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Modelling water availability, sediment export and reservoir sedimentation in drylands with the WASA-SED Model

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Abstract

The process-based, spatially semi-distributed modelling framework WASA-SED for water and sediment transport in large dryland catchments is presented. The WASA-SED model simulates the runoff and erosion processes at the hillslope scale, the transport processes of suspended and bedload fluxes in the river reaches and the retention and remobilisation processes of sediments in reservoirs. The modelling tool enables the evaluation of management options both for sustainable land-use change scenarios to reduce erosion in the headwater catchments as well as adequate reservoir management options to lessen sedimentation in large reservoirs and reservoir networks. The model concept, its spatial discretisation and the numerical components of the hillslope, river and reservoir processes are summarised and current model applications are reviewed to demonstrate the capabilities, strengths and limits of the model framework.

1 Introduction

In drylands, water availability often relies on the retention of river runoff in artificial lakes and reservoirs. Such regions are exposed to the hazard that the available freshwater resources fail to meet the water demand in the domestic, agricultural and industrial sectors. Erosion in the headwater catchments and deposition of the eroded sediments in reservoirs frequently threatens the reliability of reservoirs as a source of water supply. Erosion and sedimentation issues have to be taken into account when analysing and implementing long-term, sustainable strategies of land-use planning (e.g. management of agricultural land) and water management (e.g. reservoir construction and management).

The typical scale relevant for the implementation of regional land and water management is often that of large basins with a size of several hundreds or thousands of square kilometres. To take into account the effects of changing climatic or physiographic boundary conditions on water availability and reservoir sedimentation, quantitative and deterministic descriptions are required for the water and sediment dynamics of large river basins. For this purpose, the structure, functioning and application of the WASA-SED model has been developed and is presented here. The WASA-SED model is an integrated, spatially semi-distributed, process-based modelling framework for water and sediment transport adapted to the specific environmental characteristics of dryland catchments. It enables the modelling of erosion processes at the hillslope scale, the transport processes of suspended and bedload fluxes at the river scale and the retention and re-mobilisation processes and management options of sediments at the reservoir scale.

The WASA-SED model falls into the category of meso-scale, process-based erosion models that simulate runoff generation, soil detachment and sediment transport in a spatially semi-distributed manner. The complexity of such models increases with the detail of process representation, ranging from models representing a single process of sheet erosion (e.g., EROSION-2D Schmidt, 1991 and EROSION-3D von Werner, 1995), to models which differentiate between processes in rills and inter-rill areas (e.g., the MEDALUS model (Kirkby, 1997), LISEM (De Roo et al., 1996; Jetten, 2002), EUROSEM (Morgan et al., 1998), up to specialised gully erosion models (EGEM USDA-SCS, 1992; STABGUL DIMGUL Sidorchuk, 1998; Sidorchuk and Sidorchuk, 1998). Due to their extensive and detailed data and parameter requirements, these physically-based models are not applicable to large river basins for which usually only coarse input data sets exist. Only few models are described in the literature that deal with the quantification of erosion and sediment yield relevant for water availability and reservoir management in large river basins. The erosion component in these models usually is based on modifications of the USLE or MUSLE approach (e.g., in SWRRB Arnold et al., 1989, SWIM Krysanova et al., 2000, LASCAM Sivapalan et al., 1996 and SWAT Neitsch et al., 2002). The advantage of the new WASA-SED model in comparison to existing models is its spatial representation of hillslope processes that are described for individual terrain components along the catena and its integrated treatment of large reservoirs and reservoir networks, including reservoir management options.

The paper consists of three main parts: numerical descriptions of the erosion and sediment transport processes in the hillslope, river and reservoir modules of WASA-SED; review of current model applications at the hillslope, river and reservoir scale; and a critical discussion on its capability to develop and improve water and land management in dryland regions as well as its limitations of its availability.

2 Numerical description of the WASA-SED Model

2.1 Spatial representation of landscape characteristics

The WASA-SED model uses a hierarchical top-down disaggregation scheme developed by Güntner (2002) and Güntner and Bronstert (2004) that takes into account the lateral surface and sub-surface flow processes at the hillslope scale in a semi-distributed manner (Fig. 1). Each sub-basin of the model domain is divided into landscape units that have similar characteristics regarding lateral processes and resemblance in major landform, lithology, catena profile, soil and vegetation associations. Each landscape unit is represented by a characteristic catena that is described with multiple terrain components (lowlands, slope sections and highlands) where each terrain component is defined by slope gradients, soil and vegetation associations (soil-vegetation components) and its length. Within and between each terrain component, the lateral redistribution of surface runoff and the vertical fluxes for typical soil profiles consisting of several soil horizons is taken into account.

For a semi-automated discretisation of the model domain into landscape units and terrain components, the software tool LUMP (Landscape Unit Mapping Program) is available (Francke et al., 2008). LUMP incorporates an algorithm that delineates areas with similar hillslope characteristics by retrieving homogeneous catenas with regard to e.g. hillslope shape, flow length and slope (provided by a digital elevation model), and additional properties such as for soil and land-use and optionally for specific model parameters such as leaf area index, albedo or the occurrence of special geomorphological features (bare rocks, badland formations, etc.). In contrast to methods based on mere intersection of multiple input layers, LUMP preserves information on the distribution of input properties in relation to the river network and their topographic position and, at the same time, allows an upscaling of small-scale hillslope properties into regional landscape units. The LUMP tool is linked with the WASA-SED parameterisation procedure through a databank management tool, which allows to process and store digital soil, vegetation and topographical data in a coherent way and facilitates the generation of the required input files for the model.

