Large-scale modelling of soil erosion by water and potential Global Change impacts in the Upper Danube basin

DANIEL WALDMANN & WOLFRAM MAUSER

Department of Geography, Ludwig-Maximilians University Munich, Luisenstrasse 37, 80333 München, Germany

d.waldmann@iggf.geo.uni-muenchen.de

Abstract The project GLOWA Danube investigates regional scale implications of climate change on the water cycle. The decision support system DANUBIA integrates models of natural and social sciences. The erosion component within DANUBIA simulates soil erosion by water on a spatial resolution of 1 km² and a temporal resolution of 1 hour. This paper briefly describes the design of the soil erosion module and presents a model validation based on the analysis of results for the reference period (1990 - 2005). Furthermore the results of the simulated GLOWA-Danube Climate Change scenario runs (2011 - 2060) are interpreted with special regard to influences of changed precipitation patterns on soil erosion.

Keywords soil erosion; modelling; global change; precipitation; GLOWA Danube; scenarios

INTRODUCTION

One of the major factors controlling soil erosion by water is the climate, epecially precipitation. Changes in absolute precipitation volumes, but moreover changes in seasonal precipitation distribution and temporal precipitation patterns of single events are of relevance. The IPCC (Christensen *et al.*, 2007) mentions a possible increase in extreme events in summer in Central Europe. Because often only a few heavy precipitation events are responsible for the majority of soil loss within a year (cf. e.g. Nearing *et al.*, 2005), this statement leads to the conclusion that soil erosion risk in Central Europe might increase with changing climate.

The project GLOWA Danube investigates impacts of Global Change and Climate Change on the regional scale within the Upper Danube basin. The framework DANUBIA allows for coupling models of natural and social sciences (Barthel *et al.*, 2008). Future scenarios of climate change, based on the outputs of regional climate models are used for driving the models. Within DANUBIA the modular hydrological model PROMET simulates the water and energy fluxes of the land surface. The erosion module of PROMET has been developed by the lead author and is used in this paper to examine potential implications of changing precipitation patterns on soil erosion by water.

STUDY AREA AND DATA

The study area of the project GLOWA-Danube is the Upper Danube basin. The catchment area is 76,653 km², covering large parts of southern Germany and the Austrian Alps. The heterogeneous catchment is characterised by strong meteorological (mean annual temperature: -4.7 °C to +9 °C, mean annual precipitation: 650 mm to >2000 mm) and altitudinal (287 to 4049 m a.s.l.) gradients (Ludwig *et al.*, 2003). The main land cover in the catchment consists of forest (40%) and grassland (27%), followed by arable land (23%). Minor areas are covered by artificial surfaces and rock (4% each), water bodies and glaciers sum up to 1% each. Cereal production takes place on over 50% of the total arable land in the basin and is widespread over the whole catchment area (Wirsig *et al.*, 2006). A high percentage of agricultural land use is found in the *Tertiärhügelland* and the valley of the Danube. The fertile soils (Loess) prevailing there are particularly susceptible to soil erosion.

For model validation data from 8 gauges in the Upper Danube basin is available, ranging from 1990 – 2005. The gauges are operated by the Bavarian State Office for Environment (LfU) and measure runoff and suspended sediment yield (SSY). Table 1 lists the characteristics of the sub-catchments corresponding to the gauges. These have been selected, since they represent geographically very different regions, ranging from mountainous, forested watersheds to distinct agricultural areas on low, hilly terrain, and thus exhibit different characteristics regarding soil erosion.

