TRANSFER OF SEDIMENTS IN CATCHMENT ECOSYSTEMS ON VARIOUS SCALES

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1 INTRODUCTION

Surface runoff, erosion and sediment redistribution play a pivotal role in the terrestrial ecosystem as they directly influence water quality, soil biogeochemical cycles and soil functions (Owens et al. 2005; Walling 2006). In particular surface waters are threatened by emissions of nutrients and contaminants via eroded soil material. For Germany, about 20 % of the annual emissions of phosphorous are due to erosion. In addition erosion is an important emission pathway for contaminants such as heavy metals. In 2005 the share of chromium and lead emissions into the surface waters of Germany via erosion was estimated to account for 65 % and 50 %, respectively, of the total emissions of these metals (Fuchs et al. 2010). Sustainable management of sediments and attached nutrient and contaminant loads is thus a key challenge in river basins.

Soil erosion is a complex phenomenon which is controlled by various thresholds that operate at a hierarchy of scales. Local scale generation of surface runoff, particle detachment and rill incision depend on rainfall intensity and amount, topography, spatial patterns of soil hydraulic and mechanic parameters, land use and tillage practice (Knapen et al. 2007; Scherer et al. 2012). In addition hillslope scale surface runoff response and sediment delivery to the stream depend crucially on the spatial and temporal connectivity of overland flow paths and rill networks (Cammeraat 2004) as suspended particles may be deposited during downslope redistribution.

Erosion processes can be examined in the field and in laboratory experiments. However, only a limited number of experiments can be carried out in natural catchment systems. Numerical models are thus used to extrapolate from available measurements and to represent erosion processes at larger scales. Furthermore models are highly important for analyzing the long term consequences of changes in climate, land use and management practice. Especially lower mesoscale catchments of 10-200 km² are of utmost interest, since this is the relevant scale for planning and implementing mitigation measures.

2 MODELING APPROACHES ON VARIOUS SCALES

Approaches to model soil erosion and sediment yields can be classified as empirical, conceptual or process-based.

2.1 Process-based modeling approaches

Process-based models represent the entire interaction of relevant processes: runoff formation, erosion and particle detachment, routing of water and sediments and allow thus simulation of spatially and temporally resolved erosion and deposition patterns as well as sediment yield into river systems. A large number of process based models have been developed within the past decades, which are different in their spatial and temporal scale of application, the underlying process descriptions and the amount of necessary input parameters. A successful application of these models requires, however, a large amount of spatially highly resolved data on the above mentioned key system characteristics, which is only available for a few, well examined small catchments (Jetten et al. 2003).

As an example for a process-based approach, the model CATFLOW-SED will be introduced. CATFLOW-SED is a continuous, dynamic, spatially distributed model. Soil water dynamics is described by the Richards equation, including an effective approach for preferential flow that is numerically solved by an implicit mass conservative Picard iteration. Evaporation and transpiration is simulated, using an advanced approach based on the Penman-Monteith equation. The model simulates overland flow as sheet flow using the diffusion wave equation. Soil detachment is related to the attacking forces of rainfall and overland flow. The detachment rate further depends on the model parameter erosion resistance, which is characterized by soil properties, land use and management practice. Transport capacity and deposition are quantified using the equation of Engelund and Hansen (1967) and the sinking velocity of the sediment grains. The transfer of sediments to the surface waters is modeled for a freely selectable number of grain size fractions allowing for the coupling of particulate mass transport of nutrients and contaminants (Scherer 2008).

The model was parameterized using the data set of the Weiherbach catchment which is an intensively cultivated small loess catchment in the Southwest of Germany (Figure 1).

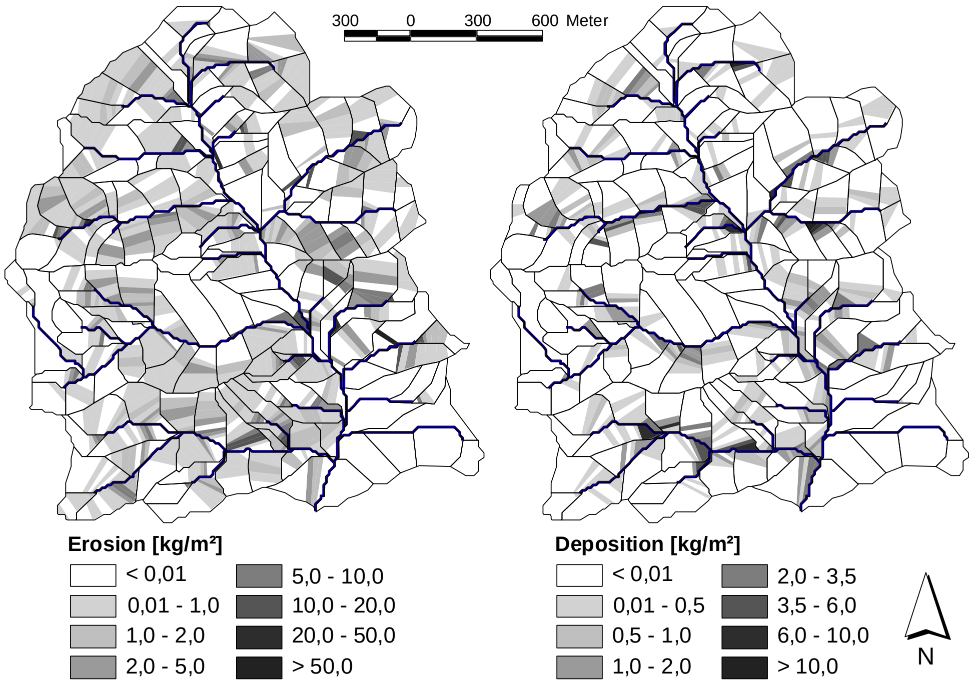

Figure 1 Simulation results for the heaviest observed storm event on 27th June 1994 in the northern part of the Weiherbach catchment. Left: Pattern of erosion rates, right: pattern of deposition rates.

To investigate the erodibility of the soils, various rainfall simulation experiments were carried out using a transportable rainfall simulator (Scherer et al. 2012). In addition to an extensive hydrological monitoring program in the catchment, sediment concentrations during storm events were measured at the catchment outlet (Plate and Zehe 2008).

CATFLOW-SED was validated for the Weiherbach catchment on various scales (irrigation experiments, hillslope, catchment). The model results were in good agreement with observed sediment loads of large erosion events. Figure 1 presents the erosion and deposition pattern for the heaviest event observed in the catchment showing a realistic distribution of erosion and deposition rates due to the land use and the geomorphology of the catchment.

2.2 Empirical and conceptual modeling approaches

For the lack of appropriate models, the empirical Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) is widely applied to quantify the sediment production in mesoscale and large catchments, although validation of most erosion studies at these scales is still missing (Wang et al., 2009). As the USLE was developed to estimate long-term mean soil loss rates on arable land, it is often combined with spatially lumped models to estimate the sediment delivery ratio (SDR) for quantifying sediment yield.

Figure 2 presents the soil erosion rates on arable land for Germany compiled by Fuchs et al. (2012) using the USLE. To quantify sediment delivery a spatially lumped approach was developed and validated using long term suspended matter loads at various monitoring stations. It showed that the sediment emission significantly depends on the large scale gradient in the catchment areas and the percentage of arable land that lies in close vicinity to surface waters (Fuchs et al. 2012).

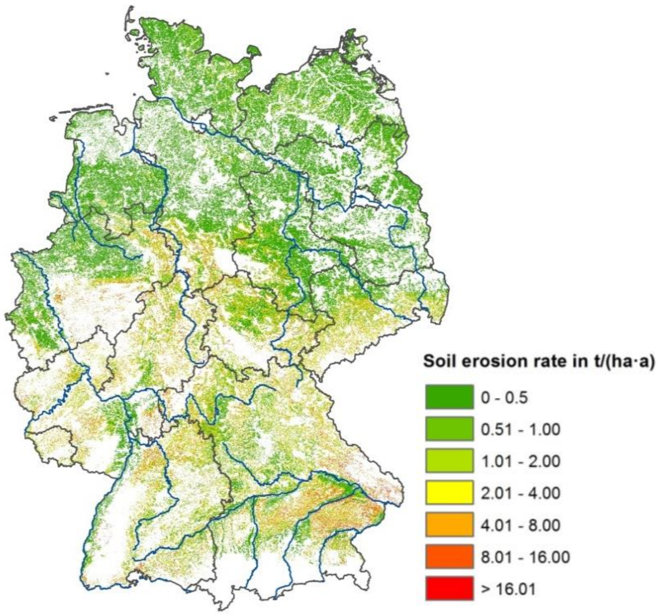

Figure 2 Soil erosion rates on arable land in Germany.

However, the combined USLE-SDR approach has received strong criticism, since various experimental data show that predictions of sediment yield may differ by orders of magnitude from observed sediment loads (Kinnell 2004). This approach is neither a priory transferable to areas with characteristics that fall outside the calibration set nor is it suitable to quantify change impacts.

