Land Use Policy 27 (2010) 997–1009

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

A pragmatic approach for soil erosion risk assessment within policy hierarchies

Martin Volk[a], Markus Möller[b,*], Daniel Wurbs[b]

[a] UFZ - Helmholtz Center for Environmental Research, Department of Computational Landscape Ecology, Permoserstr. 15, 04318 Leipzig, Germany
[b] Geoflux GbR, Lessingstr. 37, 06114 Halle (Saale), Germany[1]

ARTICLE INFO

Article history:
Received 30 May 2009
Received in revised form 3 December 2009
Accepted 8 December 2009

Keywords:
Soil erosion
Soil protection
Scales
Processes
Models
Agricultural policy

ABSTRACT

This paper presents a methodological framework for scale-specific assessment of soil erosion by water. The framework enables the definition of hierarchical, functional and modular nested reference units which result from the integrated consideration of policy, process and model hierarchies. The framework is applied on three planning levels: at first, large scale zones are designated that show a defined risk potential for soil erosion (first level: catchments and drainage areas in the German Federal State of Saxony-Anhalt, ca. 20,000 km^2). By both increasing model complexity and spatio-temporal resolution of input data, the results are locally specified within these risk zones (second level: designated farms and fields in a study area of 141 km^2). This is the basis for the prediction of soil erosion areas and sediment transport to hydrologic drainage networks as well as for small scale management and measure planning (third level: designated field blocks in the study area). On this level, the mitigation of soil erosion and sediment entry to the river system is demonstrated by simulating the introduction of conservation management practices, vegetation and riparian buffer strips.

We used a modified version of the empirical Universal Soil Loss Equation (USLE) ABAGflux, which includes functions to better describe sedimentation and sediment transport to hydrologic drainage networks. Aggregation and statistical methods like SICOM and *k means* cluster analysis were applied for objective ranking and classification of the simulation results. The study aims at contributing to an improved applicability of data and methods for the assessment of soil erosion by water and soil protection on relevant planning scales. In addition, the results are considered to be important for an improved transfer of methods developed in science to their application in soil erosion risk management.

© 2010 Elsevier Ltd. All rights reserved.

Introduction

An estimated 115 million ha or 12% of Europe's total land area are subject to water erosion (CEC, 2006), leading to losses of about 53 Euro per hectare and year in agricultural areas. The main problems for soils in the European Union are contamination and losses due to increasing soil erosion (Boardman and Poesen, 2006). It is widely believed that Europe's soil resource will continue to deteriorate, probably as a result of changes in climate, land use – including the increased cultivation of energy plants – and human activities in general (Gobin et al., 2004; Tóth et al., 2007). In Germany, an average soil loss of 5.5 t ha^{-1} yr^{-1} for arable land under the present soil management conditions is estimated (Auerswald, 2006) exceeding the assumed average annual soil formation rate of about 0.3–1.5 t ha^{-1} yr^{-1} (LUBW, 1995). Processes of soil erosion by water are the result of a disturbance of the balance between climate, terrain and land use (Herz, 1973, 1980). Soil erosion is a natural process. However, erosion is often accelerated by conflicts between agricultural production goals and soil health goals (Schmidt and Petry, 2005). Erosion reduces on-farm soil productivity and contributes to water quality problems as it causes the accumulation of sediments and agrochemicals in waterways. Prolonged erosion causes soil loss over time, and reduces soil ecological functions such as biomass production and filtering capacity (Gobin et al., 2004). Many planning and management theories and formulas have been developed in order to reduce soil loss from landscapes and river basins and, as a consequence, sediment transport to hydrologic drainage networks and reservoirs (Amore et al., 2004). Fullen (2003) suggests soil conservation services in Europe (similar to the US) and that "a participatory approach to soil conservation should be adopted, involving farmers and interested members of the public, and there should be a cost-share partnership between government and farmers in funding conservation work on farms". All these suggestions and effects make clear that soil and water protection have to be considered together; the connection of land at risk of soil erosion to rivers has to be taken into account as a potential source of water pollution. Hence this

* Corresponding author. Tel.: +49 345 1352244; fax: +49 345 2394019.
E-mail address: moeller@geoflux.de (M. Möller).
[1] http://www.geoflux.de.

0264-8377/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.landusepol.2009.12.011

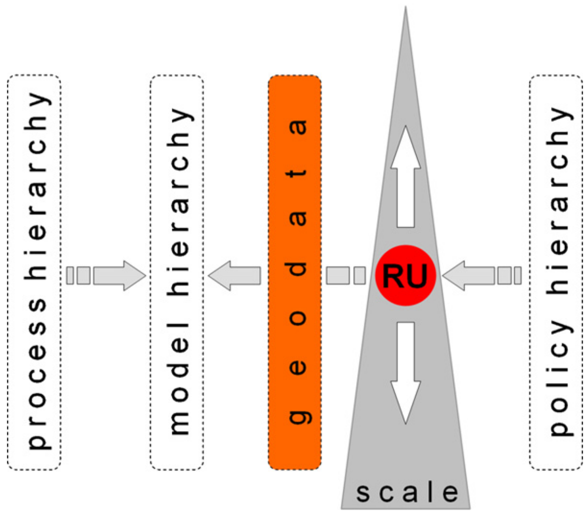

Fig. 1. The scaling elevator: a conceptual framework for the scale-specific modeling of landscape related processes against the background of policy, process and model hierarchies (RU = reference unit).

is essential for the achievement of the water quality targets of the European Water Framework Directive (WFD) as shown by Ulen and Kalisky (2005). Soil erosion processes show an obvious dependency on space and time: they are embedded in a multi-hierarchical system ranging from field to landscape scales. Each hierarchy level or scale requires the provision of data in a scale-adequate resolution and scale appropriate methods (Kirkby et al., 1998; Wickenkamp et al., 2000; Steinhardt and Volk, 2002; Verheijen et al., 2009). Various models for qualitative and quantitative erosion simulation are nowadays available for different spatio-temporal levels (Renschler, 2002, 2003; Merritt et al., 2003). However, several limitations of current approaches and problems remain, such as the hierarchical linkage of these models and their simulation results and limited data availability (Steinhardt and Volk, 2002; De Vente and Poesen, 2005; Boardman, 2006; Verheijen et al., 2009). This paper presents a methodological framework for appropriate assessment of soil erosion by water (Fig. 1). The framework bases on the definition of hierarchical reference units (RU) which result from social demands by policy and occurring erosion processes. RU are modular parts of functional hierarchies (Molenaar, 1998; Wielemaker et al., 2001; De Vente and Poesen, 2005) that can be of administrative or natural type (e.g. districts, river basins, or terrain units). Referring to the "scaling ladder" concept by Wu (1999), RU can be regarded as "scaling elevator" meaning that – similar to soil erosion processes – RU are characterized by different space-time-variabilities. Consequently, RU definition enables

- The scale-specific choice of appropriate soil erosion models.
- The selection of appropriate input data whose scale-specific availability is limited.

Thus, "hotspots" or areas of high potential soil erosion risk can be effectively localized: the smaller the assessment scale, the more complex should be the model and the higher the effort of model parameterizations (Wickenkamp et al., 2000). In general, we aim to contribute to an improved applicability of data and methods for the assessment of soil erosion by water and soil protection on relevant scales. In addition, we want to contribute to an improved transfer of methods developed in science to their application in local erosion risk management, as requested, for instance, by Veihe et al. (2003) and Boardman and Poesen (2006). The article consists of four parts: first, from a European and German perspective, an overview of relevant policy instruments and soil erosion modeling approaches and their connection to reference units is given (Section "Soil erosion assessments in the context of policy, process, and model hierarchies: a European and national perspective"). In the second part, the applied methods are presented. The methods include the soil erosion model ABAGflux as well as a procedure aggregating model results on reference units (Section "Methods"). Third, on the example of German Federal State of Saxony-Anhalt (20,446 km^2), we show the implementation of the above mentioned approach on three policy relevant scales (Section "The case study: soil erosion risk assessment in Saxony-Anhalt"). Finally, we discuss the results against the background of the applicability of input and validation data with regard to policy demands and erosion research (Section "Discussion and conclusion").

Soil erosion assessments in the context of policy, process, and model hierarchies: a European and national perspective

Erosion spans a wide range of spatial scales that includes the simple plot for scientific study, the field scale for the interest of the single farmer, catchment scale for community level issues, and regional and national scales for policy-maker interests (Kirkby et al., 1996). Little work has been done so far on the interaction between soil erosion on the one side and socio-economic and political parameters on the other side at a European scale (Veihe et al., 2003). In terms of policies affecting soil erosion rates, studies within the EU are limited. Due to CEC (2006), different European Community policies contribute to soil protection, particularly environment (e.g. air and water) and agricultural (agri-environmental and cross-compliance) policy. A variety of approaches to soil protection already exist in the member states (Fullen, 2003). Nine member states have specific legislation on soil protection. However, these laws often cover only one specific threat, such as soil contamination and do not always provide a coherent framework. For instance, Lahmar (2010) found in his studies that conservation agriculture is less adopted in Europe compared to other adopting regions and, reduced tillage is more common than no-tillage and cover crops. In Norway and Germany the adoption of conservation agriculture has been encouraged and subsidised in order to mitigate soil erosion. Veihe et al. (2003) show the problems and processes of soil erosion in Denmark and how these are interlinked with the political system through subsidies, production systems, etc. Their case study shows that both the media and Non-Governmental Organizations (NGO) can play an important role in pushing environmental problems associated with soil erosion onto the political agenda and with the NGOs having a great say in the actual shaping of the laws. Soil erosion assessment should be directly linked to policy, process and model hierarchies. This corresponds to the "Driving Force-Pressure-State-Impact-Response" (DPSIR) analytical framework of causality (Frecker, 2005) where – against the natural background of the driving forces climate and soil properties – pressures are exerted on the social or natural environment (state), to which society responds. Pressures might arise from climate change and human activities related to agriculture. These pressures change the state of the environment in terms of land, water and natural resource quality whereas the resulting direct (e.g. small scale rill erosion or large scale river eutrophication by sediment load) and indirect impacts (e.g. changes in biodiversity and crop yields) are visible on different hierarchical levels. Society may respond to changes in the environment through government policy, and changes in household and business behavior on different administrative levels. The response stage is a feedback into the state and pressure stages: response might include direct interventions in the environment, such as cleaning up a river (response influences state), or changing tax incentives to promote an environmental adapted agricultural practice (response influences pressure, pressure influences state). Research institutions and engineering companies react to the arising demands by the development of models that try to simulate the processes on different hierarchical levels. The results of these simulations can be used to derive options for soil protection measures for politicians and authorities (Renschler, 2002; Frielinghaus and Funk, 2003; Gobin et al., 2004).