Table 1 Characteristics of the sub-catchments used for model validation

Watershed	Gauge	Area (km^2)	Agricultural (arable) land	Slope min - max (mean) (°)	Main soil texture
Ammer	Weilheim	607	36.7 (1.8)	0.2 - 42.0 (10.8)	loamy sand
Glonn	Hohenkammer	408	66.2 (48.3)	0.6 - 5.2 (2.7)	silt loam, clayey silt
Grosse Laber	Schönach	399	72.2 (62.4)	0.1 - 5.7 (3.4)	silt loam, clayey silt
Iller	Kempten	1006	39.7 (0.1)	0.3 - 44.6 (17.9)	sandy loam, clayey loam
Inn (Ingling)	Ingling	26062	41.8 (9.4)	0.0 - 54.2 (17.8)	clayey and sandy loam, loamy sand
Inn (Oberaudorf)	Oberaudorf	9722	29.8 (1.1)	0.4 - 50.9 (25.4)	clayey loam, loamy sand
Naab	Duggendorf	5436	38.5 (21.8)	0.1 - 14.3 (4.6)	loamy sand, silty sand
Saalach	Unterjettenberg	919	38.7 (0.0)	0.6 - 47.0 (25.2)	clayey loam, loamy sand

METHODS

Modelling Basics

For modelling land surface processes the distributed hydrological model PROMET (PROcesses of Mass and Energy Transfer) is used. PROMET evolved from a Soil Vegetation Atmosphere Transfer (SVAT)-scheme originally developed by Mauser & Schädlich (1998) and was further extended during the past 10 years as described by Mauser & Bach (2009). PROMET simulates land surface processes grid-based. All processes considered by the model are computed for each grid cell, therefore a grid cell is termed a *proxel* (*pro*cess pi*xel*). The default spatial resolution of PROMET within GLOWA-Danube is 1 km × 1 km with a computation time step of 1 hour. The erosion model presented in this paper is implemented as a module within PROMET. The latter supplies the erosion module with the required input parameters from meteorology, soil (Muerth, 2008) and vegetation (Hank, 2008).

Meteorological input data is based on up to 370 climatological stations operated by the German Weather Service (DWD), which measure three times a day (the so-called *Mannheimer Stunden* at 7:00, 14:00 and 21:00 CET). This data is interpolated temporally and spatially in order to supply each *proxel* at each computation time step with the data required. Since the process of soil erosion is strongly dependent on rainfall intensity, precipitation is disaggregated temporally by a cascade model in order to achieve realistic intensities. For this purpose, a multiplicative microcanonical random cascade after Olsson (1998) was implemented and regionalised for the Upper Danube basin (cf. Waldmann & Mauser, 2008; Waldmann, 2010). The erosion module is based on the governing equations of EROSION2D (Schmidt, 1996) which have been adapted for the temporal and spatial modelling scale of GLOWA-Danube.

In the following paragraphs, the basic principles of the model and the modifications and extensions to the original model are briefly described. For an extensive description of EROSION2D and the erosion module the reader is referred to Schmidt (1996), respectively Waldmann (2010).