This is why conceptual models are applied to overcome some of the above mentioned difficulties. Conceptual models allow for long-term predictions of runoff, erosion and sediment transport at the basin scale, typically on a daily time step and spatially varied grids or sub-catchments under stationary climate and landuse conditions. Examples are SWAT (Arnold et al. 1998) or the Pan European Risk Assessment (PESERA) model (Kirkby et al. 2008). These types of models rely on conceptual procedures such as the modified SCS curve number method or storage threshold models to estimate daily runoff. With regard to erosion, most conceptual models use terms of the USLE or are based on its modifications RUSLE or MUSLE. In contrast, the PESERA model provides a more process-based estimate of soil erosion rates, but the focus is exclusively on estimating soil erosion at the base of the hillslopes. As a result, soil loss rates at the catchment outlet are often underestimated, since linear erosion forms and transport processes are not considered. All conceptual erosion models have in common, that they lack adequate hydrological descriptions to simulate the temporal and spatial variability and amounts of runoff rates at the basin scale. Furthermore, the complex interactions between the different active processes are only poorly represented by empirical procedures which are mostly based on the USLE.

3 CONCLUSIONS

In the introduction the importance of lower mesoscale catchments for the planning and implementation of mitigation measures in river basin management was emphasized. However, suitable modeling approaches for this scale are widely lacking. The routine application of process based models for answering practical questions is not possible because of their data needs. This is why empirical or conceptual models are typically applied at the mesoscale. But these modeling approaches cannot simply be adapted to consider landscape specific processes due to findings of field studies, because empirical approaches do not allow for modifying the representation of sub processes. It is further questionable if the variety of soil erosion processes in different landscapes can be represented by a universal model such as the USLE.

Modeling approaches which are suitable for mesoscale catchments should balance necessary complexity to resolve dominant processes with greatest possible simplicity to avoid model over-parameterization, which implies to increase the number of model and input parameters that are subject to uncertainty. Such a balanced model should thus focus on the dominant processes operating in a landscape of interest and the parameterisation and spatial discretisation of the model should represent the main structural elements that control overland flow generation, erosion and sediment redistribution.

4 REFERENCES

Arnold J.G., Srinivasan R., Muttiah R.S., Williams J.R. (1998): Large area hydrologic modeling and assessment Part I: Model development. JAWRA Journal of the American Water Resources Association 34:73-89.

Cammeraat, E. L. H. (2004): Scale dependent thresholds in hydrological and erosion response of a semi-arid catchment in southeast Spain. Agriculture Ecosystems & Environment 104 (2), 317-332.

Engelund F., Hansen E. (1967): A monograph on sediment transport in alluvial streams Teknisk Forlag (Copenhagen).

Fuchs, S., Scherer, U., Wander, R., Behrendt, H., Venohr, M., Opitz, D., Hillenbrand, Th., Marscheider-Weidemann, F., Götz, Th. (2010): Calculation of Emissions into Rivers in Germany using the MONERIS Model. Nutrients, heavy metals and polycyclic aromatic hydrocarbons. UBA-Texte 46/2010, Dessau

Fuchs, S., Wander, R., Weber, T., Hilgert, S., Scherer, U., Ihringer, J., Höllering, S. (2012): Methodische Optimierung von Modellansätzen zur Schadstoffbilanzierung in Flussgebietseinheiten. Final report for the UBA-research project FKZ 370 822 202/01. Institute for water and river basin management, Karlsruhe Institute of Technology.

Jetten V., Govers G., Hessel R. (2003): Erosion models: Quality of spatial predictions. Hydrological Processes 17:887-900.

Kinnell P.I.A. (2004) Sediment delivery ratios: a misaligned approach to determining sediment delivery from hillslopes. Hydrological Processes 18:3191-3194.

Kirkby M.J., Irvine B.J., Jones R.J.A., Govers G., team P. (2008): The PESERA coarse scale erosion model for Europe. I. – Model rationale and implementation. European Journal of Soil Science 59:1293-1306.

Knapen A., Poesen J., Govers G., Gyssels G., Nachtergaele J. (2007): Resistance of soils to concentrated flow erosion: A review. Earth-Science Reviews 80:75-109.

Owens P.N., Batalla R.J., Collins A.J., Gomez B., Hicks D.M., Horowitz A.J., Kondolf G.M., Marden M., Page M.J., Peacock D.H., Petticrew E.L., Salomons W., Trustrum N.A. (2005): Fine-grained sediment in river systems: Environmental significance and management issues. River Research and Applications 21:693-717.

Plate E.J., Zehe E. (2008): Hydrologie und Stoffdynamik kleiner Einzugsgebiete. Prozesse und Modelle Schweizerbart, Stuttgart.

Scherer U. (2008) Prozessbasierte Modellierung der Bodenerosion in einer Lösslandschaft. PhD-Thesis, Institute for Water and River Basin Management University Karlsruhe, Karlsruhe (Germany).

Scherer U., Zehe E., Träbing K., Gerlinger K. (2012): Prediction of soil detachment in agricultural loess catchments: Model development and parameterisation. Catena 90:63-75.

Walling D.E. (2006): Human impact on land-ocean sediment transfer by the world's rivers. Geomorphology 79:192-216.

Wang G.Q., Hapuarachchi P., Ishidaira H., Kiem A.S., Takeuchi K. (2009): Estimation of Soil Erosion and Sediment Yield During Individual Rainstorms at Catchment Scale. Water Resources Management 23:1447-1465.

Wischmeier W.H., Smith D.D. (1978): Predicting rainfall erosion losses – a guide to conservation planning, Agriculture Handbook No. 537, U.S. Department of Agriculture.

Transfer of sediments in catchment ecosystems on various scales

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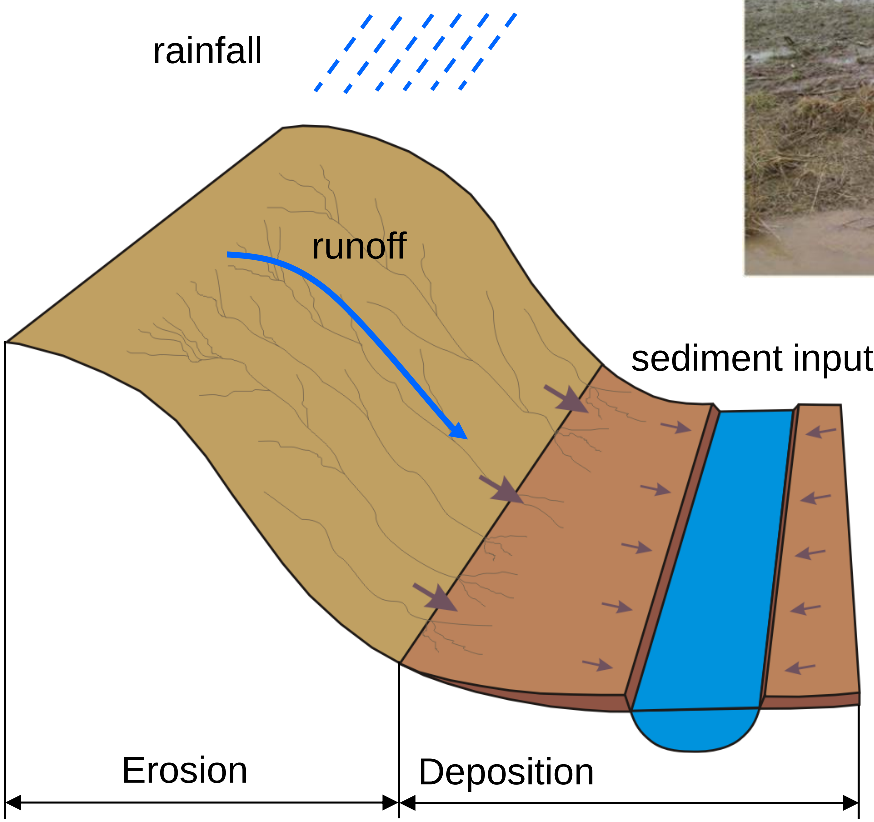
Transfer of sediments in catchments



detachment
and transport

deposition

Attert, Luxembourg (Photo: CRP-GL)

How can we measure soil erosion?

- Soil erosion rates in the field
  - Mapping of erosion forms in the field
  - Long term soil erosion plots
  - Field experiments under controlled rainfall conditions

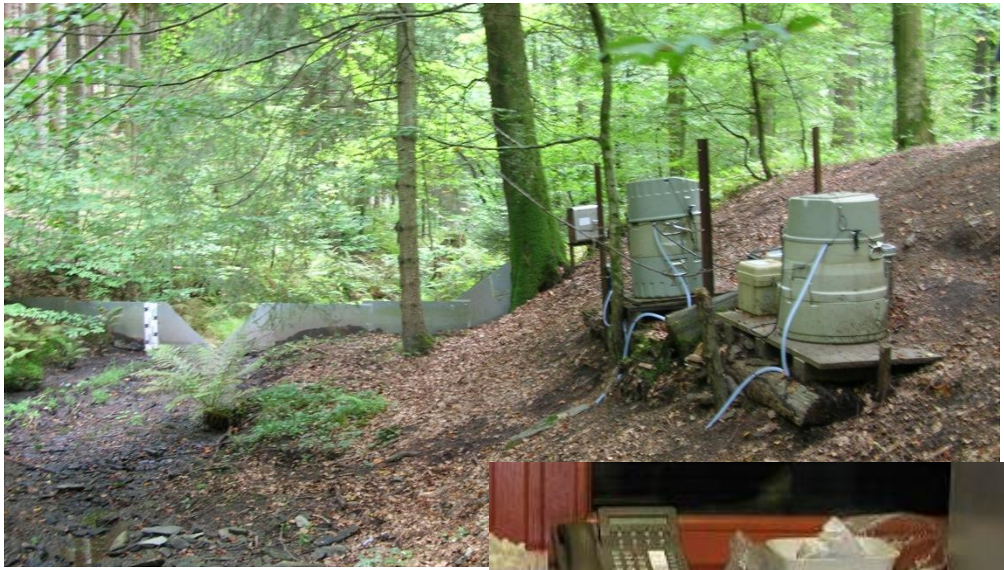
Erosion rill in corn field (Wissembourg, France)

Long term soil erosion plot (Niederoesterreich, Austria)

Rainfall simulator (Weiherbach catchment, Germany)

How can we measure sediment delivery?

