Estimating the yields of sediments and sediment-bound heavy metals using the EROSION 3D simulation model

JUERGEN SCHMIDT & MICHAEL VON WERNER

Department of Soil and Water Conservation, Technical University Freiberg, Agricolastrasse 22, D-09599 Freiberg, Germany

e-mail: jschmidt@orion.hrz.tu-freiberg.de

Abstract Yields of sediments and sediment-bound heavy metals are estimated for three drinking water reservoirs in the Eastern Ore Mountains region of Saxony, Germany. Estimates are made using EROSION 3D, a physically-based soil erosion model for simulating soil erosion by water and sediment delivery to stream networks and lakes. Model predictions are verified by comparison with measured yields of sediment and sediment-bound heavy metals.

INTRODUCTION

The long-term, continuous delivery of sediments leads to the aggradation and silting-up of stillwater reaches and reservoirs, and impairs their ecological and economic functions. Maintenance and restoration of these functions usually requires extensive technical measures such as impoundment structures or continuous dredging of the accumulated sediments. The removal and disposal of the trapped sediments may cause additional expenses if the sediment is contaminated so that special treatment or disposal is required.

The main objective of this paper is to investigate the causes of sedimentation and contamination of drinking-water reservoirs in the Saxonian Ore Mountains (Erzgebirge), Germany. Soils and sediments of these reservoirs are highly contaminated with heavy metals due to former mining activities in that region. The sediment-bound metals may be mobilized in future (e.g. in case of decreasing pH) and impair water quality drastically.

The study uses the EROSION 3D simulation model (a) to identify the main areas of sediment production and the causes of its mobilization, (b) to locate the points at which the sediment is delivered to streams, and (c) to make an estimate of the amounts of sediment including sediment-bound contaminants which are delivered to the reservoirs.

MODELLING PRINCIPLES AND METHODS

EROSION 3D is a physically-based computer model for predicting soil erosion by water on agricultural land (von Werner, 1995; von Werner & Schmidt, 1996). The model consists of two modules. The "pre-processor" module calculates the amount and direction of overland flow by taking account of the slope and exposition of the considered land surface and the infiltration rate which is estimated by an infiltration subroutine using the approach of Green & Ampt (1911). The "main module" of EROSION 3D simulates the detachment of soil particles due to overland flow and raindrop impact, the hydraulic transport of detached particles by overland flow, and the deposition of suspended particles and/or their delivery into the surface water system.

The fundamental erosion equations of the main module are based on the momentum flux approach of Schmidt (1996). In this approach, the sum of all mobilizing forces (i.e. of the overland flow) acting on the soil particle are compared to the sum of those forces which prevent the particle from being detached (i.e. cohesion, gravity). Erosion occurs if the sum of the mobilizing forces is greater than that of the resisting forces. In all other cases, no particles are eroded from the soil surface. Deposition occurs if the balance between the mobilizing and resisting forces changes in favour of the latter. This effect is usually observed at the lower part of a typical hillslope, for example, due to decreased flow velocity.

EROSION 3D requires information on site-specific relief, soil and rainfall conditions. This information is supplied to the model using the following parameters: relief parameters—x, y, z coordinates (digital elevation model); rainfall parameters—date of rainfall event (dd.mm), rainfall duration, rainfall intensity; soil parameters—texture, bulk density, content of organic matter, initial soil moisture, erosional resistance, hydraulic roughness of the soil surface and percentage ground cover. The effects of different types of land use and agricultural management practices are accounted for by varying the values for erosion resistance, hydraulic roughness and percentage soil cover. Suggested values for these input parameters can be estimated from tabular data (Michael *et al.*, 1996), which are available for various soil surface conditions and management options.

EROSION 3D uses a grid-cell data representation of the watershed. The values of all input parameters are assumed to be spatially uniform below the scale of grid resolution.

Accordingly, the model produces raster-based estimates of soil loss and deposition, and the sediment delivered to the stream network (Table 1).

Table 1 EROSION 3D output parameters.

Parameters related to area	Parameters related to cross-section of flow
Erosion and deposition for the chosen grid cell (mass/unit area)	Runoff (volume/unit width)
	Sediment delivery (mass/unit width)
Erosion, deposition and net erosion for the watershed draining to the chosen grid cell (mass/unit area)	Sediment concentration (mass/unit flow volume)
	Particle-size distribution of the suspended sediment (percentages of clay, silt and sand by mass)

RESULTS

Erosion and sediment yield simulation

The model was applied to watersheds of three reservoirs in the Eastern Ore Mountains Region of Saxony: Malter/Rote Weißeritz (81 km^2), Klingenberg-

Lehnmühle (90 km^2) and Saidenbach (61 km^2). Since EROSION 3D can only be applied to watersheds with a maximum size of 1000 ha, all reservoir watersheds were divided into sub-watersheds. The watershed of the Klingenberg-Lehnmühle reservoirs, for example, was divided into 11 sub-watersheds. Input parameters including relief, rainfall, soil, and land use were gathered from topograghic maps (1:10 000), soil maps (1:50 000), aerial photos and weather service data.