2.2 Sediment generation and transport processes in the hillslope module

The hydrological model part of WASA-SED at the hillslope scale is fully described by Güntner (2002) and Güntner and Bronstert (2004) and are not repeated here. For daily or hourly time steps, the model calculates the interception losses, evaporation and transpiration using the modified Penman-Monteith approach (Shuttleworth and Wallace, 1985), infiltration with the Green-Ampt approach (Green and Ampt, 1911), surface and subsurface runoff and ground water recharge with a multi-layer storage approach for each soil-vegetation component in each terrain component.

The sediment module in WASA-SED provides four erosion equations of sediment generation by using derivatives of the USLE equation (Wischmeier and Smith, 1978), which can be generalised as (Williams, 1995):

$$E = \chi K \, LS \, C \, P \, ROKF \, A \tag{1}$$

where E is erosion (t), K the soil erodibility factor (t. ha. hr. ha^{-1} .MJ^{-1} .mm^{-1}), LS the length-slope factor (–), C the vegetation and crop management factor (–), P the erosion control practice factor (–), $ROKF$ the coarse fragment factor (–) as used in the USLE and A the area of the scope (ha). χ is the energy term that differs between the USLE-derivatives. It computes as (Williams, 1995):

$$\text{USLE} \quad \chi = EI \tag{2}$$

$$\text{Onstad – Foster} \quad \chi = 0.646\, EI + 0.45\, (Q_{\text{surf}} q_p)^{0.33} \tag{3}$$

$$\text{MUSLE} \quad \chi = 1.586\, (Q_{\text{surf}} q_p)^{0.56}\, A^{0.12} \tag{4}$$

$$\text{MUST} \quad \chi = 2.5\, (Q_{\text{surf}} q_p)^{0.5} \tag{5}$$

where EI is the rainfall energy factor (MJ. mm. ha^{-1}. hr^{-1}), Q_{surf} is the surface runoff volume (mm) and q_{peak} is the peak runoff rate (mm/h). In contrast to the original USLE, the approaches (3–5) incorporate the surface runoff Q_{surf} (calculated by the hydrological routines) in the computation of the energy component. This improves the sediment modelling performance by eliminating the need for a sediment delivery ratio (SDR) and implicitly accounts for antecedent soil moisture (Neitsch et al., 2002). E is distributed among the user-specified number of particle size classes, according to the mean composition of the eroded horizons in the area.

Any of the mentioned approaches can be applied on the sub-basin or terrain component scale. In the former case, the USLE factors result from area-weighted means throughout the sub-basin and cumulatively for the LS-factor as proposed by Foster and Wischmeier (1974). If applied at the terrain component scale, the specific factors of each terrain component are used and sediment routing between terrain components is performed: any sediment mass SED_{in} (t) coming from upslope areas is added to the generated sediment mass E to obtain the sediment yield SY (t) of a terrain component. SY is limited by the transport capacity q_s (t) of the flow leaving the terrain component:

$$SY = \text{minimum}\, (E + SED_{in}, q_s) \tag{6}$$

Two options are available to calculate the transport capacity q_s:

(a) With the sediment transport capacity according to Everaert (1991):

$$if\, D_{50} \leq 150\, \mu\text{m} : q_s = 1.50 \cdot 10^{-5} \Omega^{1.07} D_{50}^{0.47} W \tag{7}$$

$$if\, D_{50} \leq 150\, \mu\text{m} : q_s = 3.97 \cdot 10^{-6} \Omega^{1.75} D_{50}^{-0.56} W, \text{with}\ \Omega = (\rho g q S)^{1.5} / R^{2/3}$$

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where Ω is the effective stream power ($g^{1.5}.s^{-4.5}\,cm^{-2/3}$) computed within the hydrological routines of WASA-SED, D_{50} is the median particle diameter (μm) estimated from the mean particle size distribution of the eroded soils and W is the width of the terrain component (m), ρ is the density of the particles ($g.m^{-3}$), g is the gravitational acceleration ($m.s^{-2}$), q is the overland flow rate on a 1-m strip ($m^3.s^{-1}.m^{-1}$) and R is the flow depth (cm).

(b) With the maximum value that is predicted by MUSLE assuming unrestricted erodibility with K set to 0.5:

$$q_s = E_{\text{MUSLE},K} = 0.5 \text{ using Eq. (4)} \tag{8}$$

Similar to the downslope partitioning scheme for surface runoff described by Güntner and Bronstert (2004), sediment that leaves a terrain component i is partitioned into a fraction that is routed to the next terrain component downslope ($SED_{in,TCi+1}$) and a fraction that reaches the river directly ($SED_{\text{river},i}$), representing the soil particles carried through preferential flow paths, such as rills and gullies. $SED_{\text{river},i}$ is a function of the areal fraction α_i of the current terrain i component within each landscape unit according to:

$$SED_{\text{river,i}} = SY_i \left(\alpha_i \Big/ \sum_{n=1}^{nTC} \alpha_n \right) \tag{9}$$

where i and $i+1$ are the indices of the current and the next downslope terrain component respectively, α is the areal fraction of a terrain component and nTC is the number of terrain components in the current landscape unit.