- Monitoring of sediment concentrations at the catchment outlet



Automatic water sampling
Weierbach, Luxembourg
(A. Krein, CRP-GL)

Turbidity probe in the HOAL catchment,
Petzenkirchen, Austria

Modeling of sediment transfer

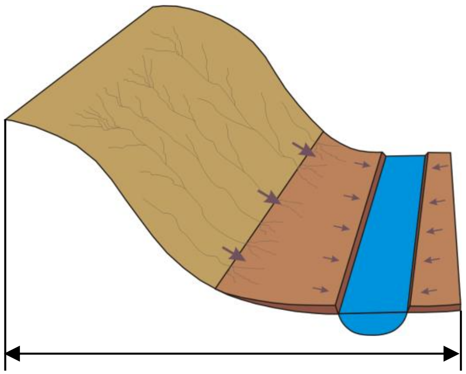
process based approaches

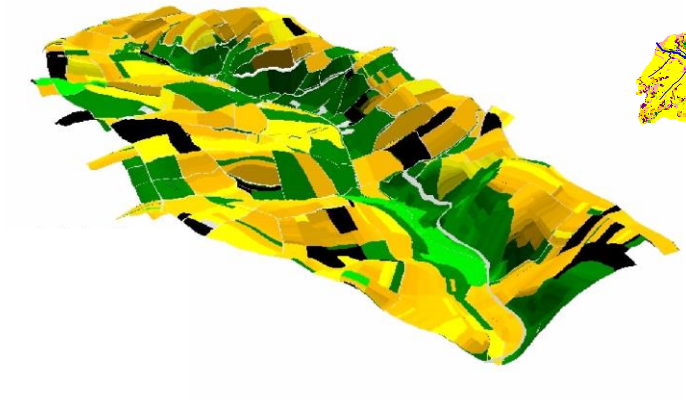
empirical/conceptual approaches

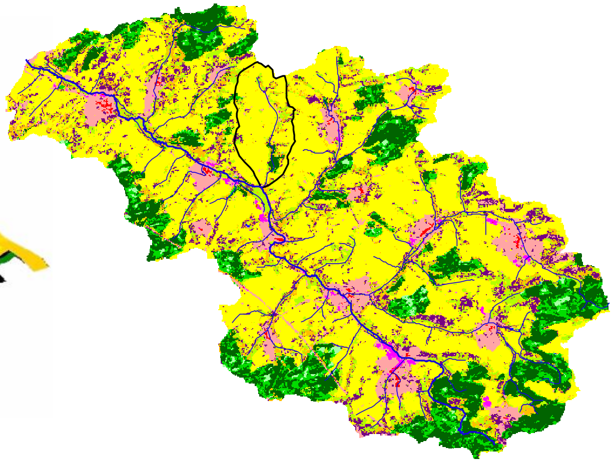
hillslope scale

small catchment

basin scale





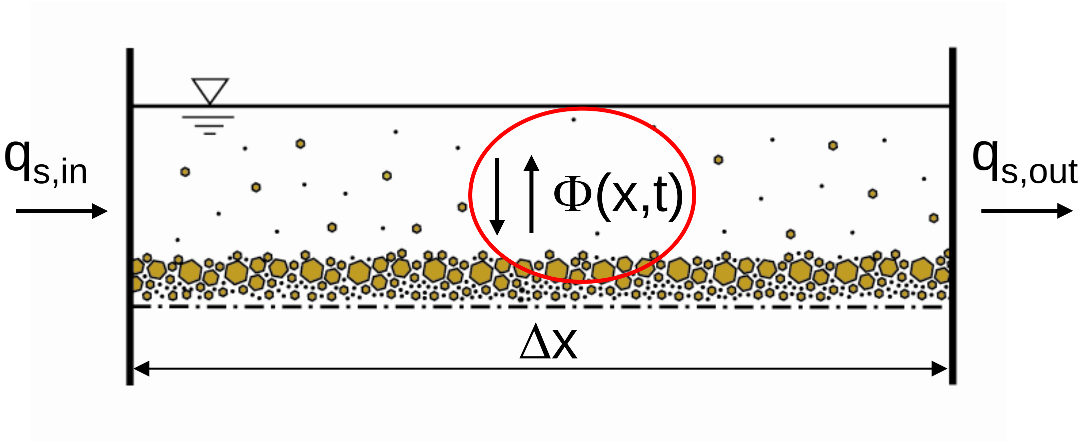


Process based modeling approaches

- Represent the entire interaction of relevant processes
  - Rainfall / runoff
  - Detachment
  - Transport
  - Deposition

  (Detachment, Transport, Deposition) of sediment particles and aggregates

- Based on the sediment continuity equation

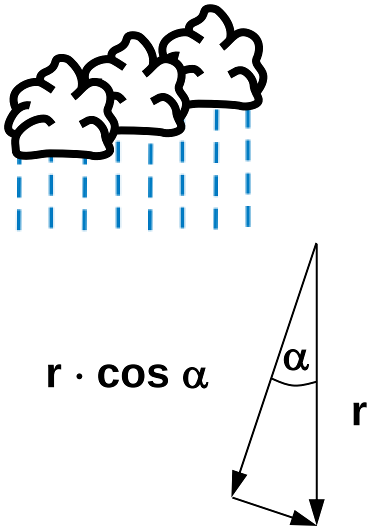


$$\frac{\partial q_s}{\partial x} = \Phi(x,t)$$

qs *solid mass flow rate, kg/(m·s)*
Φ *net in- / output of particles into / out of flow, kg/(m²·s)*

Scherer (2008)

CATFLOW-SED: Soil detachment



momentum of rainfall

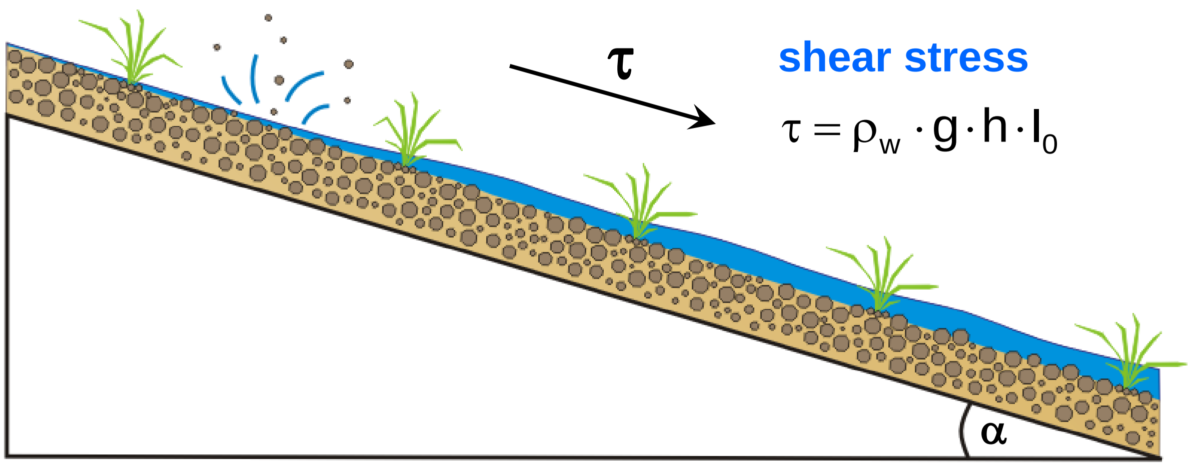
$$m_r = \rho_w \cdot r \cdot v_r \cdot \cos\alpha \cdot (1 - BBG)$$

detachment rate

$$e_{pot} = p_1 \cdot (\tau + p_2 \cdot m_r - f_{crit})$$

attacking forces

erosion resistance of the soil



shear stress

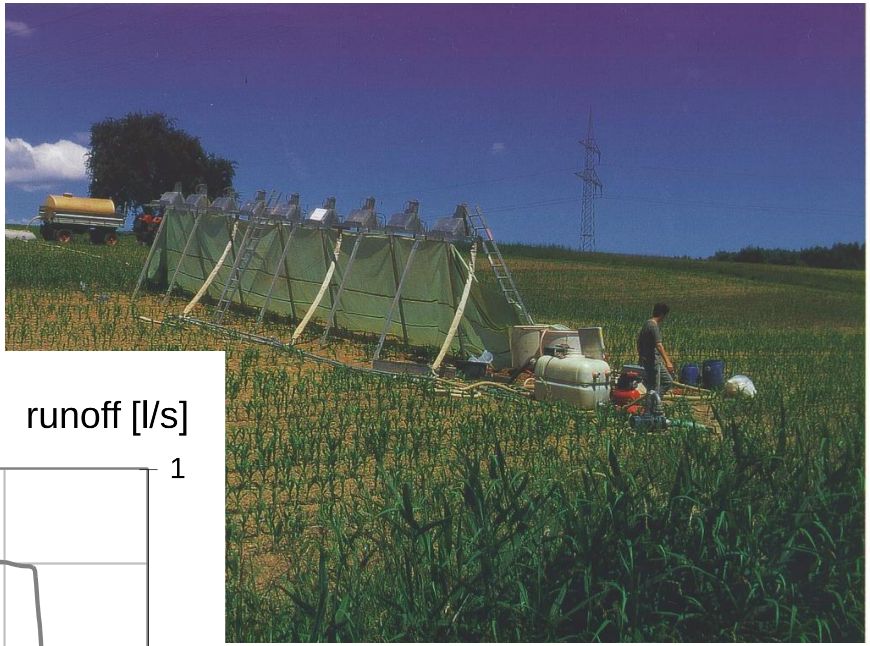
$$\tau = \rho_w \cdot g \cdot h \cdot I_0$$

