Simulation of Reservoir Siltation with a Process-based Soil Loss and Deposition Model

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Abstract

Soil erosion on arable land is the key driver of reservoir siltation in the German loess belt. In this regard, the Baderitz Reservoir suffers from deleterious sediment inputs and resulting siltation processes. In order to estimate the reservoir lifespan, the event-based soil erosion and deposition model EROSION 3D was applied. Simulations of sediment input and sediment deposition processes within the reservoir were realized using a typical crop rotation and a normal heavy rainfall year of the region. Model parameterization was enabled by existing data based on a large number of artificial rainfall simulations. Yearly soil losses of approximately 12 t/ha correspond to sediment inputs of nearly 8800 t. The mean annual increase of the reservoir bottom of 9 cm causes a 13% loss of reservoir storage in only 10 years. The model results are plausible and could be used for planning and dimensioning of mitigation measures.

Keywords: soil esoil erosion modelling, loess belt, water conservation, hydraulic engineering

1. Introduction

Soil erosion, as one of the main triggers of land degradation, seriously threatens the sustainability of cropping systems in many parts of the world. Soil erosion leads to both on-site and off-site damages. On arable land, on-site effects lead to a reduction of soil fertility, often less regarded. More attention is given to the off-site damages if sediments and/or attached nutrients are entering settlements, traffic lanes or stream networks. Since siltation and eutrophication may cause enormous costs on national economy, the latter is of special public interest. In this regard, active and passive soil conservation measures become important in order to decrease sediment inputs into surface waters.

Since soil erosion is strictly a non-continuous process, the main soil loss and sediment delivery into stream network is caused by single, extreme rainfall events [1]. Due to the highly complex nature of the physical processes involved, monitoring and surveying of soil erosion processes is associated with many difficulties. In order to overcome these problems, mathematical simulation models have been developed starting with the Universal Soil Loss Equation (USLE) by [2]. However, the USLE was derived by correlating empirical data resulting in a limited transferability of this model. Examples for successful USLE-based applications are given by [3-6]. Although such approaches fullfil their aims of sediment input calculations, they are less suitable for event-based planning purposes. Since USLE-based approaches only generate annual mean soil losses, the highly non-continuous nature of erosion processes is neglected. This renders the application of these model types for planning and dimensioning of passive mitigation measures, impossible.

A younger erosion model generation makes use of physical principles as mass and energy balances, which allow adequate representation and quantitative estimation of soil detachment, transport, and deposition processes. In this regard, only process-based models are able to focus on the challenge of planning and dimensioning of mitigation measures. As a result of high data demands and difficult parameterization procedures, only few examples are found in literature [7].

In this context, the EROSION 3D model might be a suitable tool for the estimation of soil loss, deposition and sediment input into surface waters. Since the model is physically-based, it can be applied for all types of soils and climate regions.

2. Materials and methods

2.1. Site description

The research area is located within the German loess belt (51°09′47 N, 13°10′12 E). The catchment (20 km^2) is a part of the Jahna Catchment, a tributary of the Elbe River. The dominant regional soil type is the Luvisol with high silt content. In this regard, soils are characterized by a high water-holding capacity and fertility, but vice versa highly endangered by erosion caused by low aggregate stabilities.

After [8], the study area is located in a warm oceanic Cfb-climate with 624 mm annual rainfall and 8.1 °C mean annual temperature (Figure 1). Most rainfall events occur between May and September, mainly as convective rains.

Due to low plant covers at the beginning and end of the crop year, the most intense erosion events occur between May and June (corn, sugar beet) and in September (rape, winter grains). The Baderitz Reservoir was constructed between 1985 and 1987 for purposes of flood control and irrigation. With an area of 0.1 km^2 and a mean depth of approximately 6 m, the whole

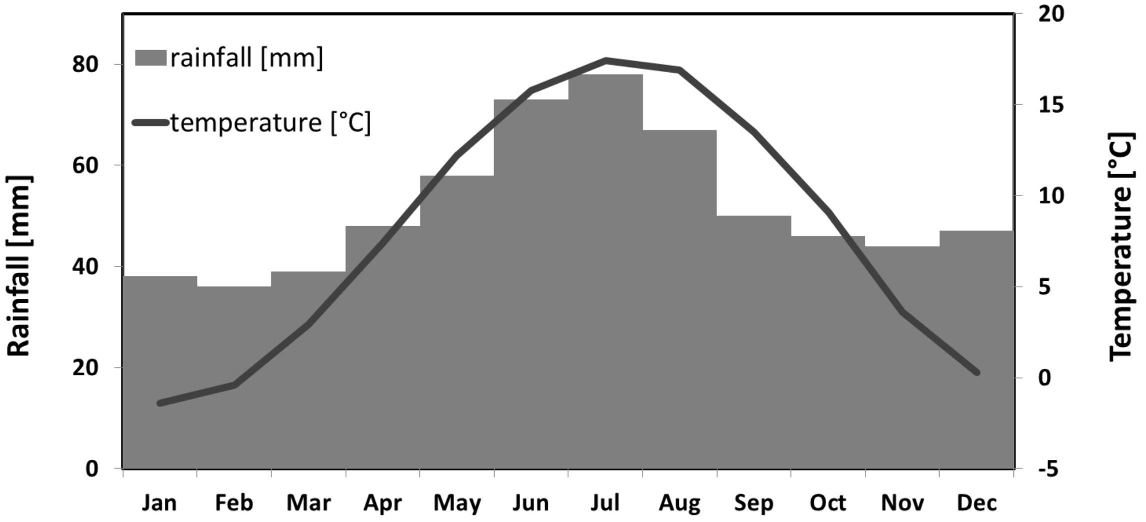

Figure 1. Climate chart of the study region.

retaining capacity amounts to 676,000 m^3, whereas 300,000 m^3 are common and 70,000 m^3 are uncommon flood retention. The dam is 9.7 m high and 180 m long. Since the last 27 years, the reservoir suffered from deleterious sediment inputs. Only between 1997 and 2006 the delta of the Jana Creek rose more than 150 m in length to an area of at least 0.02 km^2 within the reservoir (Figure 2).

Figure 2. Development of the creek delta at the inlet of Baderitz Reservoir between 1997 and 2006.