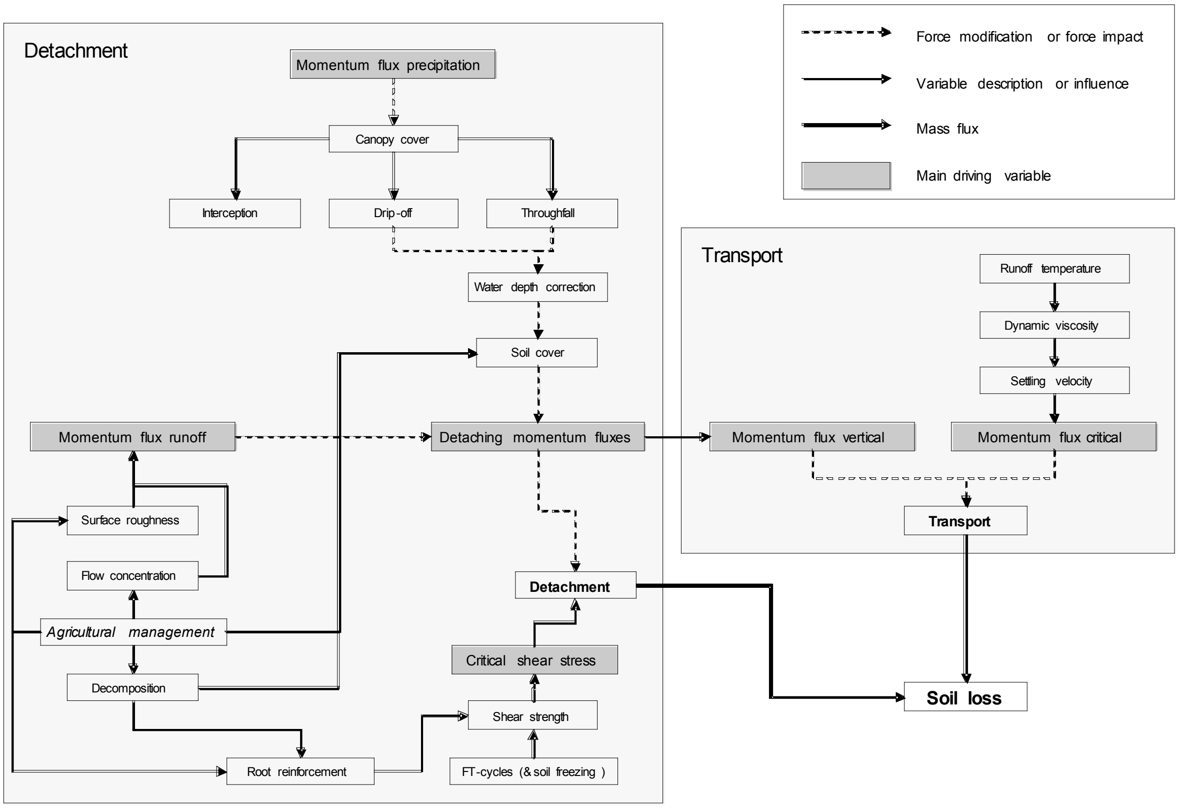

Fig. 1 Simplified overview of the erosion module presented in this paper. Only dynamic components are included in this illustration, static input parameters are omitted for reasons of clarity.

Fig. 1 shows the main process interactions within the erosion module. The calculation of particle detachment and transport is based on a momentum flux concept. The detaching momentum fluxes are composed of those resulting from runoff and precipitation. The resistance of the soil acts opposed to these two, holding the particles in place. The transport of detached particles is computed by comparing the vertical components of the momentum flux of the surface runoff and the precipitation to the settling velocity of the detached particles. Essentially this concept can be summarised in the following steps:

1. Calculation of the potential sediment mass flux $q_{s,pot}$ (kg m^{-1} $s^{-1)}$: the momentum fluxes of rainfall and runoff acting against the resistance of the soil determine the amount of potentially detached soil mass. The relationship between these two opposed forces, respectively the magnitude of detachment depending on the acting forces was empirically derived by Schmidt (1996) in numerous plot experiments for various different soils.
2. Calculation of the maximum sediment mass flux $q_{s,max}$ (kg m^{-1} s^{-1}): the vertical component of the momentum flux of the surface runoff and the precipitation lifts the detached particles, thus acting against the settling velocity of these.
3. Determination of the actual sediment mass flux $q_{s,act}$ (kg m^{-1} $s^{-1)}$: the amount of actually eroded sediment is determined by comparing $q_{s,pot}$ to $q_{s,max}$. It is limited

either by the amount of detached particles, or by the transport capacity of the flow. If $q_{s,pot} > q_{s,max}$, then $q_{s,act} = q_{s,max}$, which means that the amount of particles which may be transported is discharged actually. If $q_{s,pot} < q_{s,max}$, then all detached particles can be transported, and thus $q_{s,act} = q_{s,pot}$.

Process Descriptions

This section describes the processes composing each of the momentum flux components (cf. Fig. 1), which in turn are required for computing the actual sediment mass flux.

Momentum flux precipitation
Precipitation volume is received from the meteorology sub-component of PROMET. It is converted to momentum flux in the erosion module. Subsequently the momentum flux is modified depending on canopy cover. Fractional canopy cover is calculated from leaf area index (LAI) according to Campbell & Norman (1998), which determines the amount of intercepted water, leaf-drip, and throughfall. The resulting energy of leaf-drip and throughfall is reduced by soil cover, such as litter, and in case of surface runoff a water depth correction after Wicks & Bathurst (1996) additionally absorbs energy.