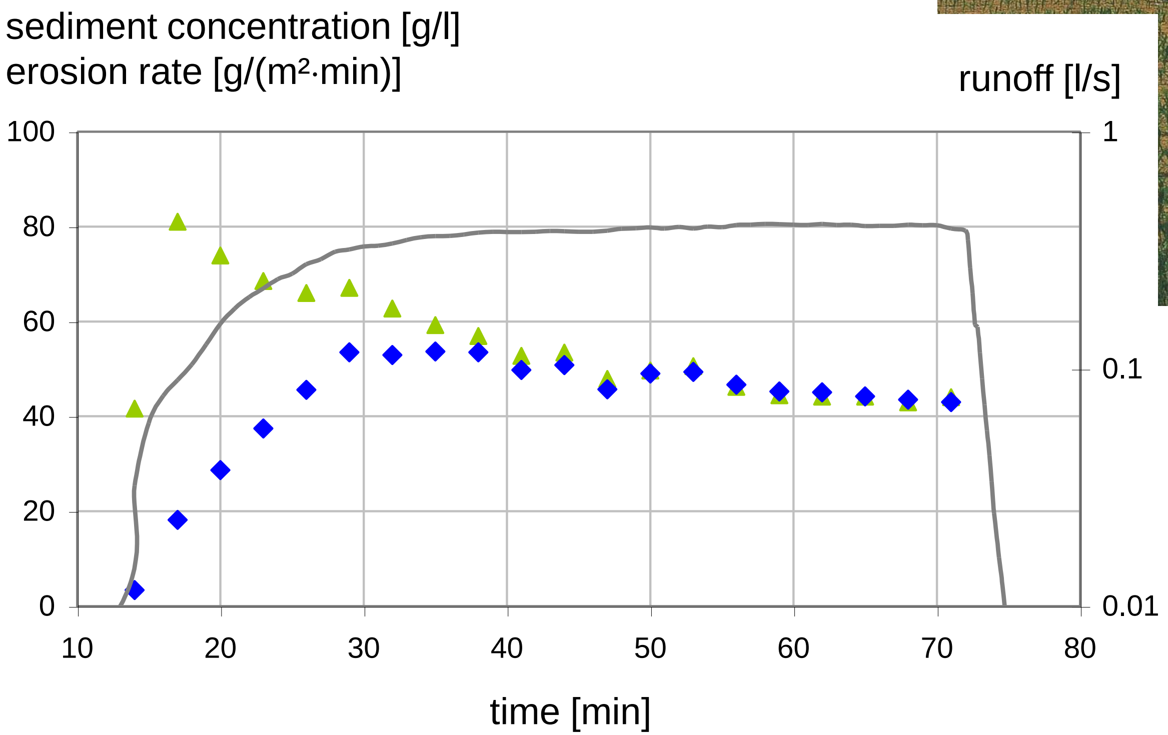
e_{pot}	*detachment rate, kg/(m²·s)*
f_{crit}	*erosion resistance, N/m²*
$p_{1,2}$	*empirical parameters*

Scherer et al. (2012)

CATFLOW-SED: Detachment

- Rainfall simulation experiments in the field to determine erosion resistance

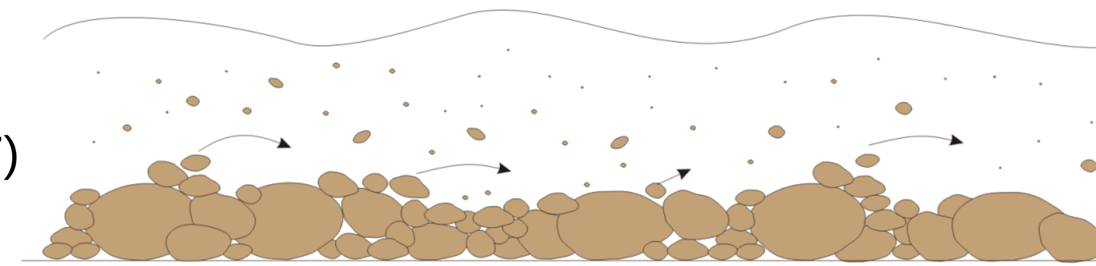




Scherer et al. (2012)

CATFLOW-SED: Transport and Deposition

- Transport capacity of overland flow controls sediment transport rate and deposition

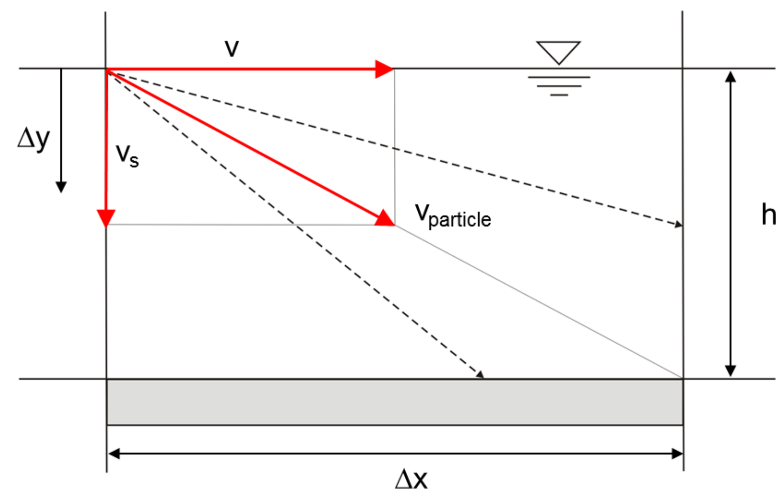


Engelund und Hansen (1967)

$$\phi = \frac{2}{5} \cdot \frac{\theta^{\frac{5}{2}}}{\lambda}$$

ϕ *transport intensity, [-]*
θ *intensity of flow, [-]*
λ *resistance coefficient, [-]*

- Deposition depends on the sinking velocity



$$\Delta y = \frac{v_s}{v} \cdot \Delta x$$

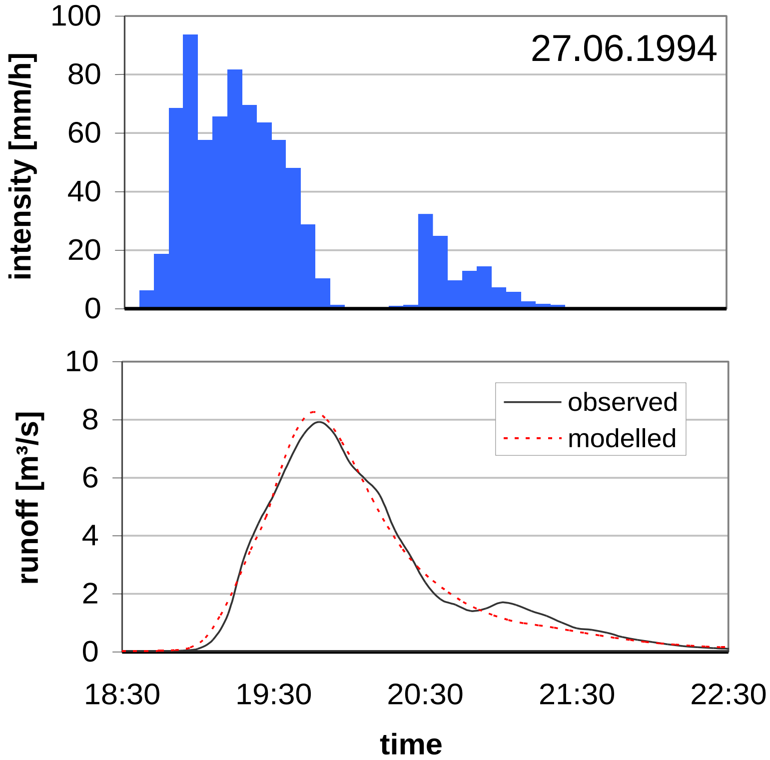
v *flow velocity, m/s*
v_s *sinking velocity, m/s*

Scherer (2008)