Jahna Creek is draining the catchment with a mean discharge of 0.15 m^3/s. Peak flows are mostly related to heavy rainfall events.

As a result of the high soil fertility, more than 75% of the catchment area are used by croplands. Typical crops are winter wheat, rape, sugar beet, and corn. Grassland is limited to narrow stripes on the valley bottoms. Settlements cover 5%, whereas forest is limited to small isles (Figure 3).

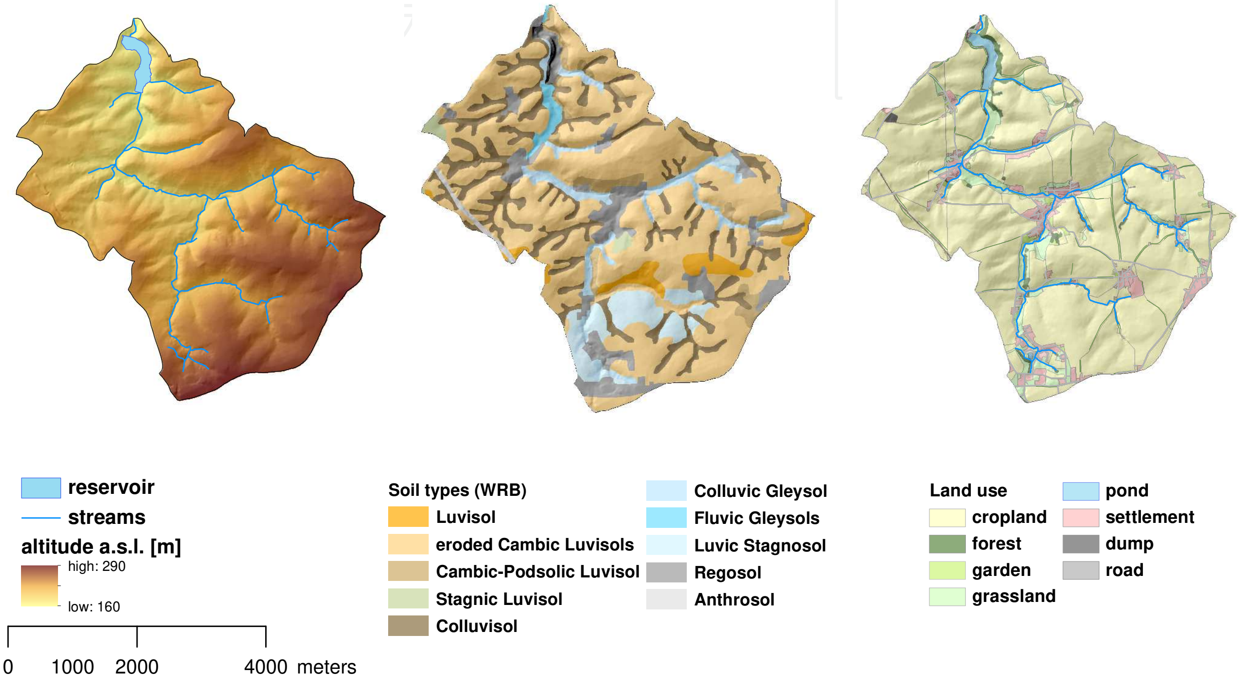

Figure 3. Relief, soil types, and land use of the Baderitz Reservoir catchment.

2.2. The soil loss simulation model EROSION 3D

EROSION 3D [9-11] is a field-tested, physically-based soil erosion model to estimate the spatio-temporal distribution of erosion and deposition, as well as the delivery of suspended soil material into surface water courses [10]. Since more than 20 years, the model was continuously improved and extensively validated using plot- and catchment-based soil erosion data [12-14].

The theoretical concept of the model is based on the momentum flux approach. The erosive impact of overland flow and rainfall droplets is proportional to the momentum flux exerted by the flow and falling droplets, respectively [9-10, 15]. In detail, the model covers rainfall infiltration, excess rainfall and subsequent generation of surface runoff, detachment of soil particles by raindrop impact and surface runoff, transport of detached soil particles by surface runoff, routing of surface runoff, and sediment transport through the catchment.

Since the model is raster-based, EROSION 3D demands a grid-cell parameter representation of the catchment. Using internal parameter transfer functions, EROSION 3D only needs few input soil parameters compared to other process-based erosion models as EUROSEM [16], WEPP [17] and LISEM [18], which allows application for research as well as planning purposes.

Overland flow routing is generated by applying a multiple flow algorithm FD8 [19-20]. After reaching a critical source area of runoff generation [m^2], multiple flow is converged to single flow (D8) [21] equivalent to channel flow. Once the runoff and transported sediments are entering the channel network, sediments are routed outside the catchment, disregarding deposition processes (Figure 4).

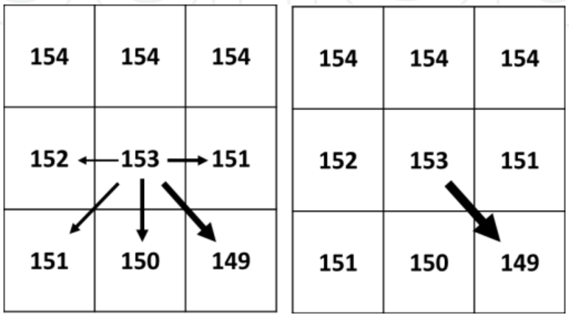

Figure 4. Multi-direction flow (FD8, left) and single direction flow (D8, right).

Regarding parameter identification, the interactive software tool DPROC was developed to enable the semiautomatic generation of model input data by using available relief, land use, and soil data sets. Model parameters (Table 1) are derived as functions of land use, soil characteristics, and simulations date, using an extensive database deducted from numerous rainfall experiment simulations on test plots in the mid-nineties [22-24] Experiments cover a broad range of different soil, crop, and tillage types, as well as special soil characteristics and crop phenology stages.

Input parameter	Unit	Method
Altitude (DEM)	[m]	Airborne laserscan
Rainfall intensity per time step	[mm/min]	Statistical analysis of the German Weather Service
Grain size distribution	[%]	Derived via sum curves of available soil map
Bulk density	[kg/m^3]	Databases*
SOC	[%]	Databases*
Surface roughness	[s/m$^{1/3}$]	Databases*
Initial soil moisture	[Vol.%]	Databases*
Skinfactor	[−]	Databases*
Resistance to erosion	[N/m^2]	Databases*
*[22-24, 27],		

Table 1. Input parameters of the EROSION 3D simulation model.