Policy hierarchy

Policy instruments related to soil protection in Germany concentrate on regulation of land management practices and on economic incentives, mostly in the frame of the EU Common Agricultural Policy (CAP) second pillar measures. The CAP midterm review (CEC, 2002) foresees an increased level of integration of environmental measures. The CAP maintains and introduces a set of soil conservation measures. Sustainable development measures such as erosion and flood prevention fall under the regional and agricultural structural funds. Against the background of the European agricultural support, main issue of the CAP reform is a sanction mechanism that is based on the "coupling" of direct or compensation payments to the farmers with "public goods" (cross-compliance, good agricultural and environmental conditions). The regulation of land management practices takes so-called "best management practices in agriculture" (BMP) as reference, as defined in the "Bundesnaturschutzgesetz" (Federal Nature Conservation Act), the "Bundesbodenschutzgesetz" (Federal Soil Protection Act, FSPA) and regulations at Federal and State level referring to fertilizer application rates and crop protection. The definition of "best management practice" provides targets and guidelines for what the society considers as sustainable agricultural land use with the aim of shaping the relation between agriculture, nature conservation and landscape planning (Deumlich et al., 2006a). Additionally, incentive policy measures such as the agri-environmental programs are increasingly conceived as means to ensure and remunerate the production of non-commodities such as the protection of abiotic and biotic natural resources and maintenance of infrastructures and attractive locations in rural areas (Schmidt and Petry, 2005; Rossing et al., 2007). Both CAP and FSPA address the farm and field level. While the CAP follows a market-oriented approach that aims to strengthen soil protection by financial support (Rothstein, 2003), FSPA defines regulations of soil-related precaution and hazard prevention (Fullen et al., 2006).

Another important legal guideline of the German soil protection is connected with the EU Water Framework Directive (WFD; Volk et al., 2008, 2009). The WFD aims at safeguarding ecological, qualitative and quantitative functions of water, and focuses on remedial actions within river basin management plans (EU, 2003). The general objective of the WFD is to achieve a good ecological status in all water bodies (rivers, lakes, groundwater, coastal waters) of the member countries of the European Union by 2015. One of the fundamental improvements of the WFD in Germany is the use of river basins and/or drainage areas as reference units. A key component of the WFD is the development of river basin management plans which set the actions required within each river basin and/or drainage area units to achieve set environmental quality objectives. Within the process of the management planning the characterization of the river basin (including an inventory of surface ecosystems and surface water bodies with which the groundwater body is connected) plays a major role, because already in this early stage decisions are made about which spatial and ecological-economic measures for water bodies are relevant or significant to the WFD. The criteria for the identification of the pressure and the evaluation of the impacts (significance criteria) are categorized in Appendix II of the WFD. A clear reference to the agricultural use of soils shows non-point source discharge (nutrient, pesticide and heavy metal entry) and phosphorus loads that can be closely linked to processes of soil erosion.

LAWA (2002) and EU (2003) assume that the objective of the WFD can only be achieved with changes of the present agricultural practice. Synergy effects are expected especially from WFD, CAP and BMP which should lead (i) to a closer relationship between agri-enviromental and other promotion measures, (ii) to an improvement of the agricultural advice activities and (iii) to a more forceful and stringent BMP implementation. Although the WFD defines only one report scale level of 1:500,000 we consider the definition of suitable scale level necessary where protection measures and management actions occur (Volk et al., 2008). That means that soil erosion processes are embedded in a hierarchical multi-functional system in which reference units (here: river basins, drainage areas) and legal-administrative scopes (here: farms, fields) interfere with each other. This requires the development of scale-specific tools for the investigation of the ecological situation in hierarchical reference units and of the effects of water and soil protection measures.

Process and model hierarchy

The processes of soil erosion follow the organization principles of hierarchical systems. The same soil erosion factors take effect on each abstraction level. However, the importance of the single factors for the soil erosion processes changes with the different scale levels (Steinhardt and Volk, 2003; Verheijen et al., 2009).

Falkenmark and Rockström (2004) give an example for that: "The water causing the erosion often originates in overland runoff produced on degraded land upgradient where the soil surface has low permeability. Runoff will start at the micro-scale as sheet flow, and accumulate into rill flow on small areas within a field (<1 ha). Rills will aggregate into small gullies in a small catchment (generally < 5 ha), which then merge into major gullies at the catchment level". Consequently, scaling up or down of erosion rates is impossible (Verheijen et al., 2009), but methods to simulate erosion as well as the measures to prevent soil erosion have to adapt to the different conditions of these different scales. In spite of the oftentimes existing lack of suitable data and methods for these relevant scales, scientists and environmental managers must nevertheless keep in mind the hierarchical organization of soil erosion processes. In many times this can be done by using pragmatic procedures as suggested in this study.

A comprehensive review of erosion models and their basic concepts, outputs and limitations are given in Merritt et al. (2003). They distinguish between empirical, physically based and conceptual model types. The main difference between this model types is related to the aggregation level of process simulation. "Whilst physically based models are based on the solution of fundamental physical equations [...], [...] empirical models rely on observed or stochastic relationships between the causal variables and modeled output [In contrast, ...] conceptual models tend to include a general and aggregated description of catchment processes, without including the specific details of process interactions". These features affect the effort of parameterization, calibration and validation as well as the temporal and geometric output resolution (Fig. 2, Table 1). The applicability of especially conceptual and physically based models is restricted by the lack of high resolution input data and of – above all – information for the validation of sediment transport processes.

Table 1
Comparison of soil erosion model types (Hennings, 2000; Merritt et al., 2003; AD-HOC AG Boden, 2003; Deumlich et al., 2006a).

	Empirical models	Conceptual models	Physically based models
Principle	Analysis of data obtained from idealized experimental sites using stochastic techniques by the assumption that that underlying conditions remain unchanged for the duration of the study period	Representation of a catchment as a series of internal storages; tend to include a general and aggregated description of catchment processes, without including the specific details of process interactions, which would require detailed catchment information	Solution of fundamental physical equations
Parametrization	Low	Middle to high	High
Calibration	no (often transferred from calibration at experimental sites)	Yes	Yes
Validation	No	Yes	Yes
Geometric resolution	Scale-independent, spatially distributed	Medium scale, lumped or semi-distributed	Small scale, spatially distributed
Temporal resolution	Simulation of broad trends	Continuous (daily) simulation	Simulation of short-duration events
Output	Pattern of potential long-term soil erosion risk	Aggregated values of streamflow, sediment and associated nutrient generation in catchment	Event-based and spatially distributed values of streamflow, sediment and associated nutrient generation in catchment
Limitations	Unrealistic assumptions about the physics of the catchment system Ignoring the heterogeneity of catchment inputs and characteristics (e.g. rainfall and soil types) as well as the inherent non-linearities in the catchment system	Often no data for the validation of sediment and nutrient generation available Depending on complexity many few or possible 'best' parameter sets for calibration available exist Depending on complexity the parameters have limited physical interpretability	Model parameters must often be calibrated against observed data Over-parameterization Unclear scale dependencies of parameters and input data Lack of identifiability of model parameters and non-uniqueness of 'best fit' solutions Often no data for the validation of sediment and nutrient generation available
Common models applied in Germany	ABAG (Schwertmann et al., 1990)	SWAT (Arnold et al., 1993) AGNPS (Young et al., 1989)	Erosion 3D (Schmidt, 1991)

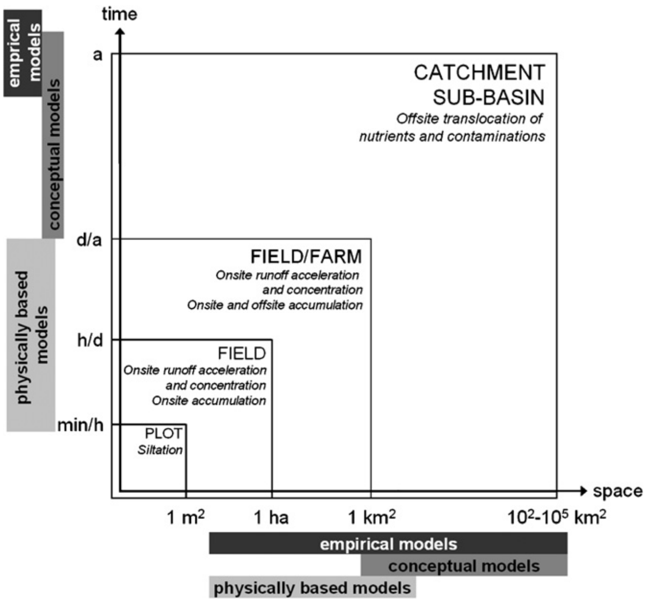

Fig. 2. Model types, soil eroision processes and refererence units depending on space and time.