Momentum flux runoff
Surface runoff volume is imported from the soil water sub-component. In order to compute the runoff velocity, *Manning*'s equation is applied, which uses dynamic surface roughness values depending on agricultural management conditions (ploughing, seedbed, etc.) and vegetation development. Agricultural management also influences soil cover (e.g. by leaving crop residue on the field after harvest) and decomposition of crop residue (based on Renard *et al.*, 1996) and dead roots in soil. Furthermore, it modifies the flow concentration factor, which separates runoff into a rill and interrill component, according to flow paths influenced by the crop row distance.

Critical shear stress
The computation of the critical shear stress of the soil is based on the calculation of the shear strength of the soil after Vanapalli *et al.* (1996). The shear strength depends on static properties of the soil, like cohesion, but also the dynamic variables matric suction and effective saturation. The shear strength is modified by root reinforcement (Gyssels *et al.*, 2005) and freeze-thaw cycles (borrowed from Flanagan & Nearing, 1995). Finally the shear strength is converted to critical shear stress after Léonard & Richard (2004).

Critical Momentum flux
The momentum flux indicating downward movement of particles depends on the settling velocity of these. Settling velocity is calculated depending on particle size after Cheng (1997) holding for a wide range of Reynolds numbers from the Stokes flow to the turbulent regime. Solving Chengs' (1997) equation requires knowledge of the dynamic viscosity, which can be computed after Gordon *et al.* (2004) if the surface runoff temperature is known. The latter is derived from the soil surface temperature received from the soil sub-component of PROMET and from the approximated precipitation temperature.

Computation of soil loss
Knowing all these momentum fluxes allows for the computation of the total soil loss on a proxel at the given model time step, as described above. Theoretically sediment inflow and outflow must be considered for each proxel in order to gain the net soil loss. In PROMET, each proxel is connected to the channel network, which is managed by a sub-component that routes runoff with the kinematic wave approach of the Muskingum-Cunge-Todini method (Cunge, 1969; Todini, 2007). It is assumed that the runoff of each proxel is discharged into this network, thus also the sediment of each proxel. This assumption is constituted by an empirical validation of Mauser & Bach (2009), who found a threshold in the Upper Danube basin of 200 m × 200 m, above which a drainage channel exists, i.e. the catchment is carved by a dense channel network. Similar findings have been made by von Werner (1995), who modelled a watershed of 0.78 km² (i.e. smaller than the proxel size of 1 km²) with a spatial resolution ranging from 2.5 m × 2.5 m to 100 m × 100 m and reported deficient model results due to drainage channels and pipeworks.

RESULTS

Validation Period (1990 – 2005)

Validation runs have been made for the whole Upper Danube basin for the period 1990 – 2005. For validation of temporal soil loss patterns, statistics have been calculated for each of the 8 sub-catchments presented above. The SSY does not correspond to the computed soil loss on a *proxel*, since SSY measured at the gauge is modified by a number of processes in the river itself, such as sedimentation, remobilisation or bank erosion. Theoretically, it is possible to convert gross erosion to SSY with a sediment delivery ratio (SDR) (cf. e.g. de Vente *et al.*, 2007). But as the SDR usually has to be calibrated to the characteristics of the study area, respectively to the model applied, in this study a standardisation of computed soil loss and measured SSY is applied:

$$z = \frac{x - \mu}{\sigma} \tag{1}$$

where x is the raw score to be standardised, μ is the mean value and σ is the standard deviation. The standardisation allows for computation of the coefficient of model efficiency (CME, Nash & Sutcliffe, 1970). For model validation, monthly sums of measured SSY and modelled soil loss have been calculated and the resulting statistics are presented in Table 2.

Table 2 Statistics of model performance based on monthly sums of measured suspended sediment yield vs. modelled soil loss from 1990 – 2005.

	Ammer	Grosse Laber	Naab	Glonn	Iller	Inn (Oberaudorf)	Saalach	Inn (Ingling)	Mean
R^2	0.80	0.09	0.39	0.25	0.46	0.30	0.55	0.43	0.41
Pearson	0.90	0.30	0.63	0.50	0.68	0.55	0.74	0.66	0.62
CME (std.)	0.79	-0.40	0.26	0.00	0.36	0.10	0.49	0.32	0.24

Comparing the results, it is noticeable that the statistics differ distinctly for the sub-catchments. Considering the characteristics of the watersheds (cf. Table 1) it is obvious, that particularly the agriculturally intensively used regions perform weaker. The main reasons for this are:

- The agricultural areas are located on soils, which are difficult to model in terms of soil water budget. This means, the surface runoff calculated by the soil sub-component is deficient, which introduces errors in the computation of soil loss.