Figure 1 shows the erosion predicted for a single rainfall event on sub-watershed 1 of the Klingenberg-Lehnmühle reservoirs. Areas of erosion are indicated by yellow to red, and green to blue indicates areas of deposition. The map shows that, in some locations, deposition fans are formed in the reservoir despite the buffer strip surrounding the reservoir. Areas of maximum erosion are usually found in slope depressions which are drained by concentrated overland flow.

Sediment delivery to each reservoir was predicted from annual estimates of soil loss. These estimates are based on a baseline or reference year scenario which reflects the average changes in the climatic and farming conditions during one year. Simulation results are listed in Table 2.

Table 2 Predicted mean annual sediment delivery to the Klingenberg-Lehnmühle, Malter and Saidenbach reservoirs (Schmidt *et al.*, 1995; Schmidt & von Werner, 1998).

Reservoir	Watershed area (km^2)	Predicted sediment delivery (kt year^{-1})
Lehnmühle	61	2.6
Klingenberg	29	5.6
Malter	81	5.6
Saidenbach	61	7.9*

* Preliminary value.

Comparison of predicted and measured sediment yields

Measured sediment yield data are available only for the Malter and the Saidenbach reservoirs. The data are based either on information on the dredged volume of the trapped sediment, or on the surveying and volumetric estimation of the sediment volume.

Mean annual sediment inflow was then estimated from the time interval between two dredgings, the volume, and the specific weight of the accumulated sediment.

Malter Reservoir

The Rote Weißeritz drains approximately two thirds of the total watershed area of the Malter Reservoir. Most of the smaller streams flow directly into the main reservoir, whereas the suspended sediment of the Rote Weißeritz is trapped in a retention basin located at the head of the Malter lake. The sediment in this basin is removed approximately every ten years. The dredging for the period from 1984 to 1994 yielded a mean annual sediment inflow of about 3 kt.

