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Distributed modelling of mean annual soil erosion and sediment delivery rates to surface waters

Björn Tetzlaff [a,*], Klaus Friedrich [b], Thomas Vorderbrügge [b], Harry Vereecken [a], Frank Wendland [a]

[a] Forschungszentrum Jülich GmbH, Agrosphere Institute (IBG-3), D-52425 Jülich, Germany
[b] Hessian Agency for the Environment and Geology, Department for Soil Protection and Soil Information, Rheingaustraße 18, D-65203 Wiesbaden, Germany

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ABSTRACT

Soil erosion on arable land and on steep vineyards is a major problem in the state of Hesse (21,115 km^2) in central Germany. The aim of a joint study between the Research Centre Jülich and the Hessian Agency for the Environment and Geology was to identify parcels which are severely affected by water erosion and to identify areas at risk for sediment input to surface waters. For this purpose, the ABAG, an adaption of the USLE approach to German conditions, has been employed with the best available data sets on K-, C-, R- and LS-factors. Model results show that soil losses in Hesse vary between <0.5 and >15 tonnes/(ha·year). The mean loss amounts to ca. 4.3 tonnes/(ha·year). The sediment delivery ratios for 450 sub-catchments range between 0.5 and 78% with a mean of 18%. An uncertainty analysis based on Gaussian error propagation and Monte Carlo simulation showed that the uncertainty of model results induced by input data is ±1.7 tonnes/(ha·year) or ±34%. The model results are employed for further use in a soil erosion atlas and internet-based soil data viewer.

1. Introduction and background

Impaired quality of surface waters is a major issue in the state of Hesse, central Germany. Achieving environmental targets is at risk due to the ecological harm caused by high sediment and phosphorus inputs from diffuse sources. Therefore, decision-making in soil and water resources management is crucial, e.g. in the frameworks of the Federal Soil Protection Act from 1998 and the Federal Soil Protection and Contaminated Sites Ordinance from 1999, with regard to the implementation of the European Water Framework Directive (EU-WFD) or concerning the implementation of integrated agri-environmental schemes. Devising cost-efficient measures should be based on spatially distributed data on water erosion and sediment delivery to streams in order to delineate priority areas. The Hessian area prone to soil erosion makes up 19% of the total state area (21,115 km^2) comprising arable land, vegetable production and vineyards on steep slopes. Furthermore, crops are grown partly on loess sites at higher inclination. 98% of all slopes in the area potentially prone to erosion show an inclination of lower than 10° (Fig. 1).

Since 1988 decision-making for tackling water erosion on agricultural land in Hesse is based on the erosion risk map (Mollenhauer and Richtscheid, 2006; Richtscheid, 1996). This map differentiates six risk classes depending on the degree of slope, soil texture, amount of precipitation as well as the consideration of loess distribution and slope shape. This results in qualitative descriptions of the natural disposition for erosion on a medium scale (ca. 1:50,000). Problems related to the use of this map are, among others, heterogeneous methodologies applied to arable land and vineyards, big scale differences of input data (1:25,000 up to 1:1 Mio) and the use of soil textures averaged over the entire soil profile.

To solve these problems comprehensive re-modelling of the erosion risk in Hesse is indispensable. As mentioned before, it is intended to employ these modelling results for several fields of application in the field of soil and water resources management by the Hessian Agency for the Environment and Geology. Therefore the chosen model approach needs to be sufficiently detailed to make use of the available data sets with high spatial resolution at the field and watershed scale. Additional data collection in the field for the entire state area is not feasible at this stage. The aim of a joint project between the Hessian Agency for the Environment and Geology and the Forschungszentrum Jülich was to achieve parcel-differentiated, semi-quantitative results on erosion risk and sediment input to surface waters for the entire state of Hesse (21,115 km^2). Here, sediment is understood as detached soil being transported to streams. Stream bank, bed erosion or other sediment sources in the landscape are beyond the scope of this study.

The aims of this paper are (i) to give an overview on the model routines to quantify water erosion and sediment delivery, (ii) to analyse the uncertainty of a large-scale model application using spatial data with high resolution and (iii) to demonstrate the model application for a large-scale study region in central Germany.

* Corresponding author. Tel.: +49 2461 613648; fax: +49 2461 612518.
E-mail address: b.tetzlaff@fz-juelich.de (B. Tetzlaff).

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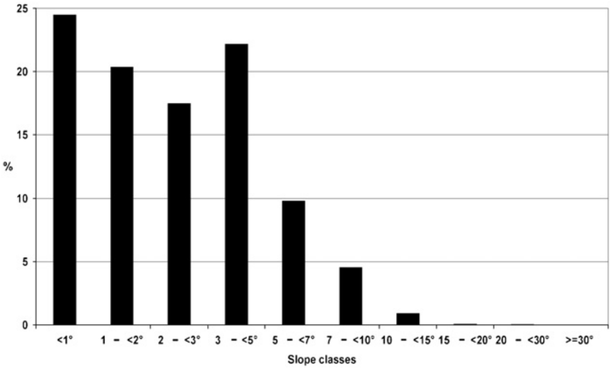

Fig. 1. Distribution of Hessian slope classes for the arable land area prone to erosion.

2. Methodologies and input data

The approaches for modelling sediment input to surface waters are part of the MEPhos model for area-differentiated quantification of mean long-term phosphorus inputs in large river basins or landscapes. MEPhos considers point and diffuse sources via eight different pathways. It has been applied already to six different German states to estimate phosphorus loadings in streams for planning purposes (Tetzlaff, 2006; Tetzlaff et al., 2009a,b).