2.3 Transport processes in the river module

The river network consists of individual river stretches with pre-defined river cross-sections and where each stretch is associated with one sub-basin. Each stretch receives the water and sediment fluxes from one sub-basin and the fluxes from the upstream river network. The water routing is based on the kinematic wave approximation after Muskingum (e.g. as described in Chow et al., 1988). Flow rate, velocity and flow depth are calculated for each river stretch and each time step using the Manning equation. A trapezoidal channel dimension with width w (m), depth d (m) and channel side ratio r (m/m) is used to approximate the river cross-sections. If water level exceeds bankful depth, the flow is simulated across a pre-defined floodplain using a composite trapezoid with an upper width of w_{floodpl} (m) and floodplain side ratio r_{floodpl} (m/m). The WASA-SED river module contains routines for suspended and bedload transport using the transport capacity concept. The maximum suspended sediment concentration that can be transported in the flow is calculated using a power function of the peak flow velocity similar to the SWIM (Krysanova et al., 2000) and the SWAT model (Neitsch et al., 2002; Arnold et al., 1995):

$$C_{s,\max} = a \cdot v_{\text{peak}}^{b} \tag{10}$$

where $v_{\text{peak}}(t)$ is the peak channel velocity (m/s), $C_{s,\max}$ is the maximum sediment concentration for each river stretch in (ton/m^3), and a and b are user-defined coefficients. If the actual sediment concentration C_{actual} exceeds the maximum concentration, deposition occurs; otherwise degradation of the riverbed is calculated using an empirical function of a channel erodibility factor (Neitsch et al., 2002):

$$Sed_{\text{dep}} = (C_{s,\max} C_{\text{actual}}) \cdot V \tag{11}$$

$$Sed_{\text{ero}} = (C_{s,\max} C_{\text{actual}}) \cdot V \cdot K \cdot C \tag{12}$$

where Sed_{dep} (ton) is the amount of sediment deposited, Sed_{ero} (ton) the amount of sediment re-entrained in the reach segment (tons), V is the Volume of water in the reach (m^3), K is the channel erodibility factor (cm/hr/Pa) and C is the channel cover factor (–).

For bedload transport, five transport formulae (Meyer-Peter and Müller, 1948, Schoklitsch, 1950, Bagnold, 1956, Smart and Jaeggi, 1983, and Rickenmann 2001) are implemented for boundary conditions commonly found in upland meso-scale dryland catchments with small, gravel-bed streams as summarised in Table 1. For the calculation of bedload transport, near-equilibrium conditions are assumed, i.e. water and bedload discharge were thought to be steady at one time step. It was furthermore assumed that no supply limitations occurred, i.e. bedload transport was at capacity, which appears feasible for short-duration, low-magnitude flood events, where a large amount of sediments is thought to have been previously accumulated from upstream, unregulated watershed. The bedload formulas consider both uniform and non-uniform sediments, grain sizes ranging from 0.4 to 29 mm or D_{50} values larger 6 mm and river slopes ranging between 0.003 to 0.2 m/m (Table 1).

2.4 Retention processes in the reservoir module

WASA-SED comprises a reservoir sedimentation module developed by Mamede (2008). It enables the calculation of reservoir life expectancy, the trapping efficiency of the reservoir, sediment deposition patterns and the simulation of several reservoir sediment management options. The water balance and the bed elevation changes due to sediment deposition or entrainment are calculated for individual cross-sections along the longitudinal profile of the reservoir. Mamede (2008) subdivided the reservoir body (Fig. 2) in a river sub-reach component, where hydraulic calculations are based on the standard step method for a gradually varied flow (Graf and Altinakar, 1998) and a reservoir sub-reach component that uses a volume-based weighting factor approach adapted from the GSTARS model (Yang and Simoes, 2002). The transitional cross-section between the two spatial components is defined as where the maximum water depth for uniform river flow, computed with the Manning equation, is exceeded by the actual water depth of the cross-section due to the impoundment of the reservoir. Consequently, the length of the river sub-reach becomes longer for lower reservoir levels and vice versa. For the reservoir routing, the water discharge Q_j

of each cross-section j is calculated as:

$$Q_j = Q_{in} - (Q_{in} - Q_{\text{out}}) \sum_{k=m}^{j} v_k \text{ with } v_k = V_k/V_{\text{res}} \tag{13}$$

where Q_{in} and Q_{out} are the inflow and outflow discharge of the reservoir, v_k is the fraction of reservoir volume represented by the cross-section, V_k is the volume represented by cross-section k, m is the index for the first cross-section belonging to the reservoir sub-reach. The inflow discharge considers the direct river runoff from the tributary rivers, direct rainfall and evaporation from the reservoir surface.

The sediment transport is computed using a one-dimensional equation of non-equilibrium transport of non-uniform sediment, adapted from Han and He (1990):

$$\frac{dS}{dx} = \frac{\alpha}{\omega q}(S^* - S) \tag{14}$$

where S is the sediment concentration; $S*$ is the sediment carrying capacity; q is the discharge per unit width; ϖ is the settling velocity; and α is the coefficient of saturation recovery. According to Han and He (1990), the parameter α can be taken as $0.25$for reservoir sedimentation and 1.0 for scouring during flushing of a reservoir and in river channel with fine bed material. Mamede (2008) adapted four sediment transport equations (Wu et al., 2000; Ashida and Michiue, 1973; IRTCES, 1985; and Ackers and White, 1973) for the calculation of the fractional sediment carrying capacity of both suspended sediments and bedload for different ranges of sediment particle sizes as given in Table 2.

The bed elevation changes of the reservoir are computed for each cross-section taking into account three conceptual layers above the original bed material: a storage layer, where sediment is compacted and protected against erosion; an intermediate layer, where sediment can be deposited or re-suspended; and the top layer, where sediment-laden flow occurs. The time-dependent mobile bed variation is calculated using the sediment balance equation proposed by Han (1980):

$$\frac{\partial(QS)}{\partial(x)} + \frac{\partial M}{\partial t} + \frac{\partial \rho_d A_d}{\partial t} \tag{15}$$

where Q is the water discharge; S is the sediment concentration; M is the sediment mass in water column with unit length in longitudinal direction; A_d is the total area of deposition; and ρ_d is density of deposited material.