Validation at the catchment scale

- Weiherbach catchment
  - Located in a loess region in Southwest Germany
  - 3.5 km²
  - Intensively cultivated

Gauge station in the Weiherbach catchment



Sediment yield	observed	modeled	bias
27.06.1994	1 815 t	1 949 t	+ 7.4 %
12.08.1994	35 t	37 t	+ 5.7 %
13.08.1995	607 t	630 t	+ 3.8 %

Scherer (2008)

Validation at the catchment scale

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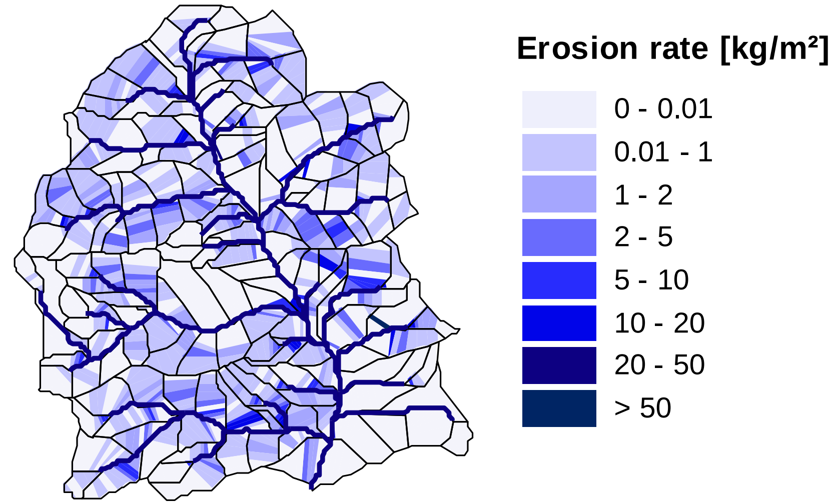
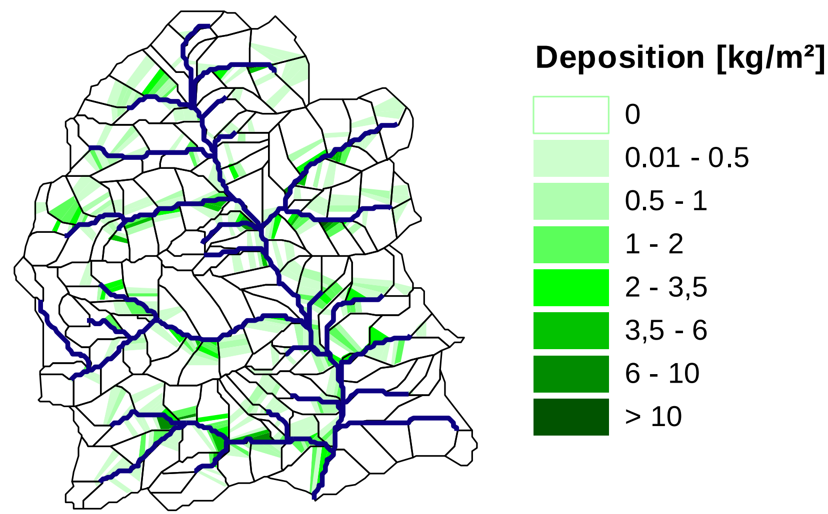
- Erosion and deposition rates in the Weiherbach catchment



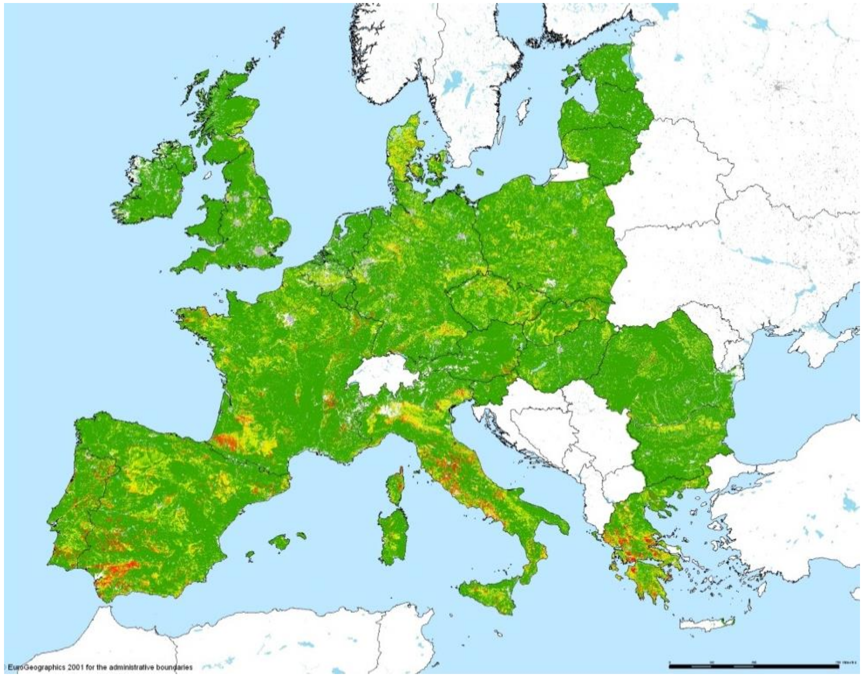


Scherer (2008)

Empirical/conceptual modeling approaches

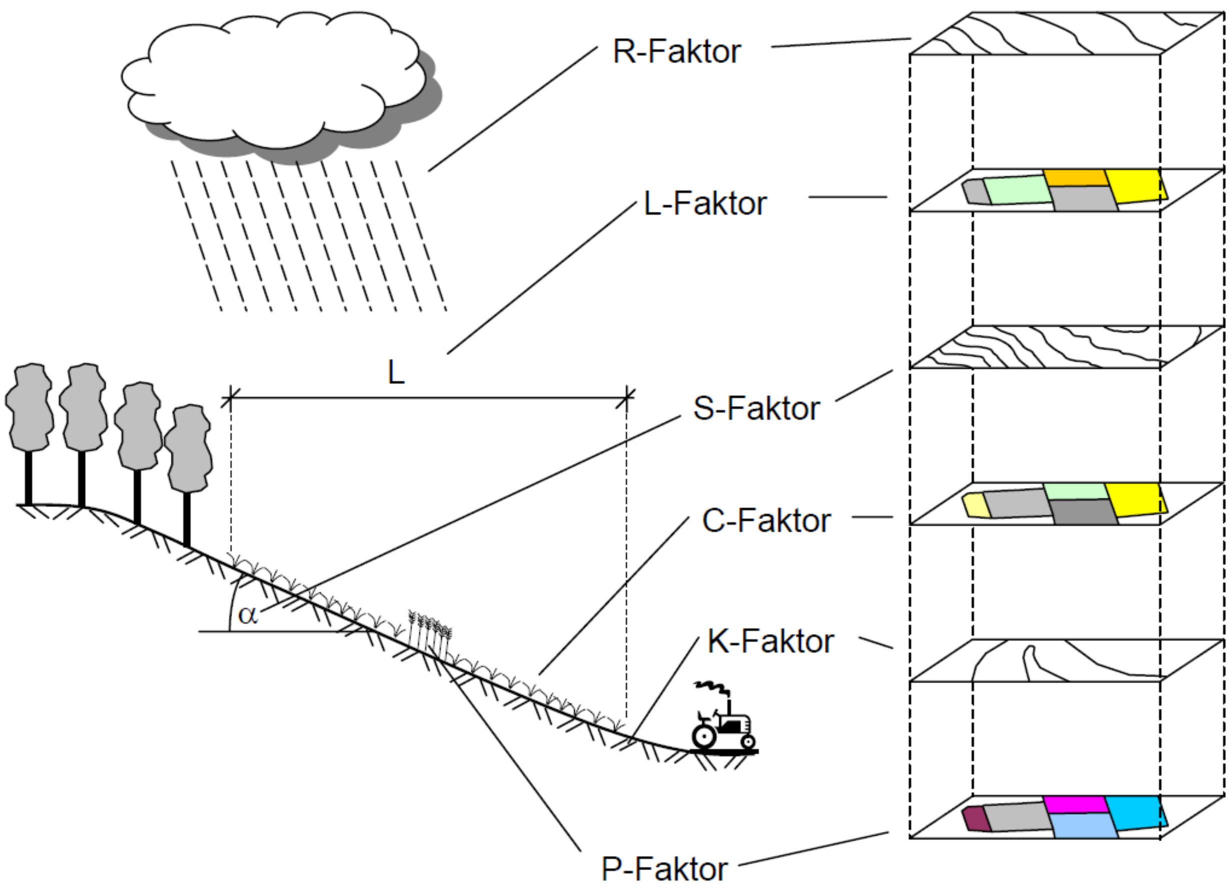
- Most widely used empirical model:
  Universal Soil Loss Equation - USLE (Wischmeier & Smith 1978)
  - National adaptations:
    i.e. Allgemeine Bodenabtragsgleichung – ABAG (Schwertmann et al. 1987)
  - Modifications:
    i.e. RUSLE, MUSLE

- Europe:
  Pan European Soil Erosion Risk Assessment - PESERA
  (Kirkby et al. 1994)