Methods

ABAGflux

A popular empirical approach for the prediction of large scale soil erosion and the designation of potential risk zones for soil erosion is the Universal Soil Loss Equation (USLE, Wishmeier and Smith, 1978) or its German adaptation (Eq. (1); Schwertmann et al., 1990).

$$A = R \times K \times L \times S \times C \times P \tag{1}$$

where A is the mean annual soil loss in $\mathrm{t\,ha^{-1}\,yr^{-1}}$, R the mean annual erosivity for a defined period, K is the soil erodibility indicating a soil's susceptibility to the erosive forces and gives the amount of soil loss per unit erosivity, LS is the length-slope factor, C is the cover management factor. The support practice factor P was not considered within this study. It reflects the effects of practices that will reduce the amount of water runoff and thus reduce the erosion rate. LS and C are ratios of soil loss on a given unit plot.

The USLE has been proven as suitable in numerous studies for decades (Eq. (1)). This can be attributed to – in comparison to physically based models – low data and parameter requirements as well as its scale-independent geometric resolution which is often a limitation of lumped conceptual models (Table 1). A significant USLE disadvantage consists of the overestimation of erosive slope lengths and the lacking possibilities for process-oriented simulations like sediment transport (Winchell et al., 2008). By means of the modification of single factors of the USLE as well as with the inclusion of further methods based on terrain analysis these deficits could be minimized. This would result in a method to model cross-scale mean soil erosion rates and transport pathways as a basis for the efficient simulation of water and soil protection measures.

To address this issue, the model system ABAGflux includes a barrier function and integrates flow accumulation algorithms (Fig. 3). Thereby the flow accumulation process is stopped at barriers (e.g. natural depressions, field borders, roads, etc.) and starts again below the barrier. The accumulation is set to a value of 0 at this location. The resulting slope fragmentation and reduction in slope length causes a segmentation of the slope and thus the consideration of more realistic erosive slope lengths (Winchell et al., 2008). Furthermore, by calculating the terrain attribute mass balance index MBI (Möller et al., 2008) within the terrain analysis module the determination of potential sedimentation areas is possible. This attribute indicates the terrain caused bias of a raster cell for erosion or sedimentation. For information about the off site potential of an area, methods are required that enable the designation of transport pathways. Similar to van Oost et al. (2000), by the linkage and transfer of the soil loss determined for a raster cell to a transport module the down-slope directed pathways is identified by the coupling with a flow accumulation algorithm. Therefore we applied the multi flow approach by (Quinn et al., 1991). This is used for the designation of areas connected to the river and the determination of transfer areas and hot spots. It also allows an estimation of potential amounts of soil transported to the river.

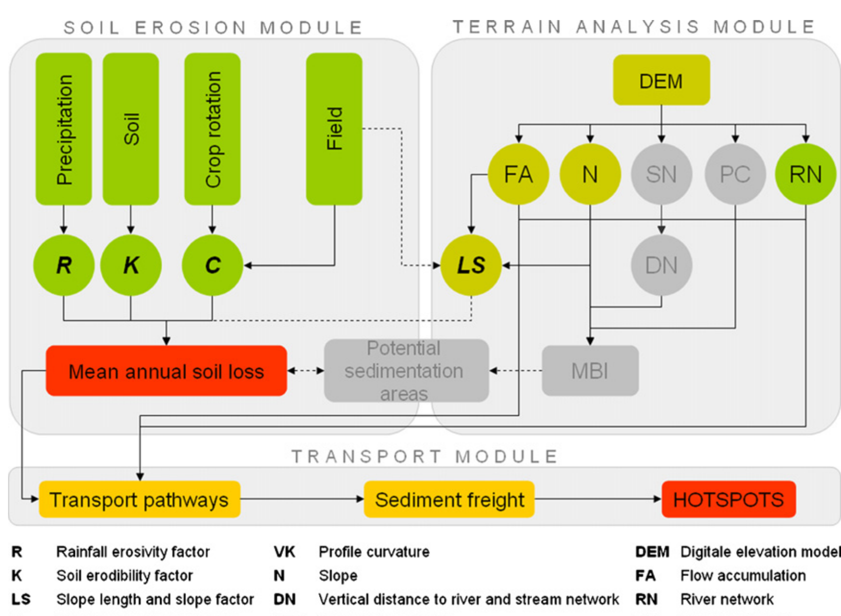

Fig. 3. Flow chart of the functionality of the model system ABAGflux. The grey emphasized functions were not applied within this study.

SICOM

The aggregation of USLE assessment on drainage areas was realized by the Site Comparison Method SICOM (Deumlich et al., 2006b) which aggregates classified values to a Comparison Index *CI*. *CI* belongs to complexity metrics characterizing landscape structure (see Gustavson, 1998) and is calculated using Eq. (2). C_i is the comparison class, that represents clustered (see Section "*k means* cluster analysis") and ranked values. The ranking is carried out by the highest value of USLE assessment (highest ranking). A_{C_i} is equivalent to the proportion of C_i within the reference units (here: drainage areas). As the name implies, the resulting *CI* values allow the relative comparison of reference units within a superior reference unit (here: Federal State of Saxony-Anhalt). The advantage of this method compared to mean average approaches is that (i) no absolute (and mostly not validated) USLE values are used, (ii) the spatial heterogeneity of soil erosion assessment classes is considered, and (iii) scale-specific assessments can be carried out.

$$CI = \frac{\sum_{i=1}^{n}(C_i \times A_{C_i})}{n \times 10} \quad \text{with} \quad \in [0, 10] \tag{2}$$

k means cluster analysis

The application of SICOM requires a classification of the continuous USLE results. Existing threshold based classification schemas as suggested by (Hennings, 2000) do not consider the variability which is affected by different factor calculation algorithms (Volk et al., 2001). For instance, the *LS* factor can be calculated by a number of approaches (e.g. Moore and Wilson, 1992; Desmet and Grovers, 1996; Hickey, 2000) leading to different value ranges. Hence, we carried out a qualitative and statistical grouping of USLE values by means of the *k means* clustering algorithm within the R environment (Reimann et al., 2008). An advantage of this approach is that the metric feature space can be structured in an automatic and comprehensible manner.

The case study: soil erosion risk assessment in Saxony-Anhalt

As part of the WFD, the planning of environmental measures requires an evaluation of the non-point source pollution affecting the surface water bodies (see Section "Policy hierarchy"). These pollutants include mainly sediments and nutrients from agricultural and forest land. Their entry into the water bodies has to be mitigated or avoided. The evaluation of the potential sediment-bound nutrient entry to surface water bodies requires models that enable both the state-wide estimation of soil erosion and the potential sediment entry from agricultural land into the rivers. Simultaneously, the results of soil erosion risk assessment should provide a regional decision basis for the European agricultural support. Apart from this requirements, specific conditions in Saxony-Anhalt has to be considered:

- Cost efficiency: all the necessary efforts for model setup and application should be as small as possible.
- The database for the validation of sediment entry is still insufficient.

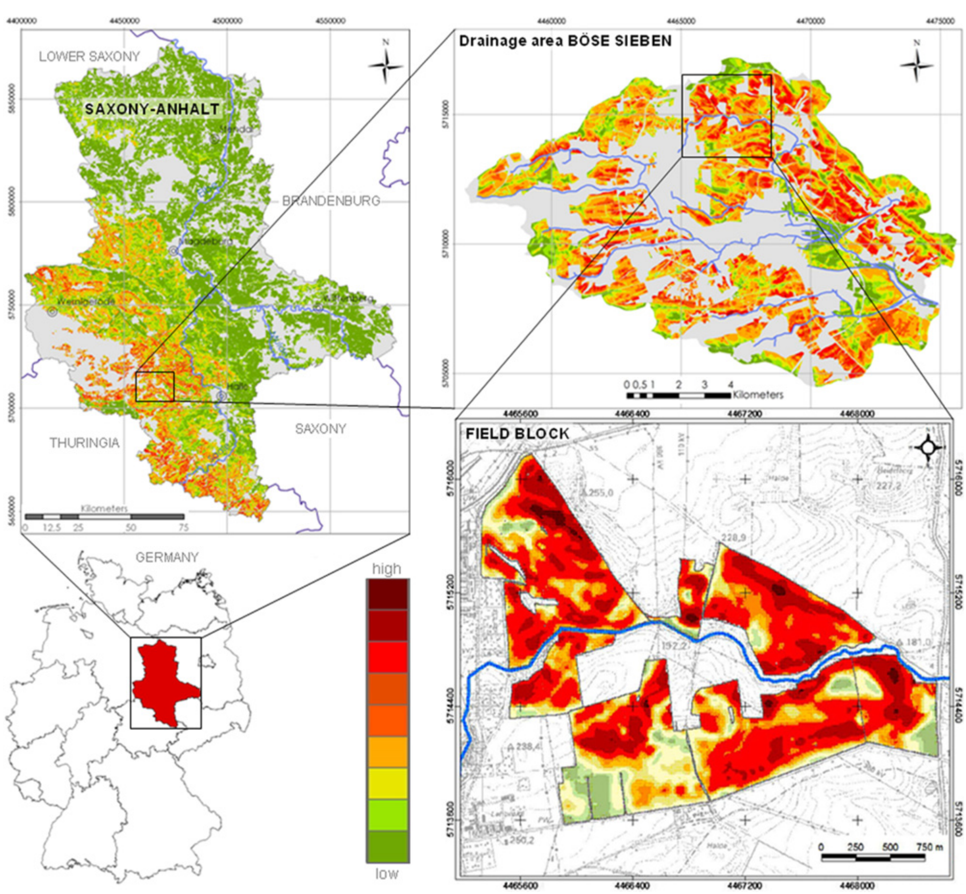

Fig. 4. The potential risk of soil erosion by water of the hierarchical nested study areas.