For each time step, the sediment balance is performed for each size fraction and cross-section, downstream along the longitudinal profile. The total amount of sediment deposited at each cross-section corresponds to the amount of sediment inflow exceeding the sediment transport capacity. On the other hand, the total amount of sediment eroded corresponds to the total amount of sediment that can still be transported by the water flux. Erosion is constrained by sediment availability at the bed of the reach. The geometry of the cross-section is updated whenever deposition or entrainment occurs at the intermediate layer. For each cross-section, the volume of sediments to be deposited is distributed over a stretch with a width of half the distance to the next upstream and downstream cross-section, respectively (Figure 3a). Suspended sediment is assumed to be uniformly distributed across the cross-section and settles vertically, hence the bed elevation e_m at a point m along the cross-section changes proportionally to water depth:

$$e_m = e_{\text{dep}} \cdot f_{d,m} \tag{16}$$

where e_{dep} is the maximum bed elevation change at the deepest point of the cross-section caused by deposition and $f_{d,m}$ is a weighting factor which is computed as the ratio between water depth h_m at the point m and the maximum water depth $h_{\max}$ of the cross-section:

$$f_{d,m} = h_m / h_{\max} \tag{17}$$

Figure 3b shows schematically, how the sediment is distributed trapezoidal along the cross-section as a function of water depth $h_{\max}$, where $A_m^{'}$ and$A_m^{''}$ are the sub-areas limited by the mean distances to the neighbour points (d'_m and d''_m, respectively, starting from the deepest point of the cross-section profile), with m running from 1 to n_w as the total number of demarcation points of the cross-section below water level.

Bed entrainment is distributed in an equivalent way by assuming a symmetrical distribution of bed thickness adapted from Foster and Lane (1983). The bed elevation change due to erosion is constrained by the maximum thickness of the intermediate layer. The bed elevation change e_m is given by:

$$e_m = e_{\mathrm{ero}} \cdot f_{e,m} \tag{18}$$

where e_{ero} is the maximum bed elevation change at the deepest point of the cross-section caused by erosion and $f_{e,m}$ is a weighting factor given by Forster and Lane (1983):

$$f_{e,m} = 1 - (1 - X_m)^{2.9} \tag{19}$$

where X_m is a normalised distance along the submerged half perimeter given by:

$$X_m = X/X_{\mathrm{max}}. \tag{20}$$

where X is the actual distance along the submerged half perimeter of the cross-section and X_{max} is the total wetted half perimeter between the cross-section point at the water surface and the deepest point of the cross-section.

The implemented reservoir sedimentation routines allow the simulation of reservoir management options for the reduction or prevention of sedimentation (Mamede, 2008) such as annual flushing operation or partial drawdown of the reservoir water level. Both management operations result in a remobilisation of previously deposited sediments and the release of sediments out of the reservoir. The management options can then be used to calculate the life expectancy of the reservoir by taking into account potential scenarios of water and land management for different land-uses and erosion prevention schemes in the upslope catchments. Besides the above sediment routine for individual large reservoirs, WASA-SED optionally provides a module to represent water and

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sediment retention processes within networks of farm dams and small reservoirs that often exist in large numbers in dryland areas. These mini-reservoirs cannot be represented explicitly each of them in a large-scale model. Instead, WASA-SED applies a cascade structure that groups the reservoirs into different size classes according to their storage capacity, defines water and sediment routing rules between the classes and calculates water and sediment balances for each reservoirs class. Details of the approach are presented with regard to the water balance in Güntner et al. (2004) and for related sedimentation processes in Mamede (2008).

2.5 Summary of model input and output data

The model runs as a Fortran Windows Application for catchment sizes of about 50 to 5 000 km^2 on daily or hourly time steps. Climatic drivers are hourly or daily time series for precipitation, humidity, short-wave radiation and temperature. For model parameterisation, regional digital maps on soil associations, land-use and vegetation cover, a digital elevation model with a cell size of 100 m (or smaller) and, optional, bathymetric surveys of the reservoirs are required. The soil, vegetation and terrain maps are processed with the LUMP tool (see above) to derive the spatial discretisation into soil-vegetation units, terrain components and landscape units. Table 2 summarises the input parameters for the climatic drivers and the hillslope, river and reservoir modules. The vegetation parameters may be derived with the comprehensive study of, for example, Breuer et al. (2003), the soil and erosion parameters with the data compilations of, e.g., FAO (1993, 2001), Morgan (1995), Maidment (1993) and Schaap et al. (2001), or from area-specific data sources.

The model output data are time series with daily time steps for lateral and vertical water fluxes and sediment production from the sub-basins, the water and sediment discharge in the river network and the bed elevation change due to sedimentation in the reservoir as summarised in Table 3. A manual for model parameterisation and a trail version plus the latest updates of the model, LUMP and auxiliary tools can be found on the WASA-SED internet page at http://brandenburg.geoecology.uni-potsdam.

de/projekte/sesam/.

3 Review, uncertainty and limits of WASA-SED model applications

The model has been employed in several recent research studies to evaluate the effects of land and reservoir management on the water and sediment export of large dryland catchments. Güntner and Bronstert (2004) and Güntner et al. (2004) applied the hydrological part of the model to assess water availability in large river basins (up to several 10 000 km^2) in the semi-arid northeast of Brazil. By comparing simulation results to observed time series of river discharge and reservoir water storage they showed that the model could reasonably represent the pronounced seasonal and inter-annual hydrological variations in this environment.