2.3. Data preprocessing and parameterization

GIS data preprocessing of land use, soil type, relief, and rainfall information was accomplished according to [24]. Land use maps were applied from available sources in a scale of 1:25,000, soil maps in a 1:50,000 scale. Since soil erosion is a complex process, highly influenced by local morphology, the DEM of 20 m cell size was interpolated to a 5 m grid according to [25].

2.3.1. Digital elevation model

Considering the morphological shape of the reservoir bottom, no digital information was available from official sources. Consequently, the resulting shape of the reservoir bottom is a more or less flat surface. Isolines of a historical topographic map [26] were digitized, interpolated, and merged with the existing DEM. This map of 1935 represents the land surface prior to the construction of the reservoir and so the assumed underwater relief. Finally, the dam of 9 m height was attached (Figure 5).

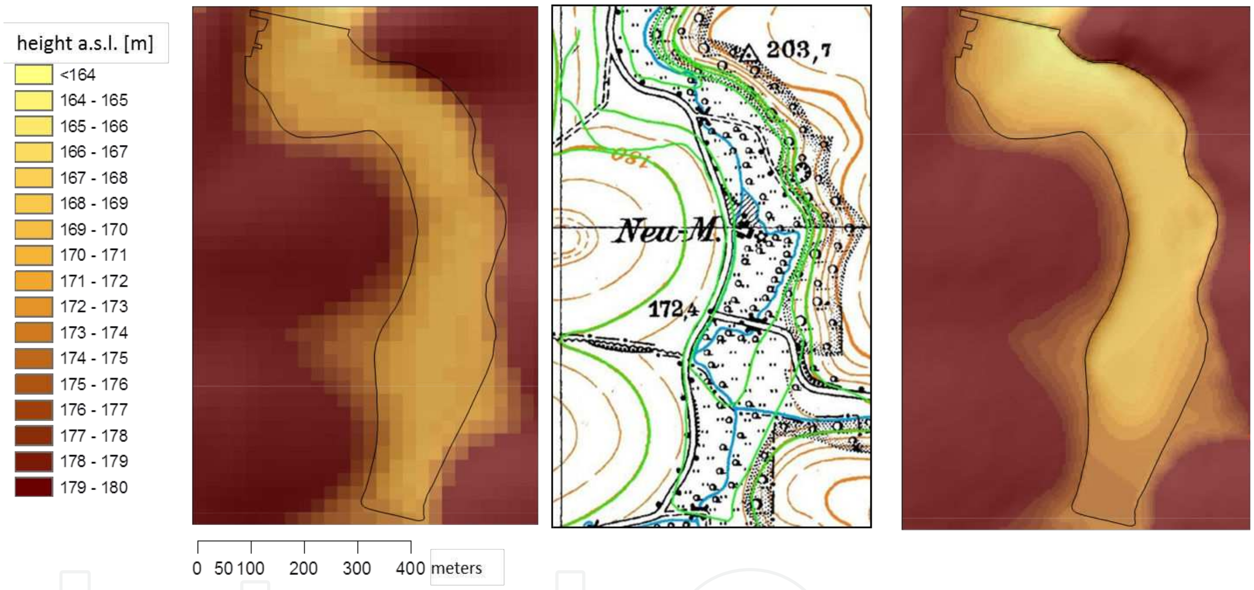

Figure 5. Original DEM in a 20 m cell size (left), digitized contour lines of a historical map of 1935 (center), and modified DEM of 5 m cell size with the elevated dam.

2.3.2. Representation of water bodies in the EROSION 3D model

Since the EROSION 3D model was originally developed for runoff and deposition processes on arable land, complex hydrodynamic 2D or 3D flow algorithms for water bodies are not included. Considering a critical source area of concentrated flow in the study region of approximately 0.08 km^2, the reservoir is among the channel network, only permitting single direction flow. Since hydrodynamic conditions in stand water are different to those in a turbulent stream, single flow calculations need to be disabled within the reservoir body. Additionally, hydraulic roughness needs to be increased on that area to enable sedimentation processes as they take place in water bodies.

2.3.3. Parameterization of the worst-case scenario

As a first step of model application, a worst-case scenario is simulated in order to identify the most important sediment delivery areas, as well as the sediment pass over points into surface waters. In this regard, all croplands are assumed to be under seedbed conditions related to conventional tillage with the moldboard plough. This implies no soil cover of plants or plant residues, low hydraulic roughness due to the fine soil management, and high soil moisture contents (field capacity).

2.3.4. Parameterization of normal heavy rainfall years

Since the model is capable to process single storms as well as storm sequences, annual soil losses and sediment input into the stream network can be simulated. For this purpose, the model demands single events of a normal heavy rainfall year (Figure 6), which was generated by the [27].

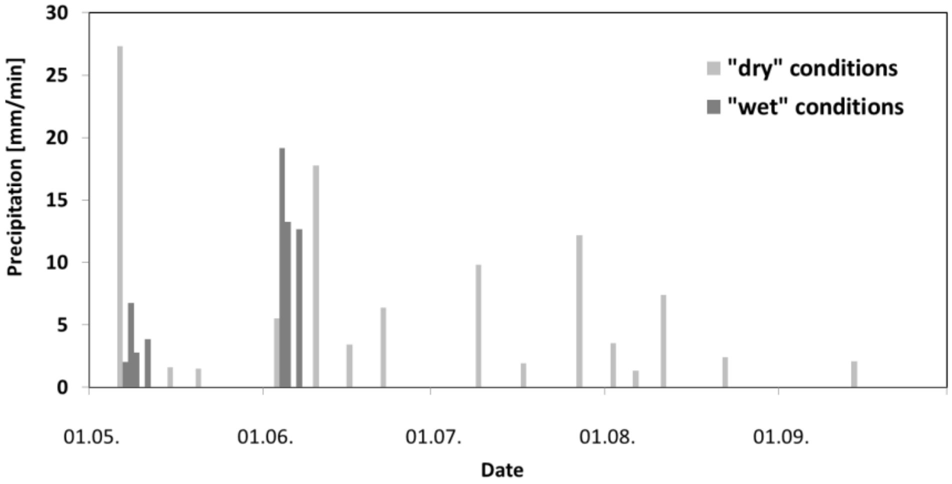

Figure 6. Normal heavy rainfall year of the study region.