USLE – Universal Soil Loss Equation

BA = R · K · L · S · C · P in t/(ha·a) → long term erosion rate



BA: *average long-term soil erosion rate, t/(ha·a)*

R: *rainfall erosivity index, (kJ·m)/(m²·h)*

LS: *topographical factor, [-] (slope length and gradient)*

C: *plant cover and tillage factor, [-]*

K: *soil erodibility factor, (t·m)/(ha·a·kJ·h)*

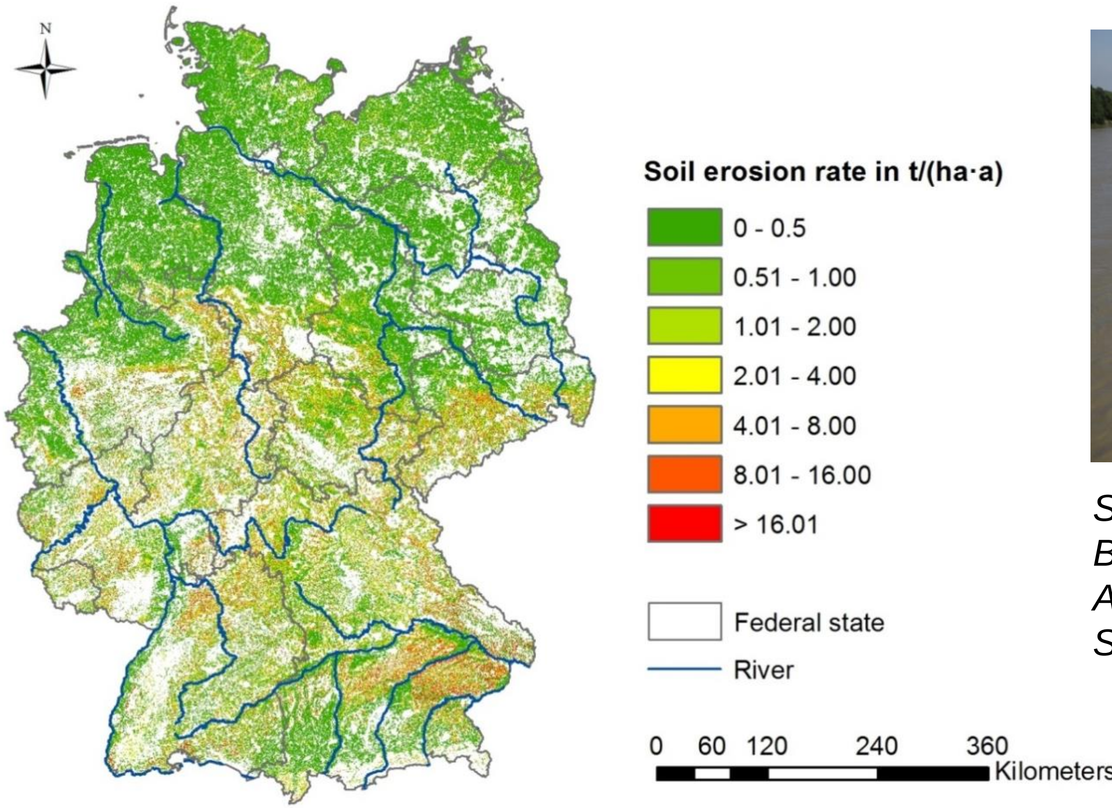
P: *specific erosion control practices, [-]*

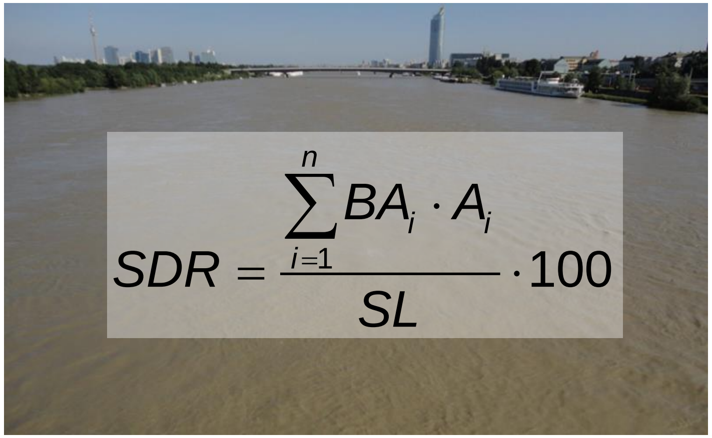
Butz (2005)

USLE – Application for Germany

- Erosion rates quantified by USLE are combined with SDR approaches to quantify sediment yields

Soil loss → Sediment delivery ratio





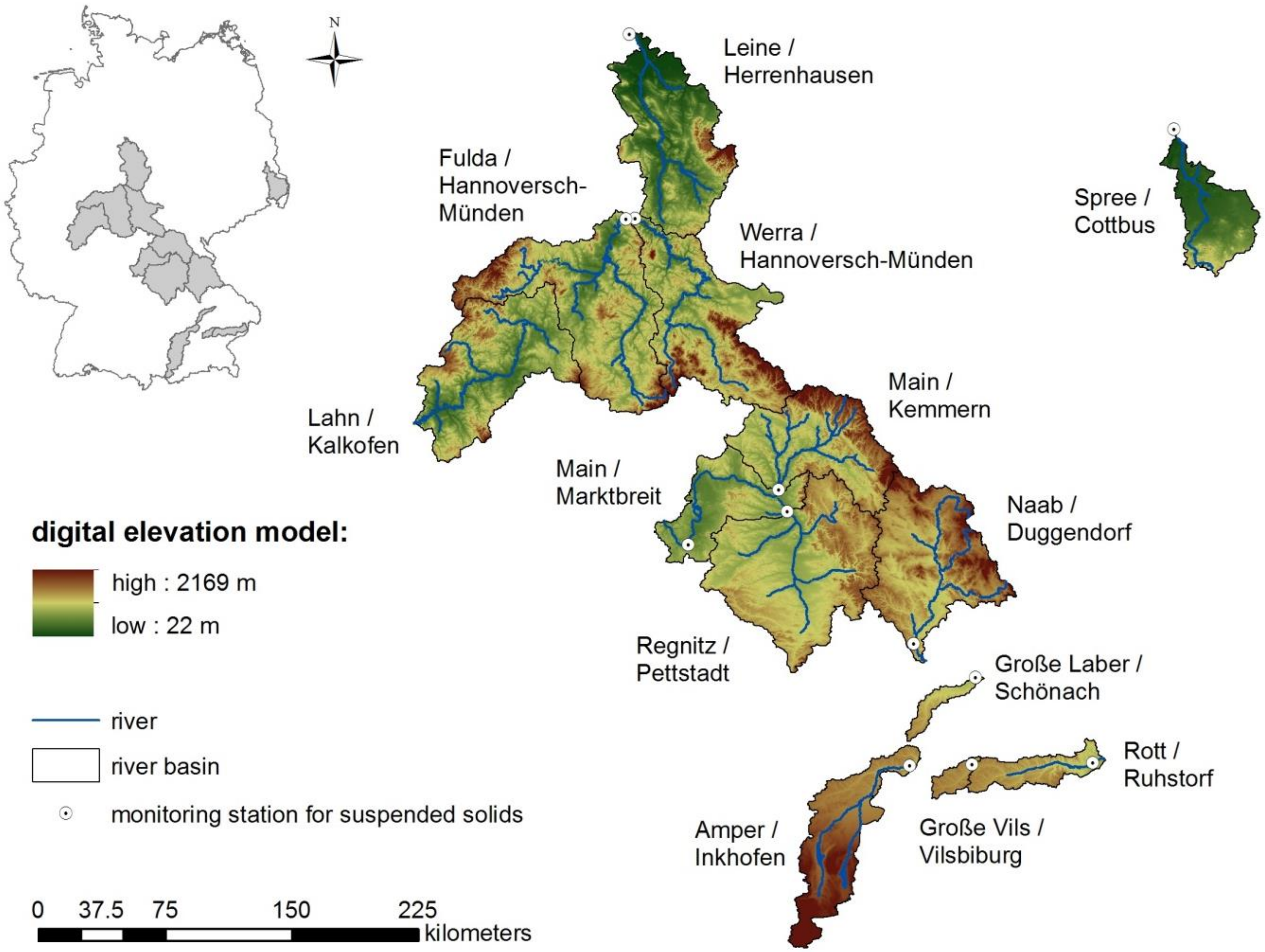
$$SDR = \frac{\sum_{i=1}^{n} BA_i \cdot A_i}{SL} \cdot 100$$

SDR	*sediment delivery ratio, %*
BA_i	*long term soil erosion rate, t/(ha·a)*
A_i	*size of the area i, ha*
SL	*long term sediment load, t*

Fuchs et al. (2012), Wurbs and Steininger (2011)