Mueller et al. (2008a,b) yielded good results when testing the model against measured daily water and sediment discharge (suspended and bedload) data for a 2.5 km^2, a 65 km^2 and a 222 km^2 catchment in the Pre-Pyrenees of Spain. No model calibration was required which suggests a sufficient reproduction of the underlying generation and transport processes. The temporal dynamics of individual flood events that trigger soil erosion at the mountainous hillslope and sediment transport in the river reaches was reproduced in most cases. The simulated values of suspended sediment concentration and bedload compared well to measured ones obtained from ISCO 3700 automatic samplers and manual sampling over a time period of three years (Batalla et al., 2005). The tested model was then used to develop an effective, erosion-prevention scheme through a selected afforestation of steep hillslopes for the region that was previously heavily used for agricultural production. The spatial model representation of hillslopes into individual, subdivided terrain components with separate terrain, soil and vegetation characteristics (Fig. 1) made the WASA-SED model particularly functional for the detection and management of erosion-prone hotspots. Other large-scale models do not provide such a suitable spatial structure of the landscape. The spatially semi-distributed SWAT model (Neitsch et al., 2002), for example, uses hydrologic response units to group input information in regard to land-use, soil and management combinations, thus averaging out spatial variations along the hillslope essential for sediment generation and transport. In comparison, grid-based models such as the LISEM model (Jetten, 2002) may incorporate a higher degree of spatial information, but are often limited in their applicableness due to computing time (for small grid sizes) and lack of exhaustive spatial data. The advantage of the terrain component concept in the WASA-SED model is that it captures the structured variability along the hillslope essential for overland flow generation and erosion, but at the same time does not require the parameterisation and calculation of otherwise micro-scale processes.

Medeiros et al. (2008) evaluated the spatial and temporal patterns of connectivity in regard to sediment generation and transport for a 933 km^2 dryland basin in the semi-arid northeast of Brazil in the State of Ceara. The dryland region is exposed to prolonged droughts and runoff frequently occurs only during high-intensity rainstorm events on a few days per year, resulting in high erosion rates on degraded fields. Using the landscape unit approach, Medeiros et al. (2008) evaluated the effects of slope and position of terrain components on the lateral redistribution and re-infiltration of overland flow and consequent deposition patterns of suspended sediments. Erosion rates and sediment export out of the catchment could be assessed in a spatially distributed way in a relation to how well individual hillslopes and sub-catchments of the basin were connected to the river network and to the catchment outlet. It could be shown how catchment connectivity and thus basin response in terms of water and sediment export varied as a function of rainfall event characteristics.

Reservoir sedimentation triggered by erosion from badland areas was modelled by Appel (2006) and Mamede (2008) for a 1 340 km^2 catchment in the north-east of Spain. The high erosion rates from badlands, which are a typical landform of that region consisting of unvegetated unconsolidated marl sediments, leads to significant sedimentation and hence reduction of storage capacity for downstream reservoirs, which are intensively used for water supply and power generation. Appel (2006) showed that the erosion module of WASA-SED is able to reproduce the extreme erosion rates of

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badlands that reach up to 550 t/ha per year, equivalent to circa 3 centimetres per year. Mamede (2008) then applied the reservoir module to the Barasona Reservoir with a maximal storage capacity of 92 Mm^3 and a length of ca. 10 km using a total number of 53 cross-sections. Mamede was able to reproduce annual bed elevation changes due to sedimentation of badland sediments along individual cross-sections of the reservoir. The testing data for bed elevation change along those cross-sections were available from repeated, annual bathymetric surveys that were repeatedly taken over the last 20 years. In addition, the WASA-SED model was applied to predict the development of the storage capacity and the expected life time of the Barasona Reservoir as a function of badland erosion and implemented management options such as frequent flushing or partial draw-down of the reservoir to release sediment through the bottom outlets. Model results showed the significance of the management options: if no management options are applied, the entire reservoir is filled with sediments after 47 years; with different draw-down scenarios the life expectancy is calculated to vary between 64 and 80 years, whereas with frequent flushing operations, sedimentation occurs at much lower rates, thus preserving the original storage capacity perpetually.

The modelling studies demonstrated the wide range of environmental problems at the meso-scale where the WASA-SED model may be employed to comprehend the underlying sediment transfer processes and to develop sustainable management strategies for land and water resources. Nevertheless, the success and, hence, the uncertainty of process-based erosion modelling at large scales have always been influenced by two major shortcomings (Quinton, 2004; Boardman and Favis-Mortlock, 1995; Beven, 2001): the lack of spatial input data at that scale and the knowledge gap on how to integrate over small-scale processes. The above review of model applications showed several shortcomings of WASA-SED. Uncertainties towards process descriptions existed in regard to processes that occur in the interstorm period such as the soil moisture dynamics under different vegetation and the erosion processes that are governed by the weathering, freezing and thawing cycles of the upper soil layer. In addition, the model contains only limited descriptions of processes which are com-

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monly not regarded to be relevant for dryland settings, but may influence the hydrological regime under certain conditions, such as snow melt and groundwater movement. Uncertainties existed towards model input data on the spatial variability of rainfall data for high-intensity storm events that tend to be often highly localised and are highly influential on runoff and sediment generation. Other frequent input uncertainties were soil maps at the meso-scale that normally include only a few soil profiles, which are often insufficient to describe the complex interflow and overland flow dynamics at steep, heterogeneous hillslopes.

4 Conclusions

The WASA-SED model is a new tool for the qualitative and quantitative assessment of sediment transfer in dryland environments. The model currently focuses on research applications of process-based studies on the hillslope, river and reservoir scale. However, its capabilities to evaluate land-use change scenarios and reservoir management options may as well make it a valuable decision-making tool for regional water authorities. The model's assets are threefold: Firstly, the spatially detailed representation of catena characteristics using the landscape unit approach enables an effective way of parameterising large areas without averaging out topographic details that are particularly relevant for sediment transport. Crucial spatial information on for example the slope angle is preserved for the various sections of the catena. The information on overland flow dynamics allows at the same time a realistic calculation of transport capacities and deposition patterns along the catena. The semi-distributed approach of WASA-SED model thus provides a more feasible hillslope representation than raster-based erosion models, which normally lack satisfactory aggregation methods for topographic information when large cell sizes are employed to represent the often highly heterogeneous catenas of dryland catchments.