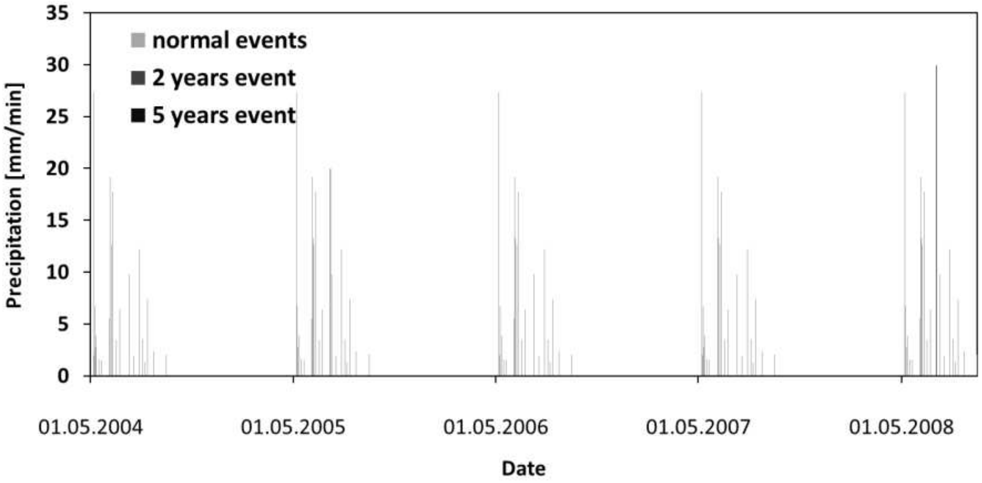

Figure 7. Five-year rainfall sequence with normal heavy rains and statistical extreme events.

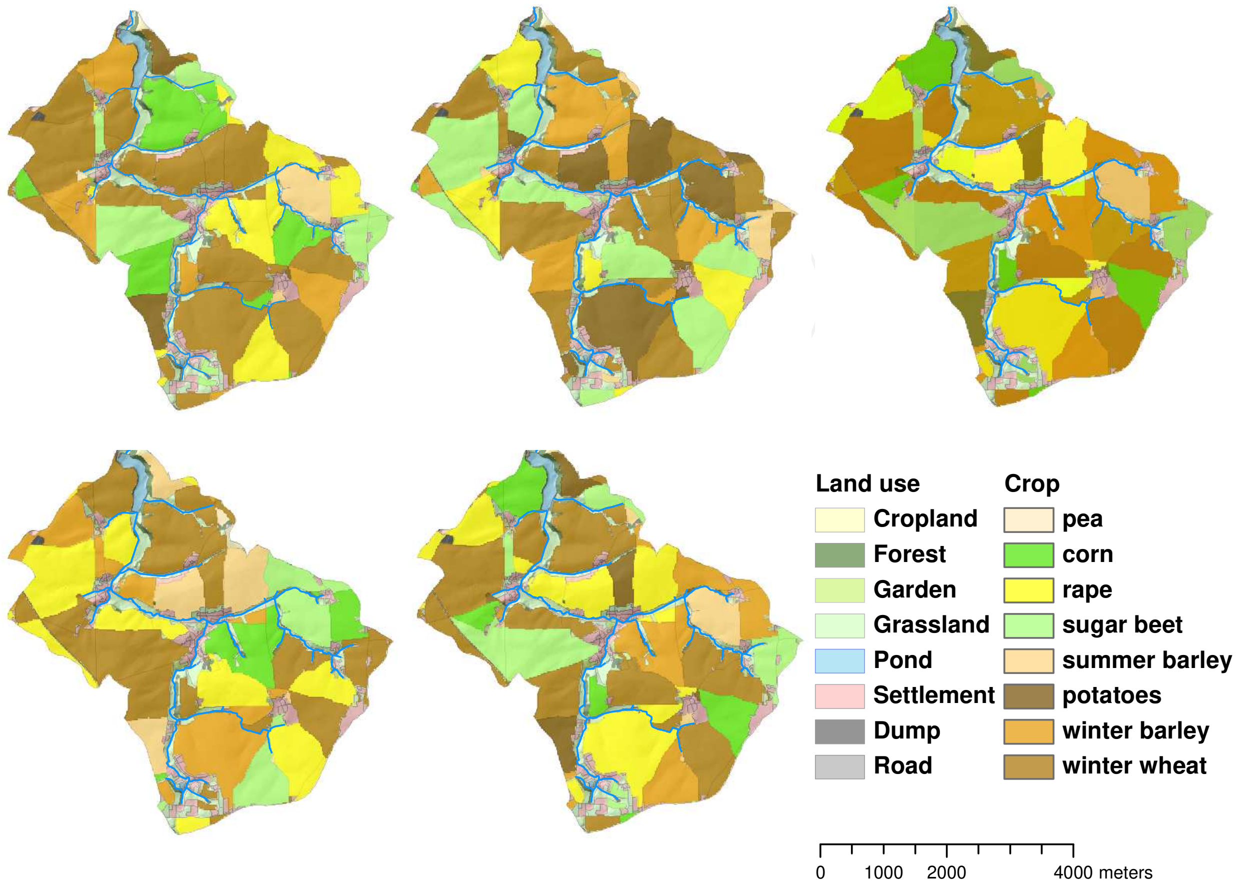

Figure 8. Crop type distribution in five crop years (start 2004).

In order to simulate a ten-year rainfall sequence, rainfall events of the normal years have to be combined with statistical extremes as it is compiled in Figure 7.

By applying land use and crop type maps from 2004 to 2009 (Figure 8), initial conditions of all rainfall occurrence dates were parameterized with the software DPROC. Considering dynamic moisture conditions, all events with previous rainfall events, less than 24 h ago, were set to high soil moisture contents (field capacity, Figure 6). Land use and soil parameters were derived from the database of DPROC. After the harvest of grains and rape in August and September, a stubble cover was assumed and the planting of rape was supposed to early September.