Table 2
Hierarchical level, input data, applied methods and results.

Hierarchical level	Input data	Methods	Results
1st level macro-scale 1:100,000–1:500,000 Federal State	DEM 40 m × 40 m Soil map 1:50,000 Biotope and land use types 1:10,000 Field boundaries Precipitation data from meteorological network of low density	Extended USLE approach (barrier function) *k means* – cluster analysis Site comparison method SICOM	State-wide potential and natural risk assessment of soil erosion by Water aggregated in drainage areas Selection of high risk areas
2nd level meso-scale 1:25,000–1:50,000 drainage area	DEM 40 m × 40 m Soil map 1:10,000 Biotope and land use types 1:10,000 Field boundaries Crop rotation data River network 1:10,000 Precipitation data from meteorological network of high density	Extended USLE approach (barrier function) Simplified sediment transport algorithm Aerial image interpretation	Localization of on site and off site risk areas Selection of fields with high risk of soil erosion and sediment transport
3rd level micro-scale 1:5000–1:10,000 field block	DEM 10 m × 10 m Soil map 1:10,000 Biotope and land use types 1:10,000 Field boundaries Detailed crop rotation and agricultural practice data Economical farm data River network 1:10,000 Precipitation data from meteorological network of high density	Extended USLE approach (barrier function) Simplified sediment transport algorithm Simulation of case scenarios Aerial image interpretation Field work Economical balancing	Scenarios for reduction of the sediment and nutrient entry into the rivers Cost-benefit-scenarios

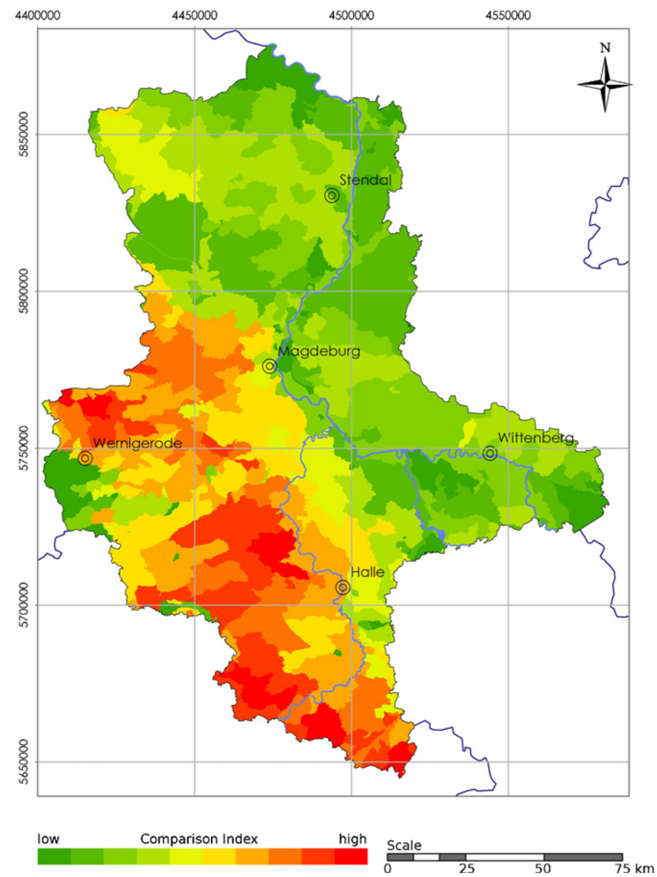

Fig. 5. First level and state-wide assessment of drainage areas regarding aggregated mean annual soil loss within Saxony-Anhalt.

The hierarchical procedure for measure planning is based on modular nested reference units. On the basis of a first large scale estimation and evaluation zones are designated (here: catchments, drainage areas) that show a defined risk potential for soil erosion. By both increasing model complexity and spatio-temporal resolution of input data, as well as by the determination of new reference units (here: farms, fields) the results will be locally specified within these designated risk zones. This is the basis for (i) the prediction of soil erosion areas and sediment transport to hydrologic drainage networks and (ii) for small scale environmental management and measure planning. Fig. 4 shows the nested study areas within the Federal State of Saxony-Anhalt which are described in detail in the following subsections. Table 2 gives an overview to the used data, applied methods and the results for each hierarchical level. The relevant reference units are highlighted. They represent official data provided by state agencies:

- A field block is a German reference unit corresponding to an agricultural area surrounded by relative long-term boundaries like other land uses (e.g. forest, towns) and/or roads.[2] It is usually composed of several field parcels. A field parcel is characterized by uniform management and farming conditions (uniform tillage operations, growing fruits, etc.; Dietzel et al., 2000; Möller et al., 2007).

[2] http://www.sachsen-anhalt.de/LPSA/fileadmin/Files/Informationsblatt_2005.pdf.

- Drainage areas correspond to so-called surface water bodies which can be defined as a significant element of the drainage system (Van der Perk, 2006).

The procedure described in the following subsections is part of the official implementation of soil precaution and hazard prevention in Saxony-Anhalt (Wilhelm, 2008; Wilhelm and Feldwisch, 2010) which follows the corresponding guidance of the German Federal Soil Association (Bundesverband Boden, BVB, 2004). The guidance helps authorities to decide where and when defined measures of precaution and/or prevention are nessecary. ABAGflux is foreseen as an auxiliary tool for the localization of such areas and the assessment of possible sanction's effectiveness.

First level assessment

The parameters required for the USLE calculation correspond to the macro-scale target scale (Table 2: 1st hierarchical level). Only such areas are considered that were derived from the thematic class "intensive agriculture" of the digital map of biotope and land use types in a scale of 1:10,000 (FANC, 2002). This thematic class was subdivided by field blocks boundaries which acted as barriers for the *LS* factor calculation.

The regions with the highest potential risk for soil erosion are located mainly in the South of Saxony-Anhalt, in the foreland of the Harz Mountains and in the West, in the Magdeburger Boerde, as the region is called. Due to the most fertile soils on Germany (e.g. Chernozems), the landscape is influenced by an intensive agriculture. The soils are at strong risk of erosion because of heterogeneous landscape terrain, the erodibility of the dominant loess substrate and the intense summer rainstorm events.

The USLE results were statistically classified into nine classes (Fig. 4, top left) and aggregated by SICOM methodology to drainage areas (Fig. 5) which correspond to defined WFD surface water bodies. Drainage areas with high *CI* values are red colored (*CI* = 10). The proportion of assessment classes with a high mean annual soil loss within agricultural land is bigger than in other drainage areas which are green (low rate of soil loss) or orange colored (moderate rate of soil loss).

Second level assessment

The study area "Böse Sieben" (141 km^2) represents the second hierarchical level. It is part of the Eastern foreland of the Harz Mountains and belongs to the catchments with the highest potential soil erosion risk in Saxony-Anhalt (Fig. 4, top right). Among soil erosion and soil degradation, off site impacts like river eutrophication by sediments and nutrients and siltation of reservoirs occur.

Most of the data listed in Table 2 (2nd hierarchical level) are suitable mainly for the application at the meso-scale. For instance, field block related crop rotation data enable the calculation of the *C* factor. Furthermore, by visual interpretation of aerial images, information can be derived on agricultural land connected to rivers as well as on the position accuracy of landscape elements (river system, riparian zones).

The combination of these methods allows an efficient verification of the agricultural land that is connected to the river system. The green and orange colored field blocks in Fig. 6 are the ABAGflux modeling results which show areas with high potential risk of sediment entry into the river network. However, the aerial image interpretation revealed that in reality the orange colored field blocks are not connected to river network. This reflects (often scale related) data inaccuracies leading to false model results. Only the green colored field blocks contain hotspots of sediment entry into the river network and can hence be considered for further planning of water and soil protection measures. Such field blocks are exemplified in Figs. 7 and 8 where the statistically classified ABAGflux

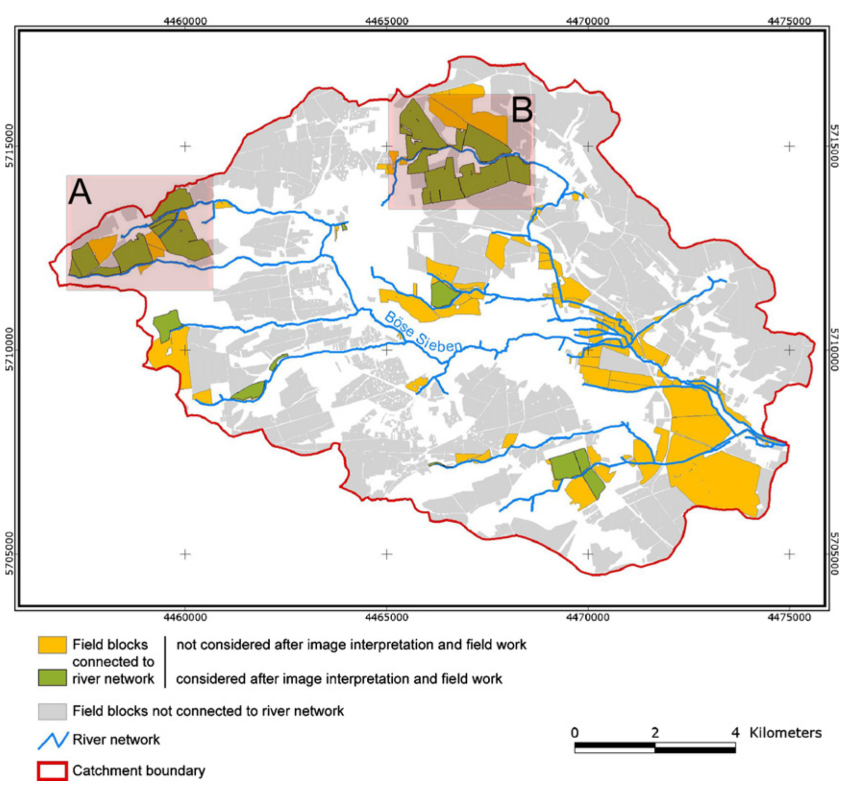

Fig. 6. Second level assessment: field blocks with sediment entry in river network (A and B – location of test sites of Figs. 7 and 8).