Secondly, the WASA-SED framework allows a coherent handling of spatial input data in combination with the semi-automated discretisation tool LUMP (Francke et al., 2008). The tool provides an objective and easily reproducible delineation of homogeneous terrain components along a catena and consequently an upscaling rationale of small-scale hillslope properties into the regional landscape units. At the river scale, representative river stretches and for reservoirs, the concept of non-localised small reservoirs provide efficient ways for regionalised parameterisation strategies. And thirdly, the WASA-SED model enables an integrative assessment of hillslope, river and reservoir processes, thus including the very different sediment transport and storage behaviour and potential management options of landscape compartments of large catchments.

Nevertheless, the uncertainties in regard to both the process descriptions and the model input of WASA-SED in combination with the potential error propagation of the hydrological modules on sediment export calculations recommend caution as with any modelling exercise at large scales.

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Table 1. Bedload transport formulae in the river module of the WASA-SED Model.

Formula	Range of conditions
1. Meyer-Peter and Müller (1948) $q_s = \frac{8(\tau-\tau_{\text{crit}})^{1.5}}{g\rho^{0.5}}1000$ with: $\tau = \rho g d S$ and $\tau_{\text{crit}} = 0.047(\rho_s - \rho)gD_m$	for both uniform and non-uniform sediment, grain sizes ranging from 0.4 to 29 mm and river slopes of up to 0.02 m/m.
2. Schoklitsch (1950) $q_s = 2500S^{1.5}(q - q_{\text{crit}})1000\frac{\rho_s-\rho}{\rho_s}$ with: $q_{\text{crit}} = 0.26(\frac{\rho_s-\rho}{\rho})^{\frac{5}{3}}\frac{D_{50}^{\frac{3}{2}}}{S^{\frac{7}{6}}}$	for non-uniform sediment mixtures with D_{50} values larger than 6 mm and riverbed slopes varying between 0.003 and 0.1 m/m
3. Smart and Jaeggi (1983) $q_s = 4.2qS^{1.6}(1 - \frac{\tau^*_{\text{crit}}}{\tau^*})/(\frac{\rho_s}{\rho} - 1)1000(\rho_s - \rho)$ with $\tau^* = \frac{dS}{(\frac{\rho_s}{\rho}-1)D_{50}}$ and $\tau^*_{\text{crit}} = \frac{d_{\text{crit}}S}{(\frac{\rho_s}{\rho}-1)D_{50}}$	for riverbed slopes varying between 0.03–0.2 m/m and D_{50} values comparable to the ones of the Meyer-Peter and Müller equation.
4. Bagnold (1956) $q_s = 4.25\tau^*0.5(\tau^* - \tau^*_{\text{crit}})((\frac{\rho_s}{\rho} - 1)gD_{50}^3)^{0.5}1000(\rho_s - \rho)$	reshaped by Yalin (1977), applicable for sand and fine gravel and moderate riverbed slopes
5. Rickenmann (2001) $q_s = 3.1(\frac{D_{90}}{D30})^{0.2}\tau^{*0.5}(\tau^* - \tau^*_{\text{crit}}) \cdot Fr^{1.1}(\frac{\rho_s}{\rho} - 1)^{-0.5}((\frac{\rho_s}{\rho} - 1)gD_{50}^3)^{0.5}1000(\rho_s - \rho)$ with: $Fr = (\frac{v}{g \cdot d})^{0.5}$	for gravel-bed rivers and torrents with bed slopes between 0.03 and 0.2 m/m and for D_{50} values comparable to the ones of the Meyer-Peter and Müller equation in the lower slope range with an average D_{50} of 10 mm in the higher slope ranges

d: mean water flow depth (m), d_{crit}: critical flow depth for initiation of motion (m), D_{50}: median sediment particle size (m), D_{30}: grain-sizes at which 30% by weight of the sediment is finer (m), D_{90}: grain-sizes at which 90% by weight of the sediment is finer (m), D_m: mean sediment particle size (m), Fr: Froude number of the flow (–), g: acceleration due to gravity (m/s^2), q: unit water discharge (m^2/s), q_{crit}: unit critical water discharge (m^2/s), q_s: sediment discharge in submerged weight (g/ms), S: slope (m/m), v: water flow velocity (m/s), ρ: fluid density (1000 kg/m^3), ρ_s: sediment density (2650 kg/m^3), τ: local boundary shear stress (kg/ms^2), τ_{crit}: critical local boundary shear stress (kg/ms^2), τ^*: dimensionless local shear stress (–), τ^*_{crit}: dimensionless critical shear stress (–).

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Table 2. Sediment transport formula in reservoir.

