment/nutrient losses. These winter conditions are characterized by highly variable and heterogeneous processes. Thus, sediment and nutrient source areas

are decoupled for some events. This limits the application of static P export coefficient methods, or similar empirical tools. The proposed model is capable of providing insights into the dynamic nature of runoff, and sediment transport within the Schäfertal catchment system, and permits a qualified estimation of sediment and sediment-associated nutrient yields. Further, the model permits the identification of different source areas for individual events. Further testing of the model is planned, under markedly different soil climate conditions, in Russian catchments.

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