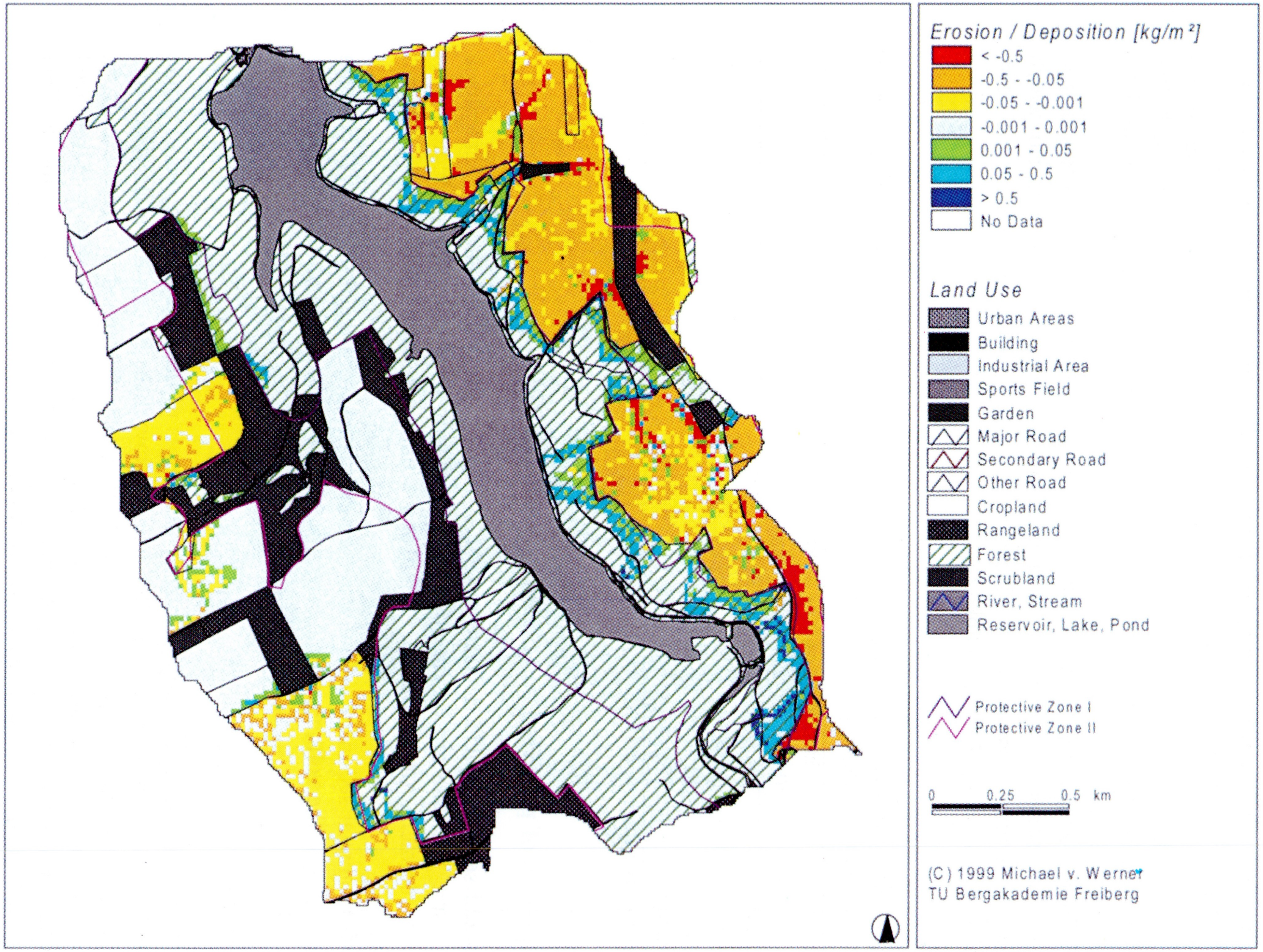

Fig. 1 Erosion map for a sub-watershed of the Klingenberg-Lehnmühle watershed (predicted for the rainfall event on 7 July of the reference-year rainfall scenario; Schmidt & von Werner, 1998).

Model calculations estimate the annual sediment inflow from the Rote Weißeritz to be approximately 5.6 kt. Compared to the mass of the sediment trapped in the retention basin, this is a surplus of 2.6 kt year^{-1}. This over-prediction could be caused by the following effects, which were not considered in the model calculations: (a) sedimentation within the river channel, and (b) incomplete retention of sediments within the retention basin. In particular, the second effect is very likely, so that the surplus estimated from this comparison appears plausible, although no quantitative evidence can be given.

Saidenbach Reservoir

Like the Malter Reservoir, the Saidenbach Reservoir is fed by several streams. Due to the high sediment load, retention basins have been built at the mouths of all major streams. For the Hölzelbach, sediment delivery into the retention basin and the main reservoir was estimated by measuring the volume of the accumulated sediments (Engelhardt, 1996).

The last dredging operation in the retention basin dates back to 1960. From measurements of the thickness of the sediment layer in 1995, the mean annual rate of sediment inflow was calculated to be approximately 50 m^3 or 24 t. Since the delivered sediment is not entirely retained by the retention basin, an attempt was made to quantify also the mass of sediment delivered into the main reservoir. This estimation was eased by the location of the retention basin; this drains into a shallow inlet of the main reservoir in which sediment is deposited as a long alluvial fan. Since the volume of the fan could be accurately surveyed, it was possible to estimate the average annual rate of sediment accumulation to be approximately 96 t since the flooding of the reservoir in 1935. Thus, the Hölzelbach watershed (0.73 km^2) delivers a total sediment mass of approximately 120 t year^{-1} to the Saidenbach Reservoir.

From simulation runs, a sediment delivery of 143 t year^{-1} was predicted; this value overestimates the measured delivery by about 20%. Considering the uncertainty associated with the surveying of the sediment in the Hölzelbach inlet, this level of agreement between the observed and predicted annual delivery rates is good.

Estimating the delivery of particle-bound heavy metals

The sediment delivery predicted by EROSION 3D provides the basis to estimate sediment-associated metal delivery. The calculation includes the following steps:

1. EROSION 3D estimates the sediment outflow totals from a given watershed (in mass/unit width) and the percentages of clay, silt and sand. In this first step, the predicted percentages are converted to absolute amounts, such as mass totals for each particle class (conversion from percent by mass to mass/unit width).
2. These sediment mass fractions are multiplied by the respective heavy metal concentrations for each textural class of the parent soil (in mass/mass). The resulting product is the absolute metal delivery from the watershed, given for each particle class of the delivered sediment (in mass/unit width).

3. These fractional contributions are added in order to yield the total mass of heavy metals contained in the delivered sediment (in mass/unit width).
4. The absolute amount of heavy metals which is delivered from the watershed to the reservoir is obtained by multiplying the total output of heavy metals (in mass/unit width) by the raster width (or spatial resolution) of the grid-cell data representation.