Authors, range of sediments	Transport formula	Auxiliary equations
Wu et al. (2000): 0.004 to 100 mm	$q_{b,k}=P_k\phi_{b,k}\sqrt{\Delta g d^3}$	$\phi_{b,k}=0.0053\cdot\left[\left(\frac{n'}{n}\right)^{3/2}\frac{\tau_b}{\tau_{c,k}}\right]^{2.2}$, $n=R_h^{2/3}S_f^{1/2}/v$, $n'=\sqrt[6]{d_{50}}/20$, $\tau_{c,k}=(\gamma_s-\gamma)d_k\theta_k\xi_k$, $\zeta_k=(P_{e,k}/P_{h,k})^{-0.6}$, $P_{e,k}=\sum_{j=1}^{q}P_{b,j}\cdot(d_k/d_k+d_j)$, $P_{h,k}=\sum_{j=1}^{q}P_{b,j}\cdot(d_j/d_k+d_j)$, $\tau_b=\gamma R_h S_f$
	$q_{s,k}=P_k\phi_{s,k}\sqrt{\Delta g d^3}$	$\phi_{s,k}=0.0000262\cdot\left[\left(\frac{\tau}{\tau_{c,k}}-1\right)\cdot\frac{V}{\omega_k}\right]^{1.74}$, $\omega=\sqrt{13.95\cdot(\frac{v}{d})^2+1.09\Delta g d}-13.95\cdot(\frac{v}{d})$
Ashida and Michiue (1973): 0.040 to 100 mm	$q_{b,k}=17\cdot P_k u_{c,k}d_k\tau_{c,k}(1-\frac{\tau_{c,k}}{\tau_k})(1-\sqrt{\frac{\tau_{c,k}}{\tau_k}})$	$\tau_k=\frac{u^{*2}}{\Delta g d_k}$, $u^*=\sqrt{gR_hS_f}$, $\tau_{e,k}=\frac{u_{e,k}^2}{\Delta g d_k}$, $u_{e,k}=\frac{V}{5.75\log\left(\frac{R_h/d_{50}}{1+2\tau_k}\right)}$, $\tau_{c,k}=\frac{u_{c,k}^2}{\Delta g d_k}$ $d_k/d_{50}<0.4$: $u_{c,k}=\sqrt{0.85\cdot u_{c,50}}$ $d_k/d_{50}>0.4$: $u_{c,k}=\log 19/\log(19\cdot d_k/d_{50})\cdot u_{c,50}$, $u_{c,50}=0.05\cdot\Delta g d_{50}$
	$q_{s,k}=C\cdot V(e^{-p\cdot a}-e^{-p\cdot h})\cdot\frac{e^{p\cdot a}}{p}$	$p=\frac{6\cdot\omega_k}{0.412\cdot u^*h}$, $C=0.025\cdot p_k\left(\frac{f(\varepsilon_0)}{\varepsilon_0}-F(\varepsilon_0)\right)$, $f(\varepsilon_0)=\frac{1}{\sqrt{2\pi}}e^{(-0.5\cdot\varepsilon_0^2)}$, $F(\varepsilon_0)=\frac{1}{\sqrt{2\pi}}\int_{\varepsilon_0}^{\infty}e^{(-0.5\cdot\varepsilon_0^2)}d\varepsilon$, $\varepsilon_0=\frac{\omega_k}{0.75\cdot u^*}$
IRTCES, (1985): 0.001 to 100 mm	$q_t=\Omega\frac{Q^{1.6}S^{1.2}}{B^{0.6}}$	$\Omega=1600$ for loess sediment $\Omega=650$ for $d_{50}<0.1$ mm $\Omega=300$ for $d_{50}>0.1$ mm
Ackers and White (1973): 0.040 to 100 mm	$q_t=P_k\psi V d_k\left(\frac{V}{u^*}\right)^{n_0}\left(\frac{F_{gr}}{F_{gr,cr}\xi_k}-1\right)^{m_o}$	$d_k^*=d_k(\Delta g/v^2)^{1/3}$ $1<d_k^*<60$: $n_o=1-0.56\cdot\log(d^*)$, $m_o=\frac{9.66}{d^*}+1.34$, $\psi=10^{-3.53+2.86\cdot\log(d^*)-\log^2(d^*)}$, $F_{gr,cr}=\frac{0.23}{\sqrt{d^*}}-0.14$ for $d_k^*>60$: $n_o=0$, $m_o=1.5$, $\psi=0.025$, $F_{gr,cr}=0.17$

$q_{b,k}$: transport rate of the k-th fraction of bedload per unit width, $q_{s,k}$: fractional transport rate of non-uniform suspended load, k: grain size class, P_k: ratio of material of size fraction k available in the bed, Δ: relative density ($\gamma s/\ \gamma-1$), γ and γ_s: specific weights of fluid and sediment, respectively; g: gravitational acceleration; d_k: diameter of the particles in size class k, $\phi_{b,k}$: dimensionless transport parameter for fractional bed load yields, v: kinematic viscosity, τ: shear stress of entire cross-section $\tau_{c,k}$: critical shear stress, θ_c: critical Shields parameter, ξ_k: hiding and exposure factor, $P_{e,k}$ and $P_{h,k}$: total exposed and hidden probabilities of the particles in size class k, $P_{b,j}$: probability of particles in size class j staying in the front of particles in size class k, τ_b: average bed shear stress; n: Manning's roughness, and n': Manning's roughness related to grains, R_h: hydraulic radius, S_f : the energy slope, V: average flow velocity, $d50$: median diameter, ω: settling velocity, q_t: total sediment transport capacity at current cross-section ($q_t = q_s + q_b$, for the equations after Wu et al., 2000 and Ashida e Michiue, 1973), S: bed slope, B: channel width, Ω: constant as a function of grain size, u^*: shear velocity, $u_{c,k}$: effective shear velocity, F_{gr}: sediment mobility number, n_o, m_o, ψ, $F_{gr,cr}$ are dimensionless coefficients depending on the dimensionless particle sized_k^*, C: concentration at a reference level a

Table 3. Model input parameters.

Type	Model input parameter
Climate	Daily or hourly time series on rainfall (mm/day, mm/h) Daily time series for average short-wave radiation (W/m^2) Daily time series for humidity (%) Daily time series for temperature (°C)
Vegetation	Stomata resistance (s/m) Minimum suction (hPa) Maximum suction (hPa) Height (m) Root depth (m) LAI (–) Albedo (–) Manning's n of hillslope(–) USLE C (–) USLE P (–)
Soil	No. of horizons* Residual water content (Vol.%) Water content at permanent welking point (Vol.%) Usable field capacity (Vol.%) Saturated water content (Vol.%) Saturated hydraulic conductivity (mm/h) Thickness (mm) Suction at wetting front(mm) Pore size index (–) Bubble pressure (cm) USKLE K (–) Particle size distribution **

Table 3. Continued.