Sediment delivery to surface waters

- Derivation of a lumped SDR approach for German river basins



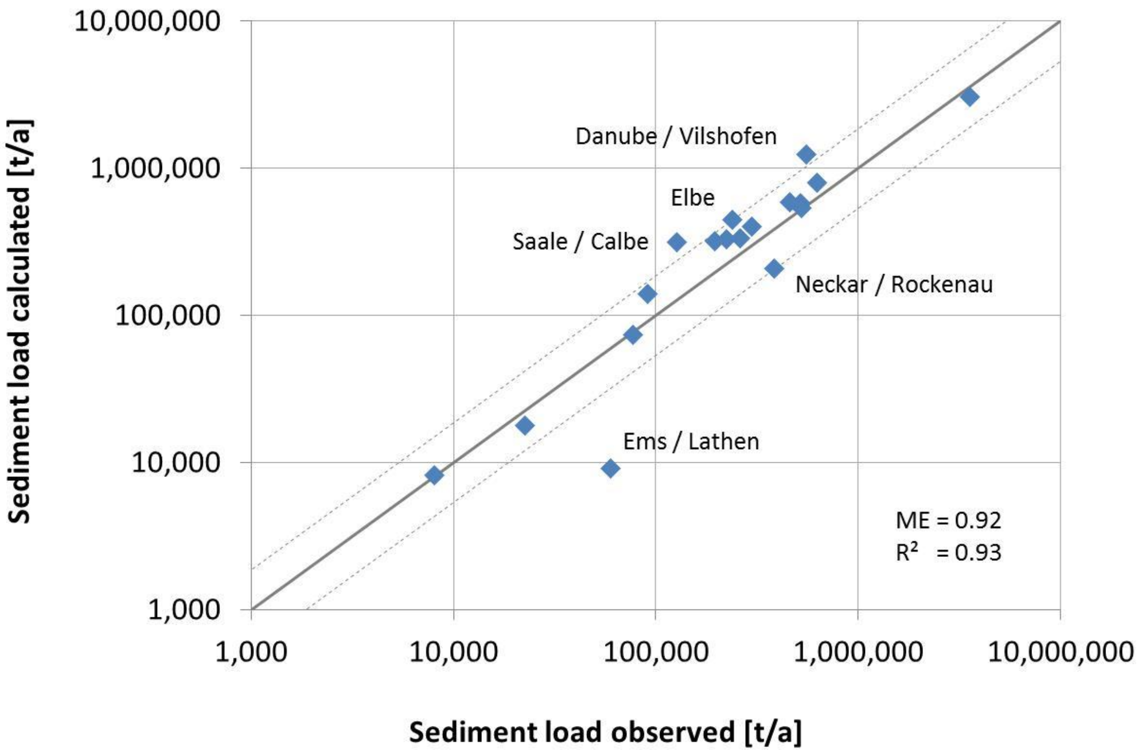
Fuchs et al. (2012)

Sediment delivery to surface waters

- Lumped SDR approach for German river basins: validation

$$SDR = 2.3 \cdot S^{0.86} \cdot A_{AL500}{}^{0.16}$$

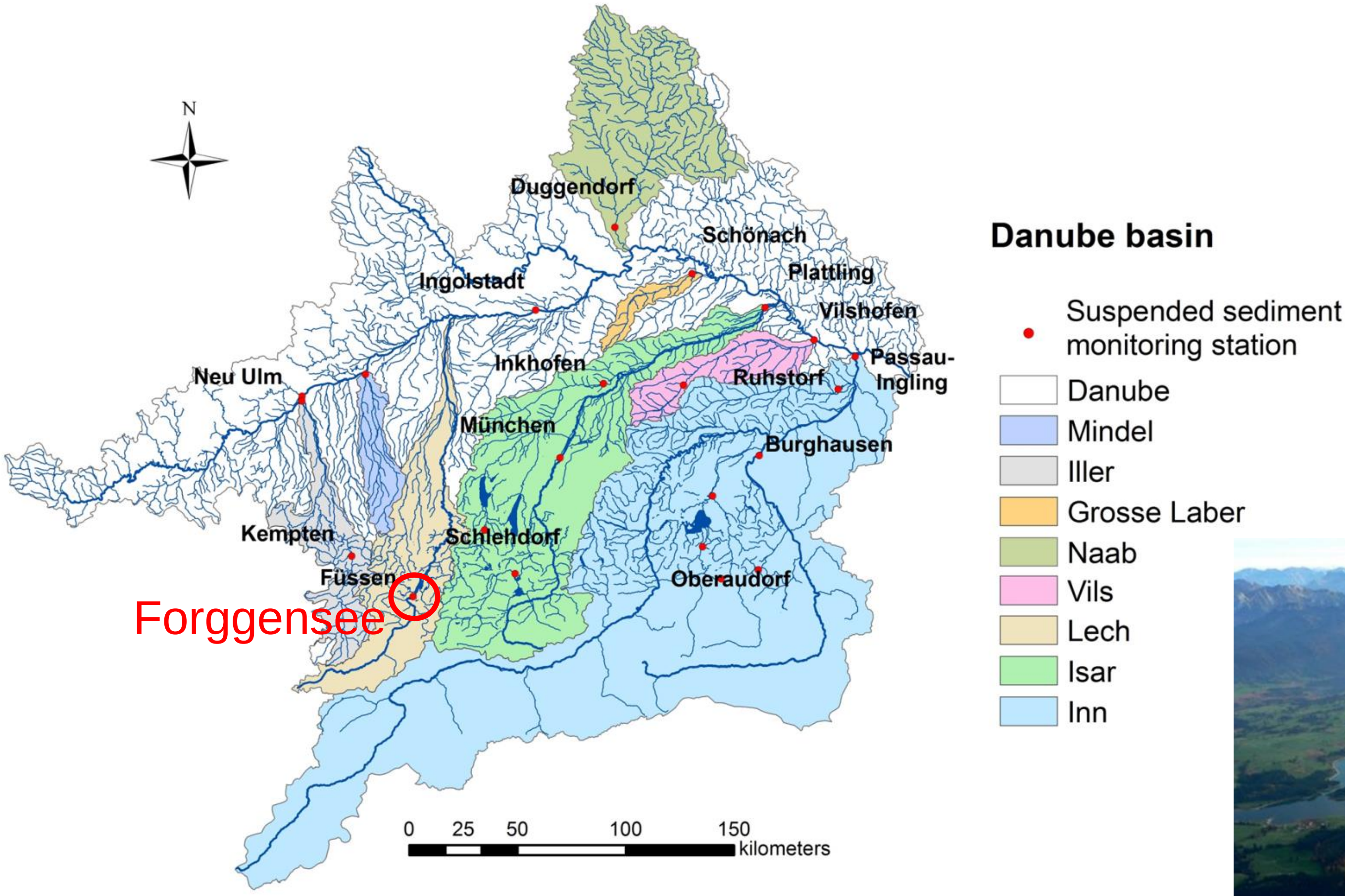
SDR	*sediment delivery ratio, %*
S	*slope, %*
A_{AL500}	*share of arable land located close to surface water bodies (flow distance < 500 m), %*



Fuchs et al. (2012)

Retention in river systems

- Analysis of local retention rates (Danube basin)



Karwendel region

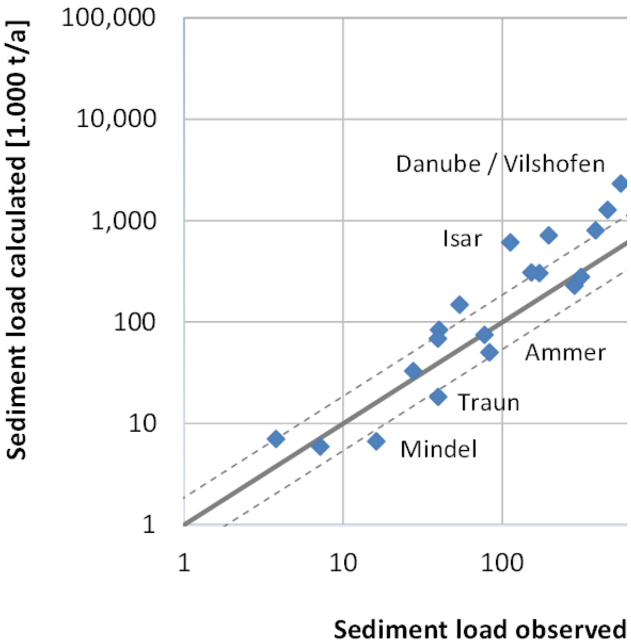
Forggensee reservoir

Retention in river basins

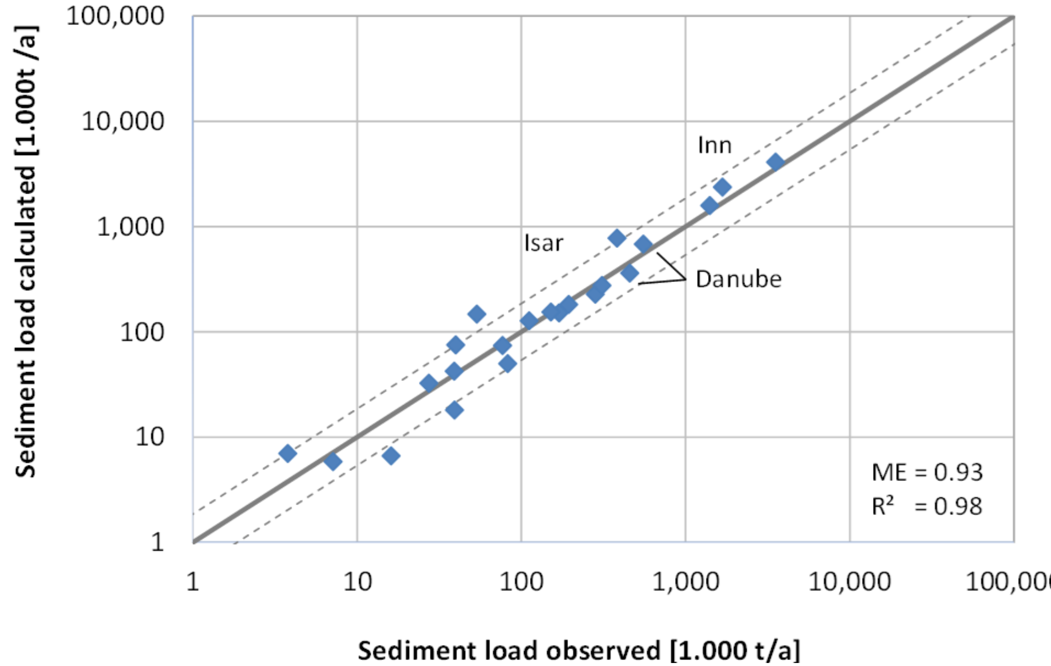
Karlsruhe Institute of Technology

- Comparison of observed and modeled sediment loads (Danube basin)