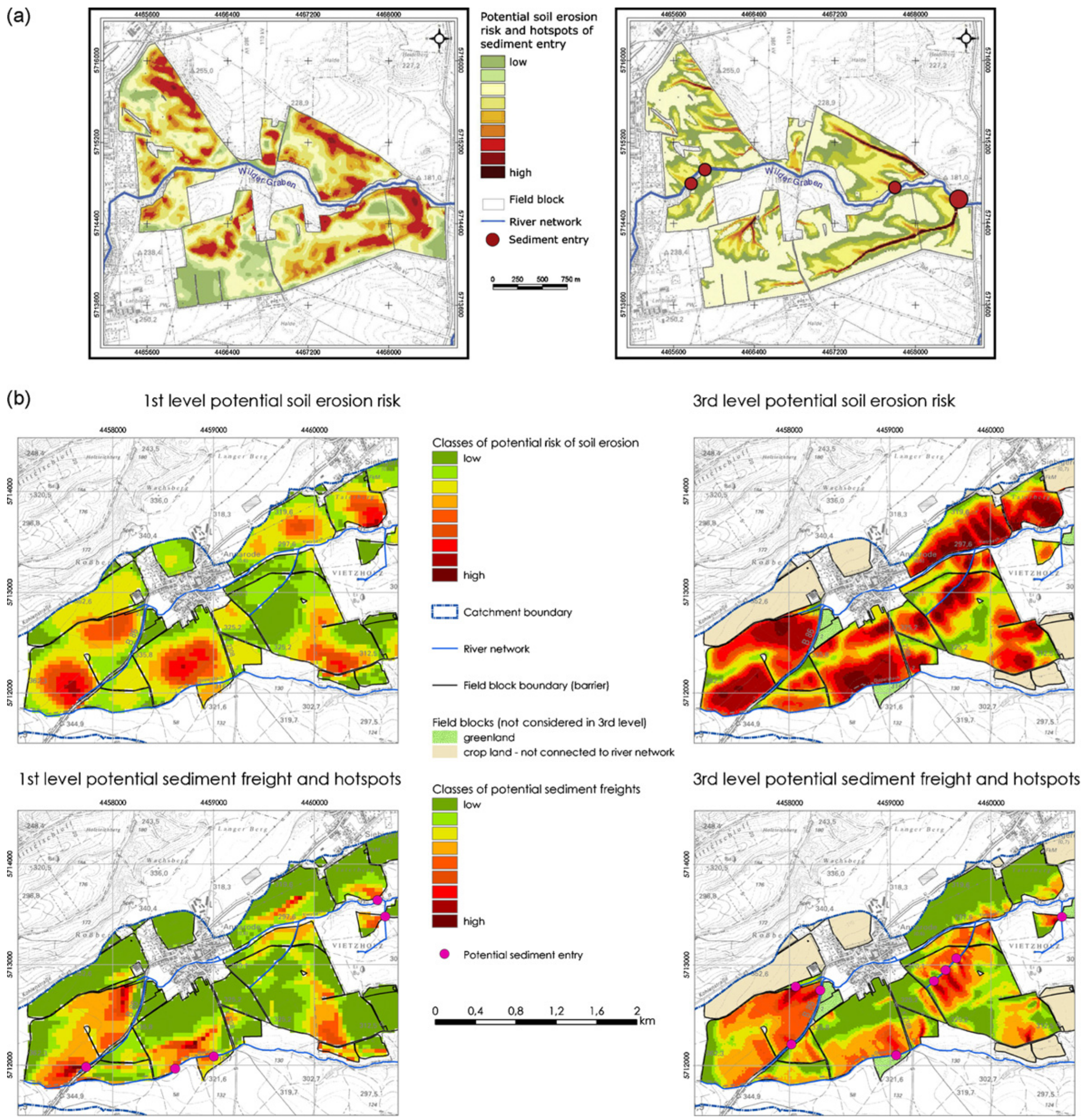

Fig. 7. Third level assessment on the example of selected field blocks. (a) Test site B: potential soil erosion risk and hotspots of sediment entry. (b) Test site A: visualization of scale effect (Left: DEM 40 × 40 m, Right: DEM 10 × 10 m).

result, the accumulated transport loads and the hotspots are visualized.

Third hierarchy level: planning and evaluation of measures

The third hierarchical level consists of field blocks along the river "Wilder Graben" within the "Böse Sieben" catchment. The selected reference units are characterized by high potential soil erosion and sediment entry risk into the river "Böse Sieben" (Fig. 7a). Due to the related degree of detail at this level, a DEM with a higher spatial resolution was applied. Because of the scale effects of a higher DEM resolution (steeply sloping and higher *LS* factor) (Thompson et al., 2001), a higher potential soil erosion risk is calculated. But the most important effect is the more accurate designation of potential sediment entries into the river (Fig. 7b).

In addition to the use of higher resolution DEM, field work was done to get detailed information about current erosion pattern, and to validate the location of hot spots. Crop rotation schemes, agricultural management practices and economical issues were also recorded by means of field work and interviews (Table 2: 3rd hierarchical level). On the example of selected field blocks, the following measures were simulated and their effects on soil and water protection evaluated (Fig. 8).

Soil conservation practices on agricultural land

Reduction of soil tillage intensity or implementation of conservation practices can positively affect numerous soil properties, such as aggregate stability, macroporosity and saturated hydraulic conductivity which increases infiltration rates and reduces surface runoff, nutrient loss and soil erosion (Jones et al., 1969; Pitkänen and Nuutinen, 1998; Schmidt et al., 2001; Kirsch et al., 2002; Pandey et al., 2005; Tripathi et al., 2005). The modification of soil tillage can be realized in the model by the adaptation of the *C* factor. The area-wide mitigation of the soil erosion leads to a reduction of the sediment and nutrient entries into the rivers (Fig. 8a).