Type	Model input parameter
Terrain and river	Hydraulic conductivity of bedrock (mm/d)
	Mean maximum depth of soil zone (mm)
	Depth of river bed below terrain component (mm)
	Initial depth of groundwater below surface (mm)
	Storage coefficient for groundwater outflow (day)
	Bankful depth of river (m)
	Bankful width of river (m)
	Run to rise ratio of river (–)
	Bottom width of floodplain (m)
	Run to rise ratio of floodplain side slopes (–)
	River length (km)
	River slope (m/m)
	D_{50} (median sediment particle size) of riverbed (m)
	Manning's n for riverbed and floodplains (–)
Reservoir	Longitudinal profile of reservoir (m)
	Cross-section profiles of reservoir (m)
	Stage-volume curves
	Initial water storage and storage capacity volumes (m^3)
	Initial area of the reservoir (ha)
	Maximal outflow through the bottom outlets (m^3/s)
	Manning's roughness for reservoir bed
	Depth of active layer (m)
	Spillway coefficients
	Dry bulk densities of deposits

[*] for each soil horizon, all following parameters in the column are required

[**] of topmost horizon

Table 4. Model output files.

Spatial unit	Output (daily time series)
Sub-basins	potential evapotranspiration (mm/day) actual evapotranspiration (mm/day) overland flow (m^3/day) sub-surface flow (m^3/day) groundwater discharge (m^3/day) sediment production (tons/day) water content in the soil profile (mm)
River	water discharge (m^3/s) suspended sediment concentration (g/l) bedload rate as submerged weight (kg/s)
Reservoir	sediment outflow from the reservoir (t/day) bed elevation change due to deposition or erosion (m) storage capacity and sediment volume changes (Mm^3) life expectancy (years) effluent size distribution of sediment (–)

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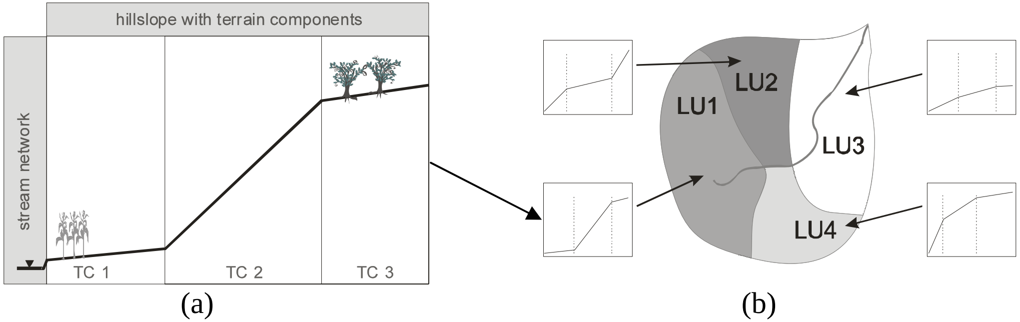


Fig. 1. Spatial discretisation of the WASA-SED model (adapted after Güntner 2002.)

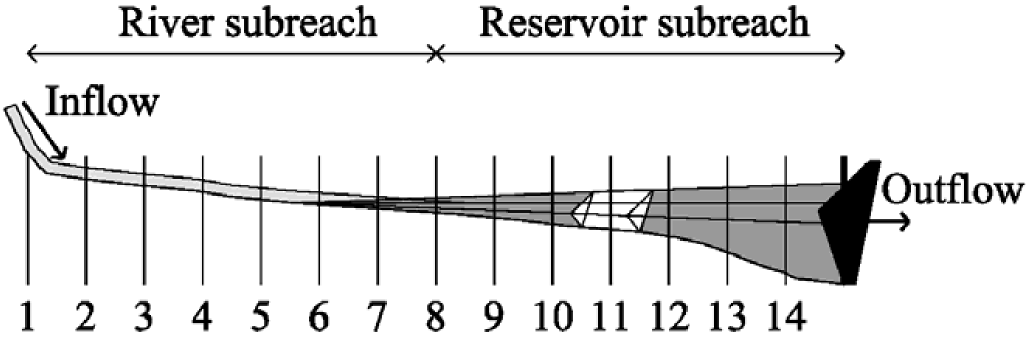
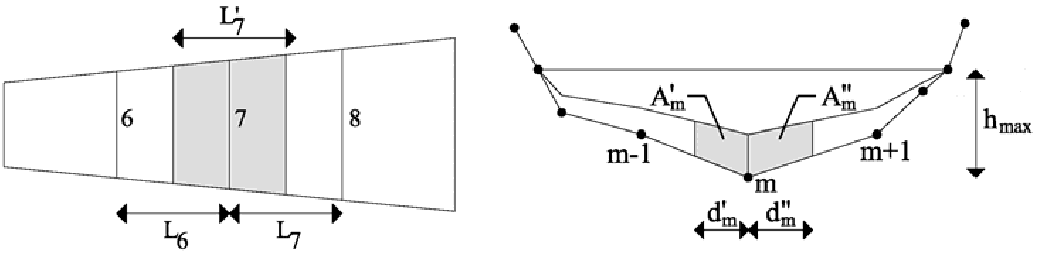


Fig. 2. Spatial discretisation of the reservoir along the longitudinal profile.



(a) (b)

Fig. 3. Bed elevation change: **(a)** plan view along longitudinal profile, **(b)** deposition along an individual cross-section of the reservoir.

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