3. Results

3.1. Soil loss and sediment flux for the worst-case scenario

The Baderitz Reservoir catchment is highly endangered by soil losses. All croplands tend to deliver considerable amounts of sediments. Since all soil types are characterized by high silt contents, soil erosion is mainly controlled by slope length and slope steepness. Highest soil loss rates are reached in thalwegs (Figure 9), where surface runoff concentration allows highest transport capacities and related sediment concentrations.

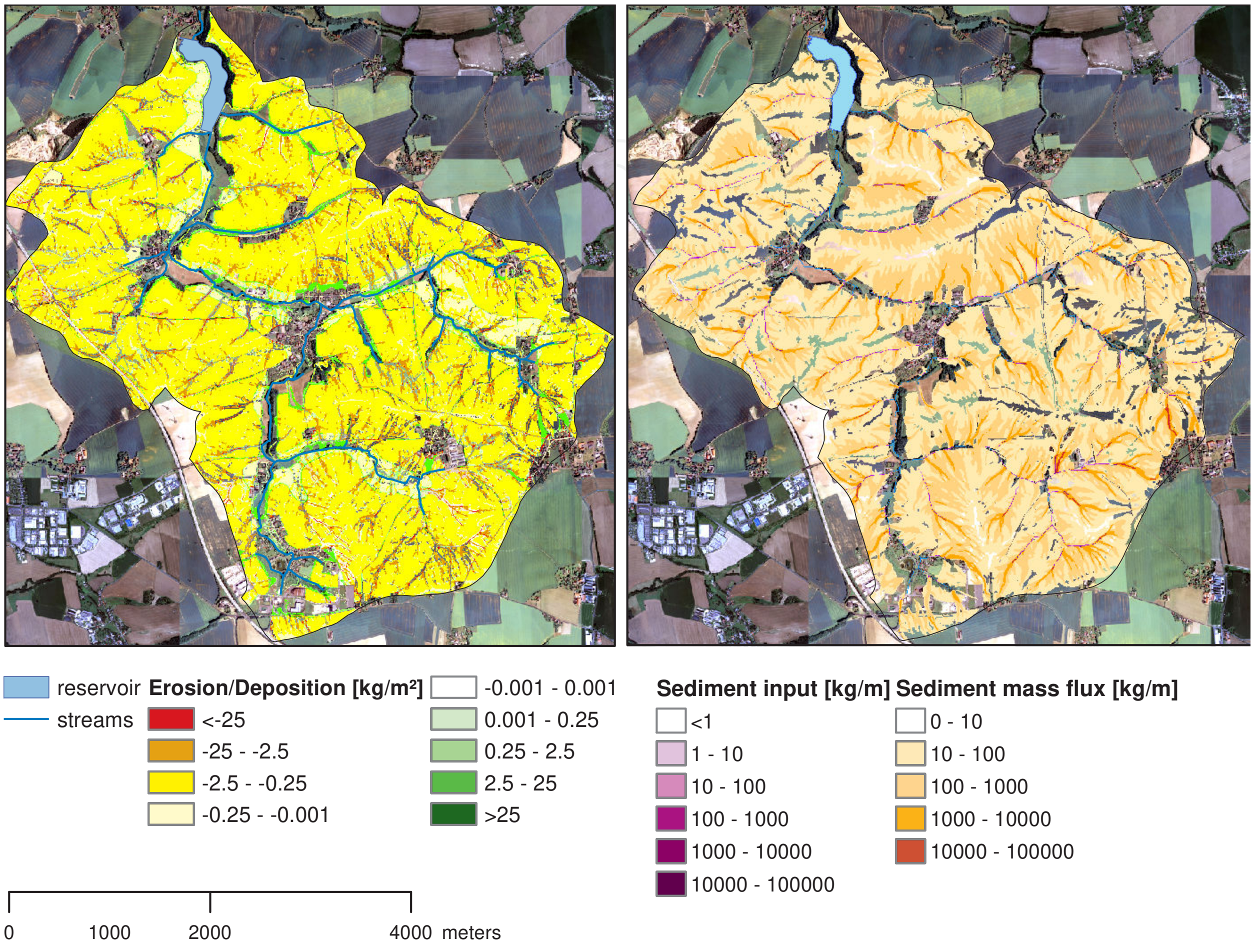

Figure 9. Sediment budget, sediment flux, and sediment input into surface waters for the worst-case scenario.

Mean soil loss amounts to 9.8 t/ha. All croplands are endangered by soil erosion, whereas grasslands, hedges, and woods act as buffers, where sediments are deposited (Figure 9). In this regard, all streams with insufficient buffers are affected by high sediment inputs.

3.2. Soil loss and sediment flux in the catchment during long-term simulations

The overall soil loss for the first reference year is 12.3 t/ha in the reservoir catchment.

Comparable to the worst-case scenario, all croplands are endangered by erosion. A distinct relation to the applied crop is visible (Figure 10).

Compared to prior simulations, croplands reveal high soil loss values, buffer stripes act as important retention areas. As overall trapping efficiency of this buffer is insufficient, effect of crop rotation becomes more important with the 10-year estimation compared to single events or single years (Figure 11). The mean soil loss after the 10-year simulation is about 193 t/ha. A distinct pattern of high endangered croplands of different categories is visible. Nearly comprehensive values of red pixels (<–25 kg/m^2), mixed of orange and red values (−2.5–25 and <–25), and a third class with red pixels only in areas of runoff concentration (Figure 11) are simulated.