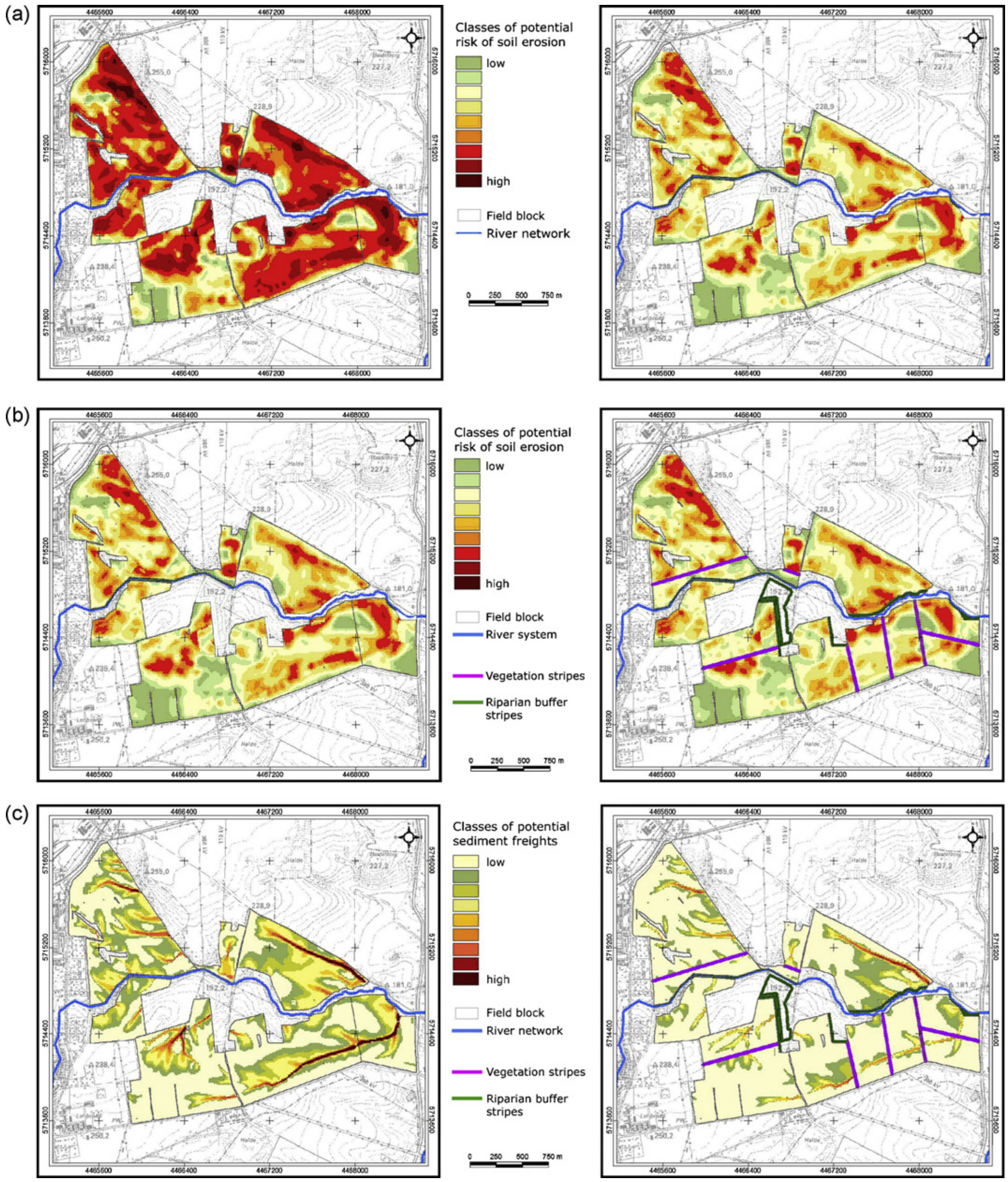

Fig. 8. Third level assessment and simulation of measures for soil and water protection within field blocks. (a) Reduction of soil loss by change of management practice (conventional practice = left, conservation practice = right); (b) reduction of soil loss by means of conservation management practice (left) as well as additional establishing of vegetation strips and riparian buffer strips (right); (c) reduction of sediment transport freights by means of conservation management practice (left) as well as additional establishing of vegetation strips and riparian buffer strips (right).

Riparian buffer strips and vegetation strips on agricultural land

Establishing vegetation strips on agricultural land has potential effects in two aspects:

1. Vegetation strips can lead to a mitigation of sediment matter transport locally and thus also abate matter entry into the river systems (Fig. 8c). The establishing of several vegetation strips in contours along the slope considerably reduces the sediment matter transport of an erosion-effective flow path within field blocks.
2. In addition, such linear elements act as erosion-mitigating barriers. The effect of such barriers can be simulated by reducing the *LS* factor of the USLE. The dynamics and the erosive effect of the down-slope surface runoff are interrupted by the slope-parallel vegetation strips (reduction of erosive slope length). The soil loss is thus limited to the slope section that is located above the vegetation strip (Fig. 8b; Bosch et al., 2006).

Riparian buffer strips act as direct filters against sediment and nutrient input into the rivers (Fig. 8b and c). Depending on the options of financial support, the riparian buffer strips are established adjacent to agricultural land, where they act as direct filters against sediment and nutrient input into the rivers. However, the impact of the buffer strips is limited to off site effects. In order to fulfill the most efficient protection function they should have a minimum width of 8 m (Fabis, 1995; Bach et al., 1997). Wider filter strips increase protection effects like reduction of overflow and throughflow risk. However, the measure effectiveness has to be balanced against costs of soil and agricultural land (Table 3).

Table 3
Third level assessment: comparison of measure variants regarding loss of soil and of agricultural land.

Measure variant	Soil loss ($t\,ha^{-1}\,yr^{-1}$)	Loss of agricultural land (ha)
Conventional soil tillage	5.4	–
Conservation tillage and riparian buffer strips	2.2	30.4
Additional implementation of vegetation strips and change of tillage direction	1.9	38.0

Discussion and conclusion

In the last few years, European (WFD, CAP) and national policy instruments (FSPA) were established (Ulen and Kalisky, 2005; Deumlich et al., 2006a) focusing on different threats by soil erosion and scales:

- The decrease of water quality by sediment and nutrient pollution as well as the loss of soil functions and fertility were identified as main impacts of soil erosion (Frielinghaus and Funk, 2003; Gobin et al., 2004; Tóth et al., 2007).
- While CAP and FSPA address farms and fields corresponding meso and micro scale, WFD uses meso and macro-scale river basins and drainage areas as reference units (Fig. 2, Table 2).

On the example of the German Federal State of Saxony-Anhalt, our study presents an applied and effective implementation of sharing WFD, CAP and FSPA aspects including both risk modeling of soil erosion and sediment entry in river network. Against the background of existing policy instruments on the one hand and the availability of input and validation data on the other hand we explained which erosion model approach has been proven to be suitable to meet the requirements. The applied procedure is an example for a conceptual framework for the scale-specific modeling of landscape related processes against the background of policy, process and model hierarchies. A framework implementation could be realized as simplified decision support system (e.g. Bierkens et al., 2000). Some important issues regarding soil erosion modeling will be discussed in the following subsections.

Which model is appropriate?

As documented in this article and in Merritt et al. (2003), a wide range of models exist for use in simulating soil erosion, sediment transport and associated pollutant transport. These models differ in terms of complexity, processes considered, and the data required for model calibration and model use. In general there is no "best" model for all applications. The most appropriate model will depend on the intended use and the characteristics of the catchment being considered. Further important factors are data requirements of the model including the spatial and temporal variation of model inputs and outputs; and the objectives of the model user(s), including the ease of use of the model, the scales at which model outputs are required and their form (such as concentration vs. load).

We used a modified version of the empirical Universal Soil Loss Equation (USLE) ABAGflux, which includes functions to better describe landscape structure-related processes such as sedimentation and sediment transport to hydrologic drainage networks, as well as additional statistical methods such as the comparison method SICOM and *k means* cluster analysis in a hierarchical procedure. We have shown that the approach can be applied – depending on the planning and information level – to watersheds, farms, fields or even landforms or slope positions. We are aware of the weaknesses and uncertainties of the USLE and its modified versions. As already emphasized by van Rompaey et al. (2003) we recommend that the regional erosion estimates should be used with caution as the uncertainty involved in the model predictions is not known. But we have chosen this empirical approach because of a lack of scale-specific calibration and validation data, which is nevertheless still a main problem with all kinds of environmental analysis and management (Stroosnijder, 2005).

Although we postulate the importance of using scale-adequate methods and data, we were not able to implement this "perfectly" because of a lack of data and measurements for all the relevant scales. However, the use of ABAGflux including the transport module and the capability to determine transfer sediment areas (land to river) allows a simplified hierarchical and nested procedure with different levels of detail regarding the relevant processes. Currently, we work together with the State Agency for Flood Protection and Water Management Saxony-Anhalt on a comparison of our approach with other conceptual and physically based models (physically based models especially on the third level) to prove the accuracy and efficiency of the methods.

Which monitoring strategies and validation data do we need?

Field scale

Validation data on field scale are only occasionally available. Event-based and direct measurements needed by physically based erosion models often require high equipment and personnel cost. In contrast, indirect and cost-effective measurements like "change in surface elevation" method provide middle-term and long-term information about soil removal or sediment deposit (Stroosnijder, 2005) which can be also used for the validation of empirical erosion models like USLE. However, erosion by wind, water and tillage has to be considered separately (van Oost et al., 2006).

Catchment scale

As shown by Volk et al. (2009), a problem yet to be addressed is the general lack of measured sediment transport and water quality data to calibrate and validate erosion and water quality models. This adds considerable uncertainty to already complicated and uncertainty situations. Thus, improved strategies for sedimentation transport measurements, water quality monitoring, and data accessibility must be established to achieve the environmental targets of soil protection strategies or of the WFD.

van Rompaey et al. (2003), which carried out a soil risk assessment for Italy using the USLE, used sedimentation records in lakes and reservoirs for a "validation" and an estimation of the sediment transport rates. The mean annual sediment volume that is trapped in reservoirs can be measured. This provides sediment flux data (i) at a regional spatial scale (the size of the contributing area) and (ii) at a long timescale (since the year of construction or last cleaning of the reservoir). It should, however, be kept in mind that not all of the eroded sediment reaches the outlet of the drainage basin. An important fraction of the sediment is deposited at intermediate locations depending on the drainage density and the spatial configuration of both land cover and topography. They showed that the variation accounted for their predicted values (using the USLE) by validation with the observed values is 70% (if the data from the alpine drainage basins are left out of the data set).

Amore et al. (2004) also used measurement of deposited sediments in reservoirs for their work on scale effects in USLE and WEPP applications for soil erosion computation from three Sicilian basins. This method can indeed help to get an idea about the accuracy of soil erosion risk assessments using empirical equations. But we have to keep in mind that these rates are different from region to region and even reservoirs or data for sedimentation rates from reservoirs are not available everywhere.

Which measure should be applied?

While riparian buffer strips are considered as the last option to mitigate the consequences of soil erosion, area-wide soil protection like conservation tillage measures lead to an essential reduction of soil loss (Schmidt et al., 2001; Deumlich et al., 2006a). The additional implementation of slope length reducing vegetation strips on agricultural land would result in a further reduction and thus also in a mitigation of potential sediment entries. But the detailed implementation of buffer strips and vegetation strips comes along with the loss of agricultural land. The related economic consequences for the concerned farmers have to be compensated by financial incentives in the frame of the European Agricultural Support, whereas savings in costs for, e.g. sediment removal can be used to increase regional erosion control subsidies. This would also ensure a higher level of farmer participation (e.g. Morschel et al., 2004). Finally, the efficiency of vegetation and riparian buffer strips depends on a lot of factors like topography, substratum or vegetation coverage (Morschel et al., 2004; Dorioz et al., 2006). Thus, we are currently investigating such dependencies in the "Böse Sieben" catchment.

Which information do we need?