- The model deficits are highest in late summer/autumn at the time of harvest. Harvest is modelled dynamically considering the phenological development stage of the plants. Analysis has shown, that this occasionally produces erroneous harvest dates due to plant parameterisation deficits of some cultivars. Furthermore sowing of cover crops is currently not implemented, but actually frequently carried out in the sub-catchments.

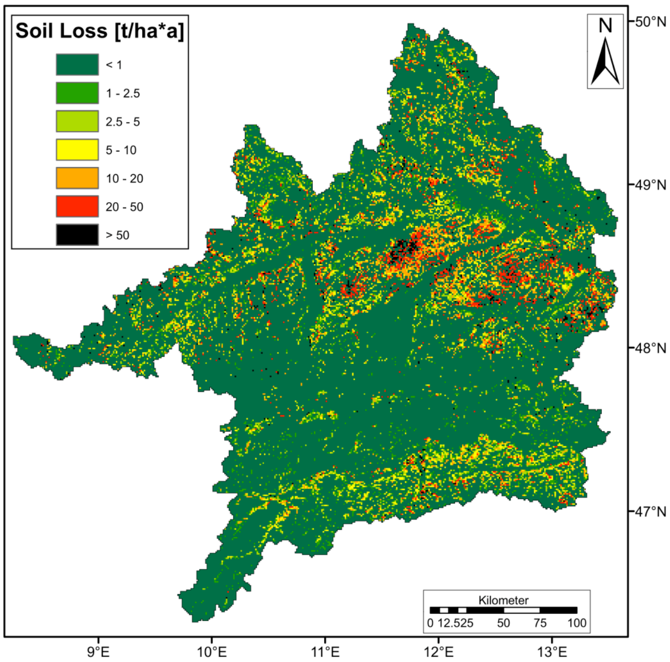

Fig. 2 Modelled mean annual long-term (1990 – 2005) soil loss [t ha^{-1}] in the Upper Danube basin.

Regarding spatial patterns, Fig. 2 shows the modelled distribution of long-term (1990 - 2005) annual mean soil loss (t ha^{-1}) in the Upper Danube basin. Soil loss averages out to an areal mean of 2.7 t ha^{-1} a^{-1}. Since it is virtually impossible to quantify soil losses by measurement over such a large area as the Upper Danube basin, Table 3 lists for comparison the model results, respectively estimates of other studies covering, or at least overlapping the Upper Danube basin.

Table 3 Results and estimates of soil loss from studies investigating areas in or around the Upper Danube basin.

Source	Region	Mean soil loss (t ha^{-1} a^{-1})
Erosion module	Upper Danube	2.7
PESERA (2009)	Upper Danube	0.8
Auerswald *et al.* (2009)	Germany	2.7
Auerswald & Schmidt (1986)	Bavaria	2.2

Scenarios (2011 – 2060)

In order to evaluate potential future impacts of Climate Change on soil erosion in the Upper Danube basin, scenario simulations for the period 2011 – 2060 are presented. For comparison, a reference model run from 1960 – 2006 is shown. It has to be noted, that this run does *not* reflect historical soil loss correctly, since the land use applied for the model run is derived from CORINE land cover data, i.e. reflects the land use of the 1990ies. Nevertheless, this long period is selected in order to identify potential trends caused by historical changes in precipitation patterns.

The meteorological scenario inputs are produced by a stochastic weather generator, which rearranges historical, measured data according to predefined temperature and precipitation trends (cf. Mauser *et al.*, 2006; Mauser & Muerth, 2008). For temporal disaggregation of precipitation, the cascade model as described above is used. A detailed description of the scenarios can be found in Kuhn et al. (2009); Table 4 briefly lists the configuration of the scenarios.