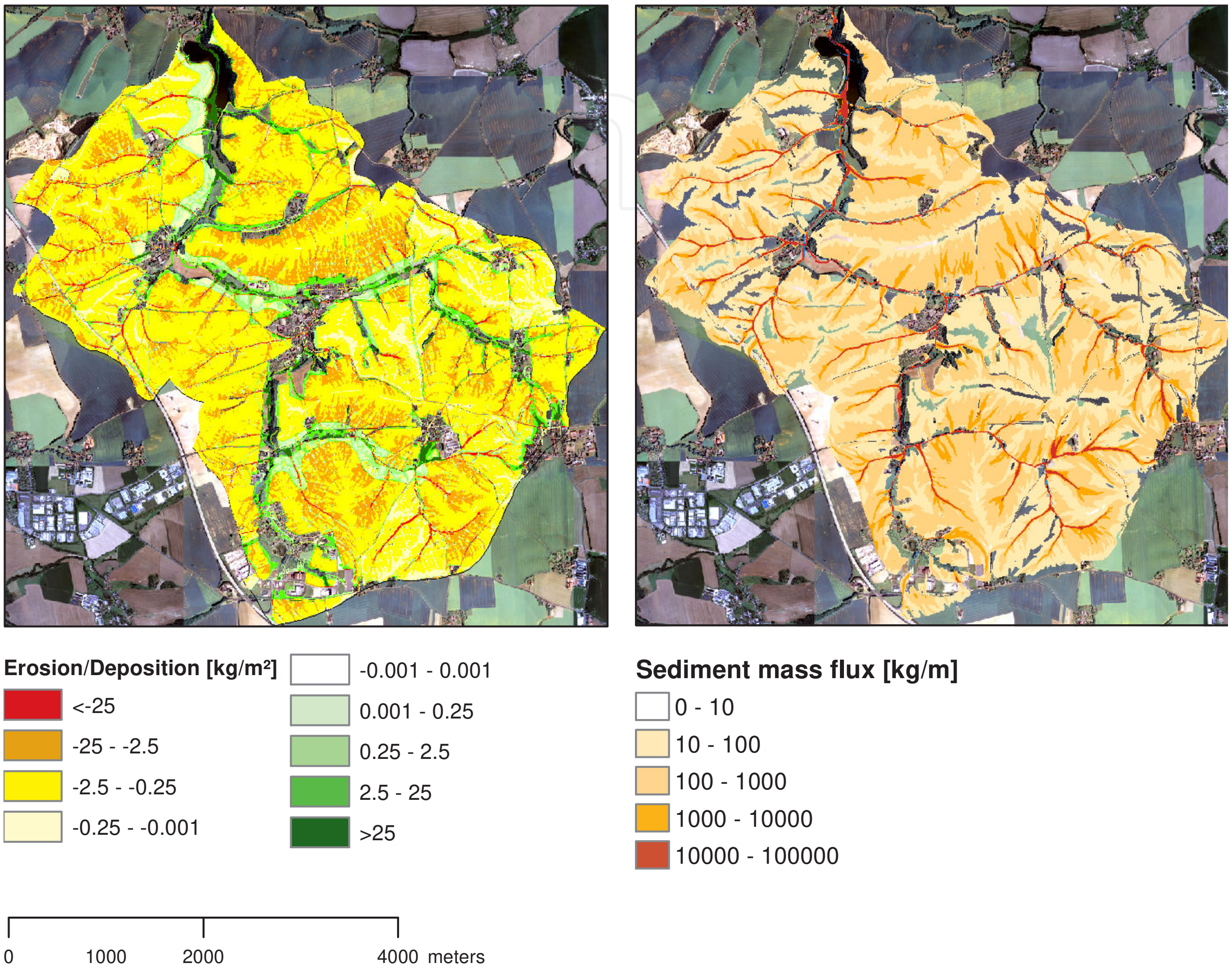

Figure 10. Sediment budget and sediment flux for the first reference year.

3.3. Sediment inputs into Baderitz Reservoir during long-term simulation.

During all simulation steps (1 year, 5 years, and 10 years) maximum sediment deposition can be identified at the water entrance area of the reservoir (Figure 12), which can be explained by the abrupt change in runoff velocity when water enters the reservoir. Additionally, sediments are deposited along the natural channel as shown in Figure 12.

Consequently, the bottom level is increasing due to sediment deposition after each erosive event. In a long-term simulation run, the EROSION 3D model adjusts the surface relief according to the amount of erosion and deposition. The changes are compiled in Figure 13, with an increasing reservoir bottom level and a resulting decreasing expanse of the water surface.