The question is always which information level is needed by environmental planners and stakeholders. Expertise within the stakeholder groups exists to undertake field-based assessment at finer spatial scales. On the basis of our own experience we agree with the findings of Newham et al. (2004): planners and stakeholder organisations are aiming to enhance their ability to identify how their individual actions fit in an integrated approach to dealing with soil erosion or water quality issues at the catchment scale. Their most immediate need is to identify priority areas at risk for soil erosion, stream reaches and subcatchments requiring management intervention to improve soil protection and water quality. Stakeholder groups also need information to assist in deciding on appropriate methods of management intervention by considering the costs of remediation and their potential environmental benefits. Our methodological framework for scale-specific assessment of soil erosion by water is developed for such support.

Acknowledgements

The authors wish to thank David Bosch, Tifton, GA, USA, for discussion and helpful comments to improve the quality of this paper. The presented case study was part of a project funded by the State Agency for Flood Protection and Water Management Saxony-Anhalt (LHW) and supported by Steffen Kußmann (LHW), Matthias Schrödter (State Agency for Agriculture, Forests and Horticulture) and Michael Steininger (Institute for Applied Land Evaluation and Soil Conservation).

References

AD-HOC AG Boden, 2003. Methodenkatalog zur Bewertung natürlicher Bodenfunktionen, der Archivfunktion des Bodens, der Gefahr der Entstehung schädlicher Bodenveränderungen sowie der Nutzungsfunktion 'Rohstofflagerstätte' nach BBodSchG. Arbeitshefte Boden 2 (2), 1–73.

Amore, E., Modica, C., Nearing, M., Santoro, V., 2004. Scale effect in USLE and WEPP application for soil erosion computation from three Sicilian basins. Journal of Hydrology 293, 100–114.

Arnold, J., Allen, P., Bernhardt, G., 1993. A comprehensive surface-groundwater flowmodel. Journal of Hydrology 142, 47–69.

Auerswald, K., 2006. Germany. In: Soil Erosion in Europe. John Wiley & Sons, Chichester, West Sussex, England, pp. 213–230.

Bach, M., Fabis, J., Frede, H.-G., 1997. Filterwirkung von Uferstreifen für Stoffeinträge in Gewässer in unterschiedlichen Landschaftsräumen, volume 28 of Mitteilungen des DVWK. Deutscher Verband für Wasserwirtschaft und Kulturbau e. V, Bonn.

Bierkens, M., Finke, P., de Willigen, P., 2000. Upscaling and downscaling – methods for environmental research. In: Developments in Plant and Soil Sciences. Kluwer Academic Publishers, Dordrecht.

Boardman, J., 2006. Soil erosion science: reflections on the limitations of current approaches. Catena 68, 73–86.

Boardman, J., Poesen, J., 2006. Soil erosion in Europe: major processes, causes and consequences. In: Soil Erosion in Europe. John Wiley & Sons, Chichester, West Sussex, England, pp. 479–488.

Bosch, D., Sullivan, D., Sheridan, J., 2006. Hydrological impacts on land-use changes in coastal plain watersheds. Transactions of the ASABE 49 (2), 423–432.

BVB, 2004. Bundesverband Boden: Handlungsempfehlung zur Gefahrenabwehr bei Bodenerosion durch Wasser, volume 1 of BVB-Merkblatt. Fachausschuss "'Gefahrenabwehr bei Bodenerosion"' des Bundesverbandes Boden e.V, St. Augustin, Germany.

CEC, 2002. Mid-term review of the Common Agricultural Policy. In: Technical Report COM 394. Commission of the European Communities, Brussels, Belgium.

CEC, 2006. Thematic strategy for soil protection. In: Technical Report COM 231. Commission of the European Communities, Brussels, Belgium.

De Vente, J., Poesen, J., 2005. Predicting soil erosion and sediment yield at the basin scale: scale issues and semi-quantitative models. Earth Science Reviews 71, 95–125.

Desmet, P., Grovers, P., 1996. A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. Journal of Soil and Water Conservation 51, 427–433.

Deumlich, D., Funk, R., Frielinghaus, M., Schmidt, W.-A., Nitzsche, O., 2006a. Basics of effective erosion control in German agriculture. Journal of Plant Nutrition and Soil Science 169, 370–381.

Deumlich, D., Kiesel, J., Thiere, J., Reuter, H., Völker, L., Funk, R., 2006b. Application of the SIte COmparison Method (SICOM) to assess the potential erosion risk—a basis for the evaluation of spatial equivalence of agri-environmental measures. Catena 68 (2–3), 141–152.

Dietzel, H., Diemann, R., Jacobs, R., Otto, R., 2000. Schlaggröße und Schlagform in Ackerbaugebieten der neuen Bundesländer. Zeitschrift für Kulturtechnik und Landentwicklung 41, 68–73.

Dorioz, J., Wang, D., Poulenard, J., abd Trévisan, D., 2006. The effect of grass buffer strips on phosphorus dynamics: a critical review and synthesis as a basis for application in agricultural landscapes in France. Agriculture, Ecosystems & Environment 117, 4–21.

EU, Ed., 2003. European Communities – identification of water bodies, volume 2 of guidance document – common implementation strategy for the water framework directive., http://www.wrrl-info.de/docs/Guidance_doc_2_waterbodies.pdf.

Fabis, J., 1995. Retentionsleistung von Uferstreifen im Mittelgebirgsraum, Volume 12 of Boden und Landschaft, Schriftenreihe zur Bodenkunde, Landeskultur und Landschaftsökologie. Universität Gießen, Gießen, Germany.

Falkenmark, M., Rockström, J., 2004. Balancing Water for Humans and Nature. The New Approach in Ecohydrology. Sterling, Earthscan, London.

FANC (Ed.), 2002. A System for the Survey of Biotope and Land Use Types (Survey Guide): Standard Biotope and Land Use Types for FCIR Aerial Photograph Supported Biotope and Land Use Survey for the Federal Republic of Germany, Volume 73 of Schriftenreihe für Landespflege und Naturschutz, Bonn-Bad Godesberg, Germany. Federal Agency for Nature Conservation.

Frecker, K., 2005. Beyond GDP: Enabling Democracy with Better Measures of Social Well-being. The Kiessling Papers. Trudeau Centre for Peace and Conflict Studies, University of Toronto, Toronto.

Frielinghaus, M., Funk, R., 2003. Soil indicator systems – the basis for soil conservation decisions. In: Francaviglia, R. (Ed.), Agricultural Impacts on Soil Erosion and Soil Biodiversity: Developing Indicators for Policy Analysis. Organisation for Economic Co-operation and Development (OECD), Rome, Italy.

Fullen, M., 2003. Soil erosion and conservation in northern Europe. Progress in Physical Geography 27, 331–358.

Fullen, M., Arnalds, A., Bazzoffi, P., Booth, C., Castillo, V., Kértesz, Martin, P., Ritsema, C., Benet, A., Souchère, V., Vandekerckhove, L., Verstraeten, G., 2006. Government and agency response to soil erosion risk in europe. In: Boardman, J., Poesen, J. (Eds.), Soil Erosion in Europe. Wiley & Sons, Chichester, West Sussex, England, pp. 806–827.

Gobin, A., Jones, R., Kirkby, M., Campling, P., Goversa, G., Kosmas, C., Gentile, A., 2004. Indicators for pan-European assessment and monitoring of soil erosion by water. Environmental Science & Policy 7, 25–38.

Gustavson, E., 1998. Quantifying landscape spatial pattern: what is the state of the art? Ecosystems 1, 143–156.

Hennings, V., 2000. Methodendokumentation Bodenkunde - Auswertemethoden zur Beurteilung der Empfindlichkeit und Belastbarkeit von Böden. In: Number SG1 in Geologisches Jahrbuch, Sonderhefte. Reihe G. Stuttgart, 2nd ed. Schweizerbart'sche Verlagsbuchhandlung, Germany.

Herz, K., 1973. Beitrag zur Theorie der landschaftsanalytischen Maßstabsbereiche. Petermann's Geographische Mitteilungen 117 (2), 91–96.

Herz, K., 1980. Ein Begriffssystem der Bodenerosion. Wissenschaftliche Zeitschrift der Pädagogischen Hochschule Dresden, Beiheft 3, 3–10.

Hickey, R., 2000. Slope angle and slope length solution for GIS. Cartography 29, 1–8.

Jones, J., Moody, J., Lillard, J., 1969. Effects of tillage, no-tillage, and mulch on soil water and plant growth. Agronomy Jornal 94, 299–304.

Kirkby, M., Abrahart, R., McMahon, M., Shao, J., Thornes, J., 1998. MEDALUS soil erosion models for global change. Geomorphology 24, 35–49.

Kirkby, M., Imeson, A., Bergkamp, G., 1996. Scaling up processes and models from the field plot to the watershed and regional areas. Journal of Soil and Water Conservation 51 (5), 391–396.

Kirsch, K., Kirsch, A., Arnold, J., 2002. Predicting sediment and phosphorus loads in the Rock River Basin using SWAT. Transactions of the ASABE 45, 1757–1769.

Lahmar, R., 2010. Adoption of conservation agriculture in Europe: lessons of the KASSA project. Land Use Policy 27 (1), 4–12.

LAWA, 2002. Gemeinsamer Bericht von LAWA und LABO zu Anforderungen an eine nachhaltige Landwirtschaft aus Sicht des Gewässer- und Bodenschutzes vor dem Hintergrund der Wasserrahmenrichtlinie. Länderarbeitsgemeinschaft Wasser, Hannover, Germany, http://www.lawa.de/lawaroot/pub/kostenlos/wrrl/Landwirtschaftspapier-Stand_24-04-02neu.pdf.