Table 4 Scenario configurations used for modelling climate change impacts.

Scenario	Temperature increase (°C)	Change of precipitation (%) winter	summer	Trend base
IPCC regional	3.3	+7	-14	IPCC (2007)
REMO regional	5.1	-4.9	-31.4	Jacob et al. (2008)
Extrapolation	5.2	+47	-69	Extrapolation of regional trend 1960 - 2006

Additionally to these scenarios one setup with direct input from REMO has been simulated, which means that no disaggregation method is required due to the high temporal resolution of REMO. The REMO meteorological outputs have been scaled down spatially to the PROMET resolution of 1 km × 1 km using the interface SCALMET, which allows for coupling land surface models with regional climate models (Marke, 2008; Marke & Mauser, 2008).

Long-term mean annual soil loss for the reference period and the scenarios is shown in Table 5 and the corresponding monthly soil loss is illustrated in Fig. 3.

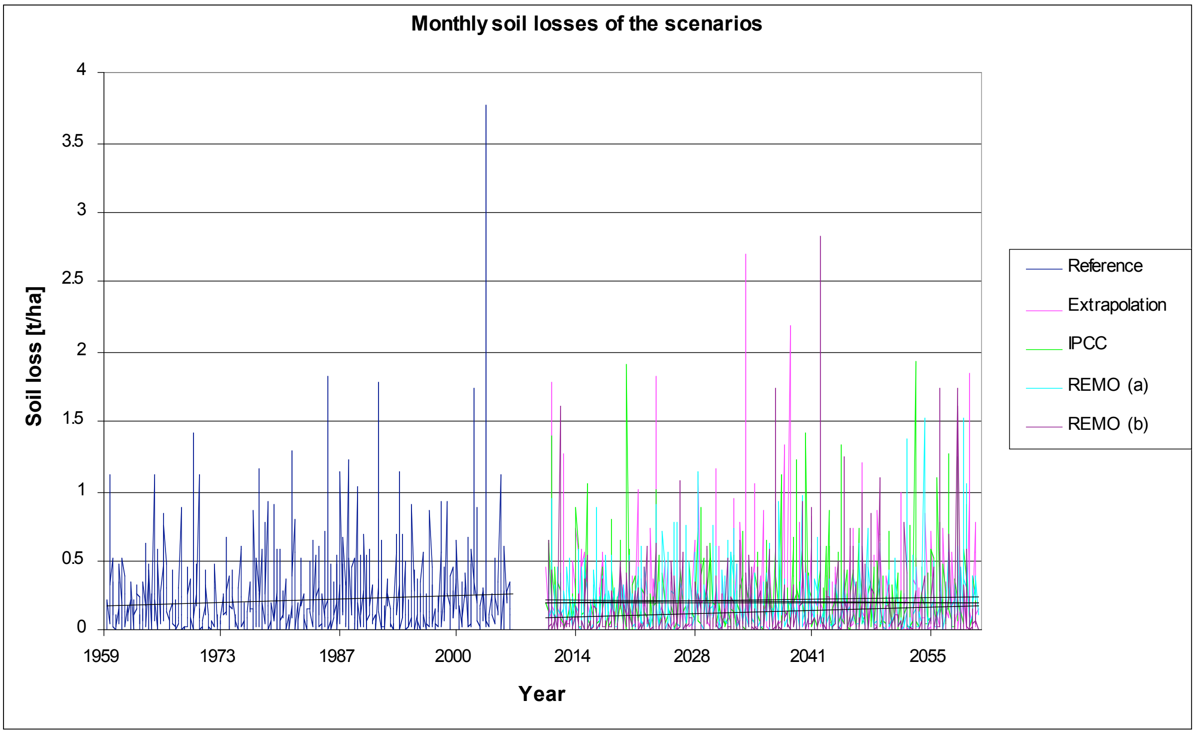

Fig. 3 Monthly soil loss of the scenarios presented in Table 4. (REMO regional (a)

represents the scenario of stochastically rearranged measured data whereas REMO (b) is the model run with the downscaling interface SCALMET).