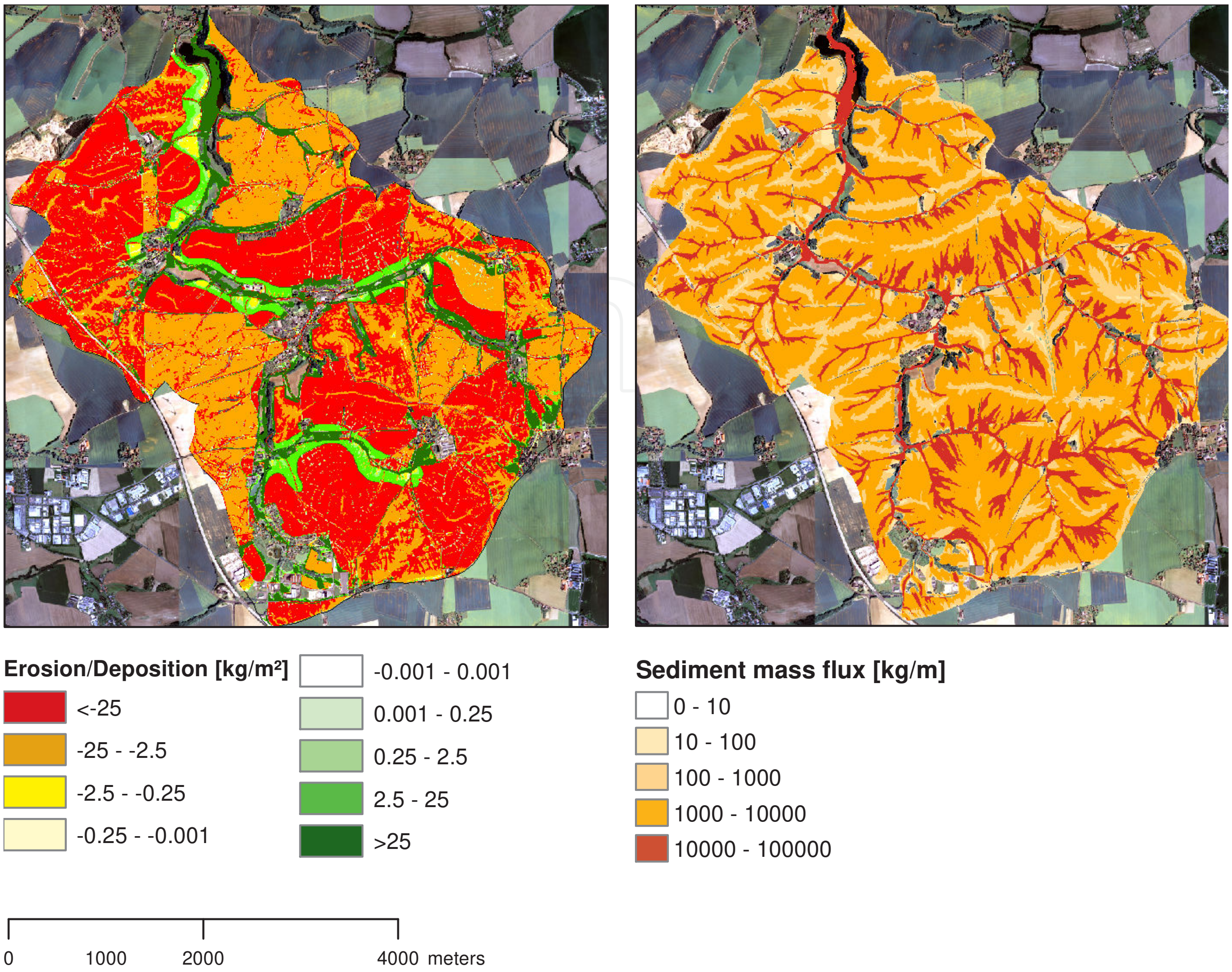

Figure 11. Sediment budget and sediment flux for ten reference years.

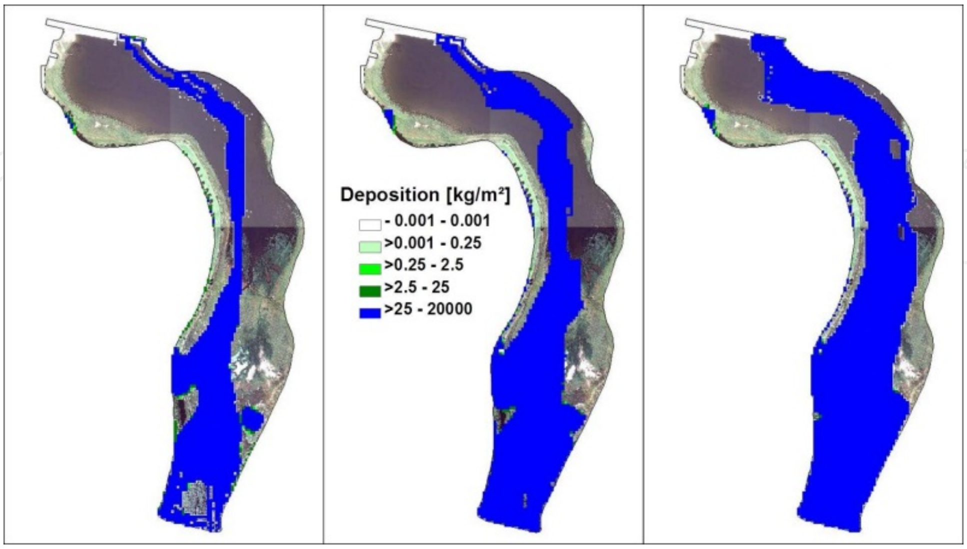

Figure 12. Siltation of the Baderitz Reservoir. Growing deposition areas after 1, 5, and 10 years.

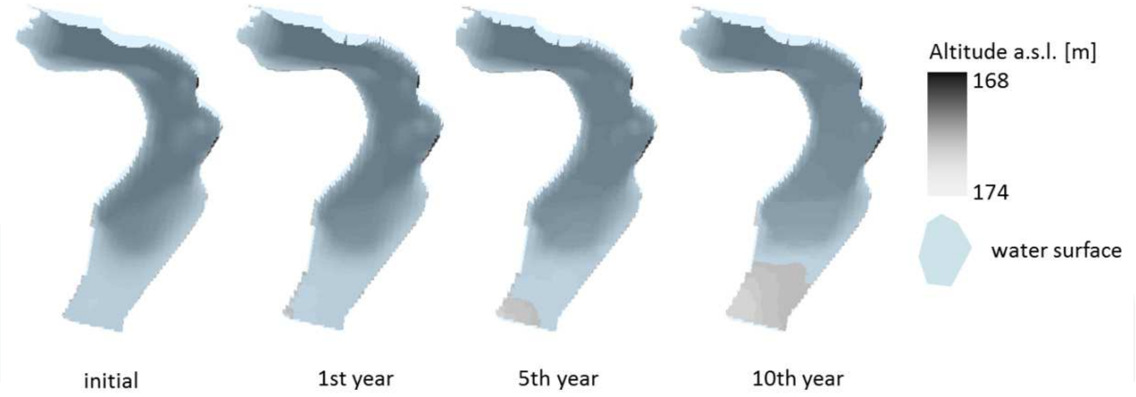

Figure 13. Siltation of the Baderitz Reservoir.

After the first year, inputs of 7943 t sediment or 5673 m^3 (estimated bulk density of 1.4 g/cm^3) were computed. This means, approximately 1% of retention reduction during the first year after installing the dam. After 10 years long-term simulation, inputs in the reservoir amounted to 124,470 t, which corresponds to 88,910 m^3 and a loss of 13% retention volume and a total elimination of the uncommon flood retention (Figure 14). On average, the reservoir bottom is heightened by about 0.9 m, with an increase of 16,900 m^2 in land surface.

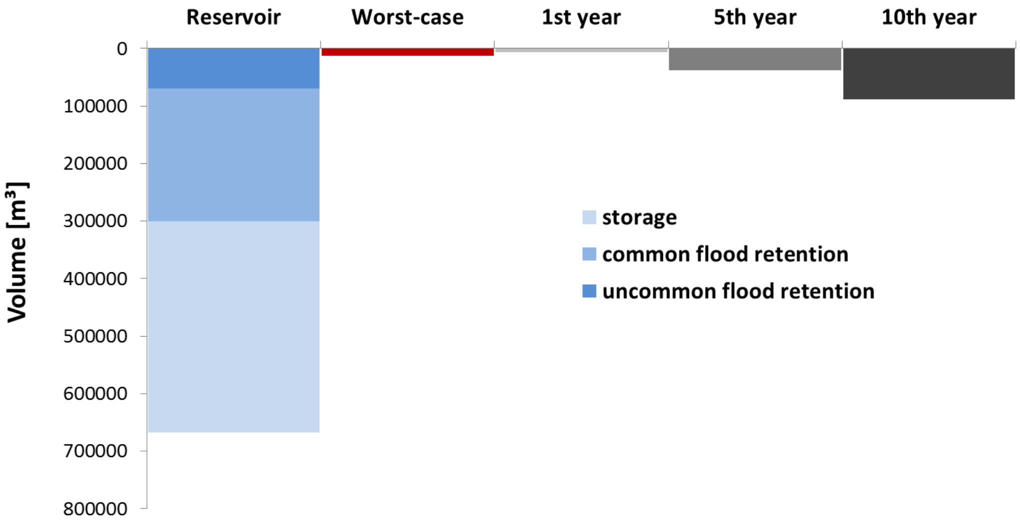

Figure 14. Siltation of the Baderitz Reservoir.