LUBW, 1995. Prognose von Bodenerosion, volume 4 of Materialien zum Bodenschutz. Landesanstalt f"ur Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW), Karlsruhe, http://www.lubw.baden-wuerttemberg.de/servlet/is/17077.

Merritt, W., Letcher, R., Jakeman, A., 2003. A review of erosion and sediment transport models. Environmental Modelling & Software 18, 761–799.

Molenaar, M., 1998. An introduction to the theory of spatial object modelling. In: Research Monographs in Geographical Information Systems. Tayler & Francis.

Möller, M., Lymburner, L., Volk, M., 2007. The comparison index: a tool for assessing the accuracy of image segmentation. International Journal of Applied Earth Observation and Geoinformation 9, 311–321.

Möller, M., Volk, M., Friedrich, K., Lymburner, L., 2008. Placing soil genesis and transport processes into a landscape context: a multi-scale terrain analysis approach. Journal of Plant Nutrition and Soil Science 171, 419–430.

Moore, I., Wilson, J., 1992. Length-slope factors for the revised universal soil loss equation. Journal of Soil and Water Conservation 47 (5), 423–428.

Morschel, J., Fox, D., Bruno, J.F., 2004. Limiting sediment deposition on roadways: topographic controls on vulnerable roads and cost analysis of planting grass buffer strips. Environmental Science & Policy 7, 39–45.

Newham, L., Letcher, R., Jakeman, A., Kobyashi, T., 2004. A framework for integrated hydrologic, sediment and nutrient export modelling for catchment-scale management. Environmental Modelling & Software 19, 1029–1038.

Pandey, V., Panda, S., Sudhakar, S., 2005. Modelling of an agricultural watershed using remote sensing and a geographic information system. Biosystems Engineering 90 (3), 331–347.

Pitkänen, J., Nuutinen, V., 1998. Earthworm contributions to infiltration and surface runoff after 28 years of different soil management. Applied Soil Ecology 9, 411–415.

Quinn, P., Beven, K., Chevallier, P., Planchon, O., 1991. The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. Hydrological Processes 5, 59–79.

Reimann, C., Filzmoser, P., Garrett, R., Dutter, R., 2008. Statistical Data Analysis Explained. Wiley & Sons, Chichester, West Sussex, UK.

Renschler, C., 2002. Soil erosion assessment tools from point to regional scales – the role of geomorphologists in land management research and implementation. Geomorphology 47, 189–209.

Renschler, C., 2003. Designing geo-spatial interfaces to scale process models: the GeoWEPP approach. Hydrological Processes 17, 1005–1017.

Rossing, W., Zander, P., Josien, E., Groot, J., Meyer, B., Knierim, A., 2007. Integrative modelling approaches for analysis of impact of multifunctional agriculture: a review for France, Germany and The Netherlands. Agriculture, Ecosystems & Environment 120, 41–57.

Rothstein, B., 2003. Landwirtschaftlicher Bodenschutz - Sicherung der Schutzfunktion durch Optimierung naturwissenschaftlicher, juristischer und ökonomischer Handlungsziele. Bodenschutz und Altlasten, Bd. 14. Erich Schmidt Verlag.

Schmidt, G., Petry, D., 2005. Möglichkeiten und Grenzen der Bodenfunktionsbewertung bei der Umsetzung von Bodenschutzzielen. In: Möller, M., Helbig, H. (Eds.), GIS-gestützte Bewertung von Bodenfunktionen – Datengrundlagen und Lösungsansätze. Wichmann, Heidelberg, pp. 147–160.

Schmidt, J., 1991. A mathematical model to simulate rainfall erosion. In: Bork, H.-R., De Ploey, J., Schick, A. (Eds.), Erosion, Transport and Deposition Processes: Theories and Models, volume Supplement 19 of Catena, pp. 101–109.

Schmidt, W., Zimmerling, B., Nitzsche, O., Krück, S., 2001. Conservation tillage – a new strategy in flood control. In: Marsalek, J. (Ed.), Advances in Urban Storm Water and Agricultural Runoff Source Control, Volume 74 of NATO Science Series, pp. 287–292.

Schwertmann, U., Vogl, W., Kainz, M., 1990. Bodenerosion durch Wasser: Vorhersage des Abtrags und Bewertung von Gegenmaßnahmen. Ulmer.

Steinhardt, U., Volk, M., 2002. An investigation of water and matter balance on the meso-landscape scale: a hierarchical approach for landscape research. Landscape Ecology 17 (1), 1–12.

Steinhardt, U., Volk, M., 2003. Meso-scale landscape analysis based on landscape balance investigations: problems and hierarchical approaches for their resolution. Ecological Modelling 168, 251–265.

Stroosnijder, L., 2005. Measurement of erosion: is it possible? Catena 64, 162–173.

Thompson, J., Bell, J., Butler, C., 2001. Digital elevation model resolution: effects on terrain attribute calculation and quantitative soil-landscape. Geoderma 100, 67–89.

Tripathi, M., Panda, R., Raghuwanshi, N., 2005. Development of effective management plan for critical subwatersheds using swat model. Hydological Processes 19, 809–826.

Tóth, G., Stolbovoy, V., Montanarella, L., 2007. Soil quality and sustainability evaluation: an integrated approach to support soil-related policies of the European union. In: Technical Report EUR 22721 EN. Office for Official Publications of the European Communities, Luxembourg.

Ulen, B., Kalisky, T., 2005. Water erosion and phosphorus problems in an agricultural catchment: lessons from implementation of the EU water framework directive. Environmental Science & Policy 8 (5), 485–492.

Van der Perk, M., 2006. Soil and Water Contamination: From Molecular to Catchment. Taylor & Francis.

van Oost, K., Govers, G., Desmet, P., 2000. Evaluating the effects of changes in landscape structure on soil erosion by water and tillage. Landscape Ecology 15, 577–589.

van Oost, K., Govers, G., De Alba, S., Quine, T., 2006. Tillage erosion: a review of controlling factors and implications for soil quality. Progress in Physical Geography 30, 443–466.

van Rompaey, A., Bazzoffi, P., Jones, R., Montanarella, L., Govers, G., 2003. Validation of soil erosion risk assessments in Italy. In: Technical Report EUR 20676 EN, European Soil Bureau Research. Office for Official Publications of the European Communities, Luxembourg.

Veihe, A., Hasholt, B., Schitz, I., 2003. Soil erosion in Denmark: processes and politics. Environmental Science & Policy 6, 37–50.

Verheijen, F., Jones, R., Rickson, R., Smith, C., 2009. Tolerable versus actual soil erosion rates in europe. Earth-Science Reviews 94, 23–38.

Volk, M., Hirschfeld, J., Dehnhardt, A., Schmidt, G., Bohn, C., Liersch, S., Gassmann, P., 2008. Integrated ecological–economic modelling of water pollution abatement management options in the Upper Ems River Basin. Ecological Economics 66, 66–76.

Volk, M., Liersch, S., Schmidt, G., 2009. Towards the implementation of the european water framework directive? Lessons learned from water quality simulations in an agricultural watershed. Land Use Policy 36 (3), 580–588.

Volk, M., Steinhardt, U., Gränitz, S., Petry, D., 2001. Probleme und Möglichkeiten der mesoskaligen Abschätzung des Bodenabtrages mit einer Variante der ABAG. Wasser & Boden 53 (12), 24–30.

Wickenkamp, V., Duttmann, R., Mosimann, T., 2000. A multiscale appraoch to predicting soil erosion on cropland using empirical and physically based soil erosion models in a geographic informations system. In: Schmidt, J. (Ed.), Soil Erosion: Applictaion of Physically Based Models. Springer, Berlin, Heidelberg.

Wielemaker, W., de Bruin, S., Epema, G., Veldkamp, A., 2001. Significance and application of the multi-hierarchical landsystem in soil mapping. Catena 43, 15–34.

Wilhelm, F., 2008. Bodenschutzrechtliche Anforderungen an den Erosionsschutz und ihre Umsetzung. In Bodenerosion: Grundlagen und Handlungsstrategien für den Boden- und Gewässerschutz in Sachsen-Anhalt. Halle (Saale), Germany, pp. 23–26 http://www.geoflux.de/workshop-bodenerosionLSAb.pdf.

Wilhelm, F., Feldwisch, N., 2010. Gesetzliche Anforderungen an den Erosionsschutz und ihre Umsetzung in Sachsen-Anhalt. In: Helbig, H., Möller, M., Schmidt, G. (Eds.), Bodenerosion durch Wasser in Sachsen-Anhalt: Ausmaß, Wirkungen und Vermeidungsstrategien. Erich Schmidt Verlag, pp. 83–88.

Winchell, M., Jackson, S., Wadley, A., Srinivasan, R., 2008. Extension and validation of a geographic information system-based method for calculating the Revised Universal Soil Loss Equation length-slope factor for erosion risk assessments in large watersheds. Journal of Soil and Water Conservation 63 (3), 105–111.

Wishmeier, W., Smith, D., 1978. Predicting Rainfall Erosion Losses—A Guide to Conservation Planning, Volume 537 of USDA Agr. Handbook. US Department of Agriculture Science and Education Administration, Washington, DC.

Wu, J., 1999. Hierarchy and scaling: information along a scaling ladder. Canadian Journal of Remote Sensing 25 (4), 367–380.

Young, R., Onstad, C., Bosch, D., Anderson, W., 1989. AGNPS: a nonpoint-source pollution model for evaluation agricultural watersheds. Journal of Soil and Water Conservation 44 (2), 4522–4562.