Table 5 Modelled long-term mean annual soil loss resulting from the scenarios presented in Table 4. (REMO regional (a) represents the scenario of stochastically rearranged measured data, whereas REMO (b) is the model run with the downscaling interface SCALMET).

Scenario	Annual mean (t ha^{-1})
Reference	2.45
IPCC regional	2.62
REMO regional (a)	2.37
Extrapolation	2.41
REMO regional (b)	1.62

Regarding long-term mean annual soil loss, only the scenario “IPCC regional” reaches a higher value, than the reference period. Looking at the linear regressions of the monthly soil loss (drawn in Fig. 3 as black lines), no clear trend is recognisable, apart from the reference period. In order to test these observations, the Mann-Kendall test (Salmi *et al.*, 2002) is applied for each series. For all of the series (including the reference period) the significance is above the 0.10 level against the null hypothesis that there is a trend. As mentioned above, according to the IPCC a possible increase in extreme events in summer might occur in future, supposing higher soil losses in the scenarios. But this clearly does not apply to the scenarios evaluated here. Therefore the 95th percentiles of daily rainfall volumes are examined in order to draw a conclusion on extreme events.

Fig. 4 shows the 95th percentile of each year, based on the daily precipitation sum. The regression lines might imply the existence of trends for all scenarios, but nevertheless the Mann-Kendall test exhibits no significance, except for the extrapolation scenario (0.10 level of significance). Unexpectedly, the uppermost trend line with the highest percentiles in Fig. 4, representing REMO (b), even leads to the lowest soil loss scenario with a mean of only 1.62 t ha^{-1}.

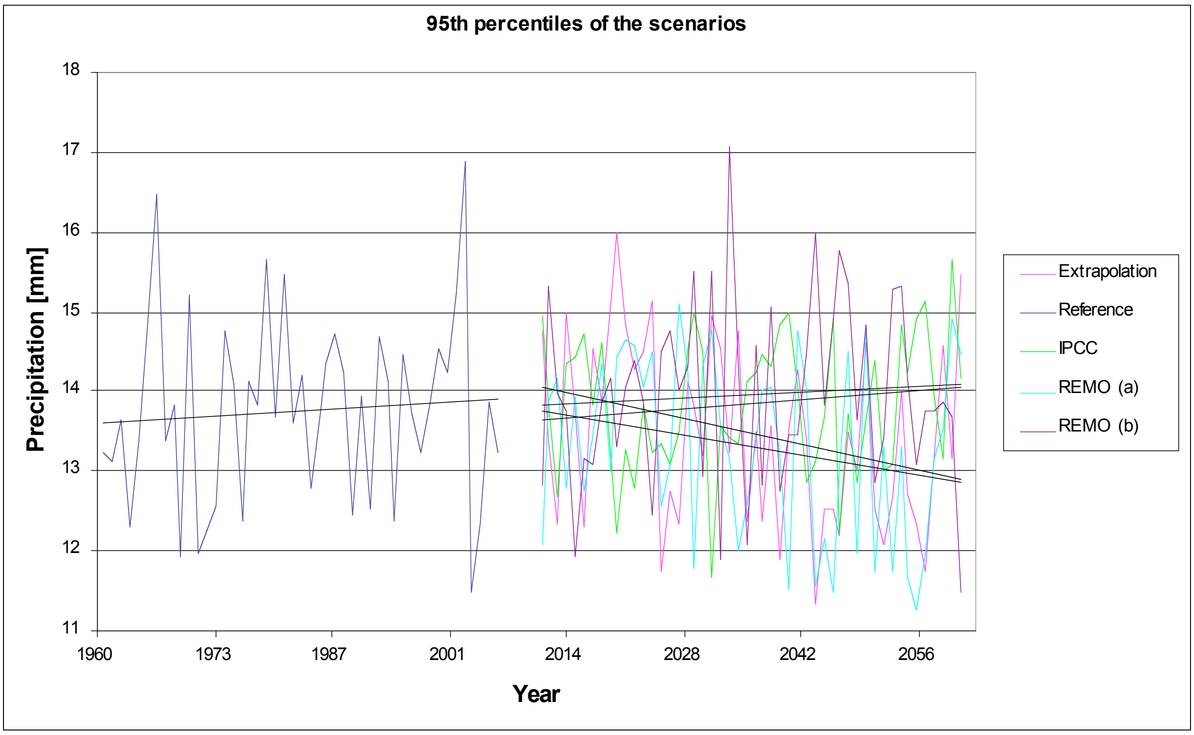

Fig. 4 Annual 95th percentiles of daily precipitation sums.