Without consideration of retention rates



With consideration of retention rates



Summary and conclusions

- Process based modeling approaches require a large amount of spatially highly resolved data, which is only available for a small number of catchments.
- This is why empirical/conceptual modeling approaches are used at larger scales. But their extrapolation capability to different landscapes and future scenarios is limited.
- For the planning and implementation of mitigation measures, the lower mesoscale (< 200 km²) is important!

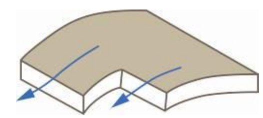
  → Suitable modeling approaches are missing…
- We need modeling approaches that balance necessary complexity with greatest possible simplicity.

Outlook

- Development of a hydrological modeling approach for meso-scale catchments: Focus on organizing principles in a specific landscape

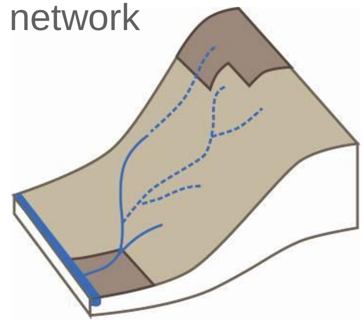
model formulation

Detachment



- rainfall kinetic energy
- attacking forces of overland flow
- resistance of soils against detachment

Super-ordinate surface flow network

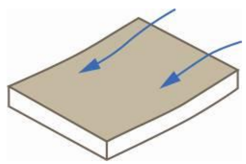


- kinematic wave approach sheet flow/rill structures

Channel

- transport capacity

Deposition



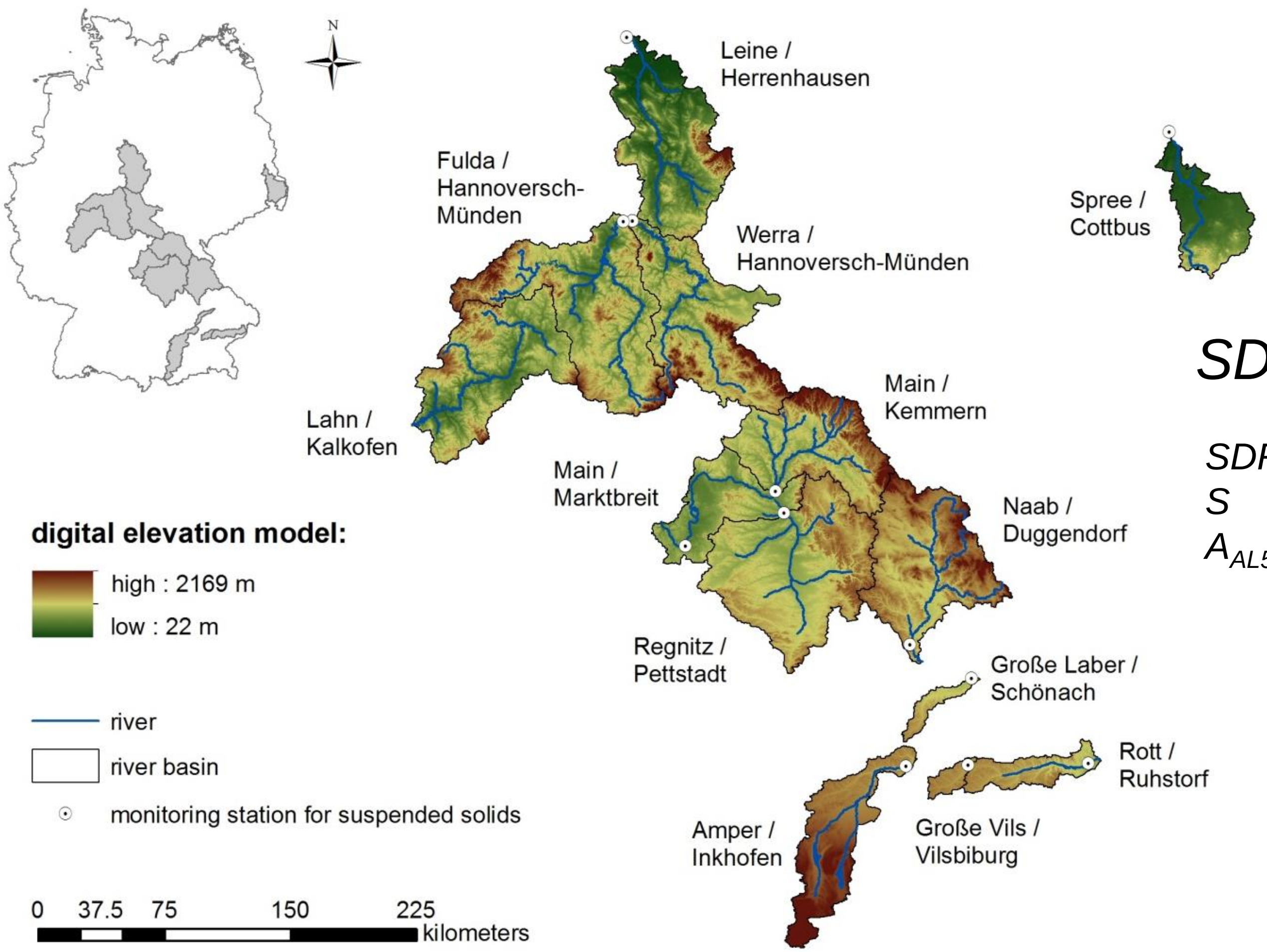
- sinking velocity of particles/aggregates

verification


Thank you!

Sediment delivery to surface waters

- Lumped SDR approach for German river basins



$$SDR = 2.3 \cdot S^{0.86} \cdot A_{AL500}^{\;0.16}$$

SDR	*sediment delivery ratio, %*
S	*slope, %*
A_{AL500}	*share of arable land located close to surface water bodies (flow distance < 500 m), %*

Fuchs et al. (2012)

Motivation: Thermodynamic Limits

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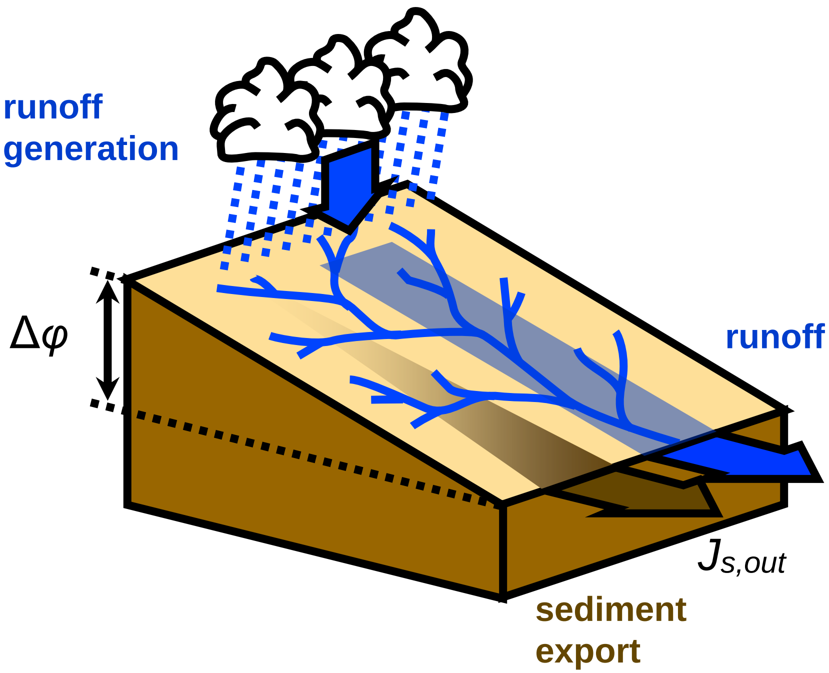

- **Limits to sediment export:**
- driving gradient is geopotential *Δφ*, resulting in water flow (*Δv*)
- drag force of water flow drives sediment export *Js,out*
  depletes *Δφ*
  depletes *Δv*
- relevant budget:
  mass balance of sediments *ms*
  balancing detachment, deposition, and sediment export

Motivation: Thermodynamic Limits

- Trade-off: more work by drag to detach sediments yields lower flow velocity *v*