This estimation procedure was applied to the Hölzelbach watershed in order to estimate its heavy metal delivery to the Saidenbach Reservoir. Heavy metal concentrations in the textural fractions of the soils were determined from 16 representative samples. Mean values are compiled in Table 3.

Values for the measured and predicted annual delivery of heavy metals from the Hölzelbach watershed are summarized in Table 4. The data referring to sediment were estimated from sample analyses and the surveying of the sediment volume. Table 4 shows that the measured deliveries are reproduced with an acceptable accuracy by EROSION 3D. A larger variation is observed for the annual delivery of zinc, which is considerably overestimated.

CONCLUSIONS

The EROSION 3D model was used to estimate the yields of sediments and sediment-bound heavy metals of drinking water reservoirs in the Eastern Ore Mountains region of Saxony, Germany. The model output enables the local authorities to identify the main areas of accelerated erosion and to locate the points at which the eroded soils enter tributary streams or the reservoirs themselves. Hereby the model calculations supply important information in order to implement soil and water conservation measures within these watersheds.

Table 3 Mean heavy metal concentrations in the main textural classes of the soils of the Hölzelbach watershed (Schmidt, 1996; Engelhardt, 1996).

Element	Element concentrations in soils (mg kg^{-1}):		
	Clay	Silt	Sand
Pb	179	85	65
Zn	317	119	55
Cd	2.2	1.0	1.0
As	49	21	11
Hg	0.4	0.2	0.1

Table 4 Comparison of measured and predicted annual heavy-metal deliveries from the Hölzelbach watershed (Saidenbach Reservoir).

Element	Total annual delivery (kg year^{-1}):	
	Measured	Predicted
Pb	13	14
Zn	15	20
Cd	0.2	0.2
As	3.7	3.4
Hg	0.03	0.03

REFERENCES

Engelhardt, S. (1996) Partikelgebundener Schwermetalltransport aus einem kleinen Einzugsgebiet—Hölzelbergbach, östliches Erzgebirge (Particle-bound transport of heavy metals from a small watershed—Hölzelbergbach, Eastern Ore Mountains, in German). Unpublished MSc Thesis, Dept Geogr., Göttingen University, Göttingen, Germany.

Green, W. H. & Ampt, G. A. (1911) Studies on soil physics. I: The flow of air and water through soils. *J. Agric. Sci.* **4**,1–24.

Michael, A. (1996) EROSION 3D—Ein Computermodell zur Simulation der Bodenerosion durch Wasser, Bd. II: Parameterkatalog Sachsen (EROSION 3D—a computer model for simulating soil erosion by water, vol. II: parameter catalogue of Saxony, in German). Saxonian Agency of Agriculture & Saxonian Agency for the Environment and Geology (eds), Leipzig/Dresden, Germany.

Schmidt, J. (1996) Entwicklung und Anwendung eines physikalisch begründeten Simulationsmodells für die Erosion geneigter landwirtschaftlicher Nutzflächen (Development and application of a physically-based simulation model for predicting erosion on agricultural land, in German). *Berliner Geographische Abhandlungen* **61**.

Schmidt, J. & von Werner, M. (1998) Einsatz hochauflösender Erosionsprognosekarten zur Verbesserung des vorsorgenden Schutzes von Böden und Gewässern. Talsperren Klingenberg/Lehnmühle, Niederstriegis (Use of high-resolution erosion maps for improving long-term soil and water conservation. Klingenberg-Lehnmühle reservoirs, Niederstriegis valley, in German). Research report on behalf of the Saxonian Agency for the Environment and Geology, Dresden, Germany.

Schmidt, J., von Werner, M. & Müller, A. (1995) Erkundung der Ursachen für Verlandung und Kontamination—Bestimmung von Sedimentationsraten—Talsperre Malter, Speicherbecken Radeburg I (Investigation of the reasons for silting-up and contamination—determination of sedimentation rates—Malter Reservoir, Radeburg I storage basin, in German). Research report in behalf of Hydroprojekt Engineering, Dresden, Germany.

von Werner, M. (1995) GIS-orientierte Methoden der digitalen Reliefanalyse zur Modellierung von Bodenerosion in kleinen Einzugsgebieten (GIS-based methods of digital terrain analysis for modelling soil erosion in small watersheds, in German). PhD Thesis, Dept Geogr., Berlin Free University, Berlin, Germany.

von Werner, M. & Schmidt, J. (1996) EROSION 3D—Ein Computermodell zur Simulation der Bodenerosion durch Wasser, Bd. III: Modellgrundlagen—Bedienungsanleitung (EROSION 3D—a computer model for simulating soil erosion by water, vol. III: modelling principles—user manual, in German). Saxonian Agency of Agriculture & Saxonian Agency for the Environment and Geology (eds), Leipzig/Dresden, Germany.