2.1. Approaches for modelling sediment input and data sources

The routine for quantifying the mean annual soil loss and sediment input is based on the ABAG approach which represents a transfer and adaptation of the Universal Soil Loss Equation (Wischmeier and Smith, 1965) to German conditions by Schwertmann et al. (1990). The ABAG approach is still the erosion estimation method which comprises the highest degree of adaptation to German conditions and is applicable to large areas with existing data. The mean annual long-term risk for sediment input to surface waters is given according to Eq. 1. The input data are listed in Table 1.

$$SI = R \cdot K \cdot LS \cdot C \cdot P \cdot SDR_{sb} \quad [\text{kg}/(\text{hectare} \cdot \text{year})] \tag{1}$$

SI: Sediment input into surface waters [tonnes/(ha·year)], R: Rainfall and surface runoff factors [N/(h·year)], K: Soil erodibility [t·h/(ha·N)], LS: Combined factors concerning hill length and slope [−], C: Cropping factor [−], P: Erosion protection factor [−], SDR_{sb}: Sediment delivery ratio [%/100]

Field data of arable land, vineyards and areas with specialised crops are available with parcel geometries for the entire state (ca. 655,000 parcels, Table 1). Furthermore, annual crop type information for arable land and specialised crops is provided for the years 2004–2008 allowing for the estimation of field-specific C-factors which have been determined in line with recommendations of Schwertmann et al. (1990) first and then approved by regional agricultural experts. C-factors in Hesse vary between 0.03 and 0.35 with a mean of 0.13. Conventional tillage is assumed to occur state-wide due to a lack of additional information. No information is available for the P-factor, hence it is set equal to 1.

Table 1
Data sources for modelling erosion risk and sediment input risk in Hesse.

Data set	Source
Land use and crop information	InVeKoS field data (years 2004–2008), land parcel information ALK F021, Vineyard register
K-factor	Soil mapping on field scale 1:5000, soil texture of the upper horizon, stone content
R-factor	Precipitation data 1971–2000 (National Meteorological Service DWD)
Digital Elevation Model	DRM 20 (20 m·20 m)
Infrastructure network	Railway lines, motorways, national and county roads, farmers roads
River network	ATKIS DLM 25 (Hessian State Office for Land Management and Geoinformation)

Soil erodibility data (K-factor) is provided by the soil data base of the Hessian Agency for the Environment and Geology. These data result from field mapping, where, among others, soil texture and stone content of the upper horizon were determined. The Eqs. (2) and (3) describe the way how these field observation data were transformed into K-factors using classified soil texture data Eq. (2) or lab analyses on soil textures Eq. (3). K-factors in Hesse range between 0.01 and 0.63 and have a mean of 0.4.

$$K = (KB \cdot KH + KA + KD) \cdot KS \tag{2}$$

K: K-factor, K_B: Share of K-factor depending on soil texture, K_H: Share of K-factor depending on humus, K_A: Share of K-factor depending on soil aggregation, K_D: Share of K-factor depending on hydraulic conductivity, K_S: Share of K-factor depending on stone content

$$K = 2.77 \cdot 10^{-6} \cdot M^{1.14} \cdot (12 - OS) + 0.043 \cdot (A - 2) + 0.033 \cdot (4 - D) \tag{3}$$

M: (% Silt + very fine sand) · (% Silt + % Sand), OS: % organic substance, A: class of soil aggregation, D: class of conductivity.

Rain erosivity was estimated from long-term precipitation measurements at 18 stations, equipped with pluviographs for continuous recording of precipitation. Breakpoints were reached after 10 mm rainfall. The stations were located in the neighbouring state of Bavaria, south-east to the state of Hesse (Schwertmann et al., 1990). State-wide applicability has been achieved in Bavaria by a regression between the rain erosivity estimated for the stations and the precipitation sum from May–October 1967–1976 with a correlation coefficient r of 0.961 (Eq. (4)). This regression is also being used for Hesse. The R-factors in Hesse vary between 41 and 75 and have a mean of 50.

$$R = 0.1408 \cdot P_{Sum} - 1.47 \tag{4}$$

R: R-factor [N/(h·year)], P_{Sum}: Precipitation sum May–October (mm/year)

The LS-factor is derived in MEPhos after the algorithm from Moore and Burch (1986) pointed out in Eq. (5). Dirt roads and railway lines flatten the slope locally and act as barriers reducing the erosive hill length in most cases. Therefore, the road and railway networks are considered in the delineation process of the LS-factor using a highly-resolved digital elevation model (20 · 20 m^2), see Table 1. Furthermore, the parcel boundaries are considered as barriers, too, based on the field observation that small grass strips and/or small trenches exist between most fields in Hesse. The mean LS-factor in Hesse is 1.7. Values <1 occur in flat regions, like the Hessisches Ried (between the Odenwald forest and the Upper Rhine valley), in the Wetterau north-east of Frankfurt and the Hessian depression. High LS-factors >5 are to be found rarely, because terraces and dirt roads in the steep vineyards along the River Rhine have a strong reducing effect on the LS.

$$LS = 1 + 0.4 \cdot \left(\frac{A}{22.13}\right)^{0.4} \cdot \left(\frac{\sin S}{0.0896}\right)^{1.3} \tag{5}$$

LS: length–slope-factor, A: contributing area (m^2), S: degree of slope (°)

Sediment delivery to streams affects only a small share of agricultural land prone to erosion, due to the fact that a hydraulic connectivity between parcels and sediment receiving streams is required. Studies on