4. Discussion

Erosion and sedimentation processes are driven by temporal dynamic characteristics as land use, crop types and crop rotation, and relative constant catchment characteristics such as slope morphology and soil type.

Since most endangered rainfalls and "high" moisture conditions occur in late spring, crops with low plant cover reveal high losses of <–2.5 kg/ha after the first simulation year. Although winter wheat has a comparable high plant cover in May, high soil bulk densities decreasein-filtration rates and water storage capacities of the soil. As most of the precipitation is runoff, protection value of plant cover is obsolete.

Croplands with phenologically dependent high plant covers in the most endangered spring season (e.g., rape, Figure 8) are less affected.

Considering long-term simulation, especially croplands with a high amount of winter wheat and rape are overall less endangered. As the two extreme events statistically occur during July, crops with low cover in this month reveal high soil losses.

Compared to the worst-case scenario, sediment delivery ratio (SDR), described as throughflow in Figure 15 for one-year or ten-year long-term simulation, is much smaller. This means that the retention efficiency of sediment buffers is increasing with decreasing sediment fluxes. During high fluxes as simulated with the worst-case run, two-third of the sediments are routed into the water network and only 6% are remaining within the reservoir.

Decreasing SDR with increasing simulation year is caused by a cumulative bank up and resulting trapping efficiency of deposition areas. Between 70 and 75% of the sediments are deposited in the morphology of the catchment and between 12 and 15% are remaining in the reservoir (Figure 15).

Figure 15. Sediment budgets for worst-case and long-term simulation, changed after [3].

Since bathymetric data is lacking so far, sediment inputs only can be plausibly tested by comparisons with ortho-photos (Figure 16).

The picture was taken in 2009 after the reservoir was drained and reflooded. The water level is 3 m below the original level. Simulation results for a 20 year long-term run reveal an almost identical extent and shape. As this project was simulated with standard pre-calibrated database values, the results reveal high model quality, which makes further application for reservoir siltation even on larger scales possible.

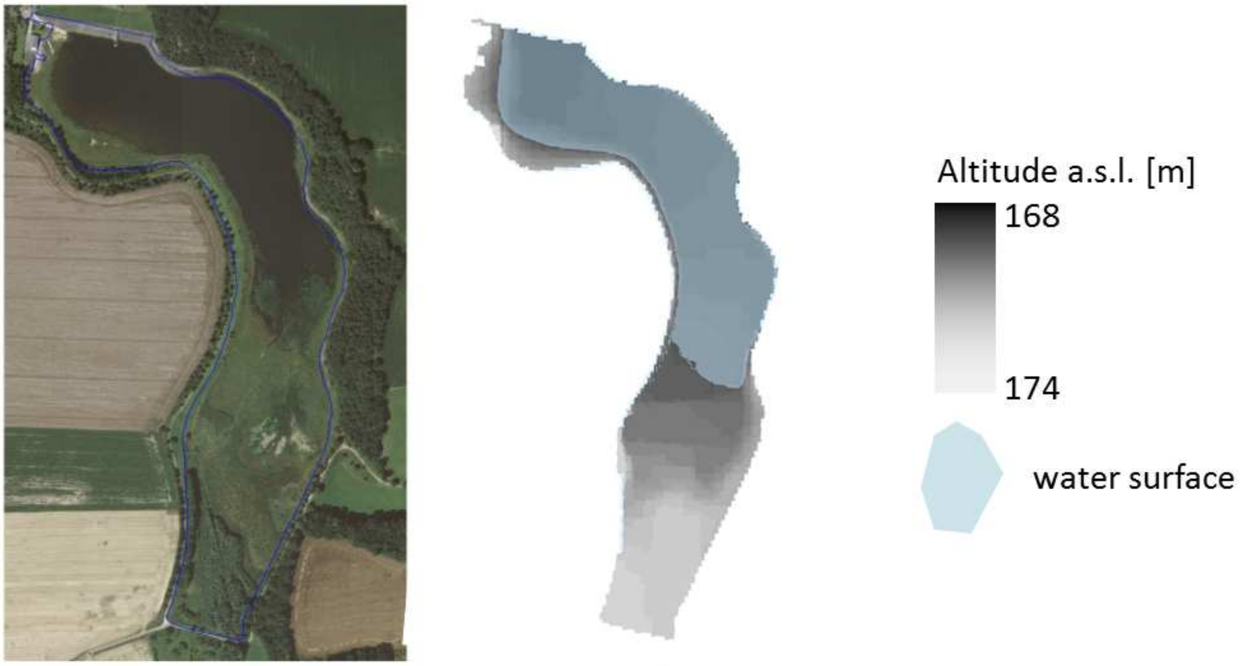

Figure 16. Comparison of observed and simulated sediment fan.

5. Conclusion

The process-based EROSION 3D model was successfully applied to simulate reservoir siltation in a meso-scaled German loess catchment. The simulation results in a progressive siltation of the reservoir, which is seriously impairing the primary purposes of the reservoir. Reservoir live span as flood retention is halved after 20 years, which immediately makes a sediment disposal essential.

To avoid excessive siltation, soil conservation measures should be implemented within the catchment. The EROSION 3D-based soil loss prediction maps could help to identify the most erosion-sensitive areas within the catchment, as well as the points of sediment transfer into surface water bodies. Further studies should focus on modelling and implementing of soil loss mitigation in the catchment. Both, local authorities and farmers will be made aware to take appropriate and effective actions to reduce soil loss.

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