CONCLUSIONS AND OUTLOOK

The results lead to the conclusion that the regional climate scenarios used for the study (REMO and stochastic climate generator) in the Upper Danube basin show no (significant) trend towards short-term high-rainfall-intensity events, and thus no (significant) trend in soil loss is caused by changed precipitation patterns. Nevertheless, one has to bear in mind, that here only the long-term monthly trends have been analysed over the whole Upper Danube basin, without inspecting seasonal and regional trends. The project KLIWA (Klimaveränderung und Wasserwirtschaft, Climate Change and water resources management) analysed the long-term behaviour of heavy precipitation events in Bavaria from 1900 – 1999 (KLIWA, 2002). Results indicated no significant changes in the summer months. Furthermore land-use change caused by climate change has not been considered in the current model runs. It is very likely that the increasing temperatures and changing rainfall patterns in the future will make land suitable for annual crops, which are not suitable today. This will most likely affect the regions close to the Alps, which are now dimunated by pasture. Therefore, future analyses should focus on land use changes and their impact on erosion as well as on seasonal and region-specific investigations.

ACKNOWLEDGEMENT

The study has been carried out within GLOWA-Danube, which has generously been funded by the German Ministry for Education and Research (BMBF), the Free State of Bavaria and the University of Munich. Provision of meteorological date by the German and Austrian Weather Services as well as runoff, temperature and SSY data by the Bavarian Environmental Agency (LfU) are gratefully acknowledged

REFERENCES

Auerswald, K. & Schmidt, F. (1986). Atlas der Erosionsgefährdung in Bayern. Karten zum flächenhaften Bodenabtrag durch Regen. (Atlas of erosion risk in Bavaria. Maps of areal soil loss by rainfall). GLA-Fachbericht 1, Bayerisches Geologisches Landesamt, Munich.

Auerswald, K., Fiener, P., & Dikau, R. (2009). Rates of sheet and rill erosion in Germany - A meta-analysis. Geomorphology, 111,, pp. 182 – 193.

Barthel, R., Janisch, S., Schwarz, N., Trifkovic, A., Nickel, D., Schulz, C. & Mauser, W. (2008). An integrated modelling framework for simulating regional-scale actor responses to global change in the water domain. Environmental Modelling and Software, 23, pp. 1095 - 1121.

Campbell, G.S. & Norman, J.M. (1998). An Introduction To Environmental Biophysics. Second edn. Springer New York Berlin Heidelberg.

Cheng, N.S. (1997). A simplified settling velocity formula for sediment particle. Journal of Hydraulic Engineering, 123(2), pp. 149 - 152.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A., & Whetton, P. (2007). Regional Climate Projections. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, & H.L. Miller (Eds.) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, chap. 11. Cambridge University Press, Cambridge.

Cunge, J.A. (1969). On the subject of a flood propagation method (Muskingum Method). Journal of Hydraulic Research, 7(2), pp.. 205–230.

Flanagan, D.C. & Nearing, M.A. (1995). USDA-Water Erosion Prediction Project (WEPP) Technical Documentation. Tech. rep., USDA.

Gordon, N.D., Finlayson, B.L., McMahon, T.A., & Gippel, C.J. (2004). Stream hydrology: an introduction for ecologists. John Wiley & Sons.

Gyssels, G., Poesen, J., Bochet, E., & Li, Y. (2005). Impact of plant roots on the resistance of soils to erosion by water: a review. Progress in Physical Geography, 29(2), pp. 189 - 217.

Hank, T. (2008). A Biophysically Based Coupled Model Approach for the Assessment of Canopy Processes under Climate Change Conditions. Ph.D. thesis, Ludwig-Maximilians University, Department of Geography, Munich.

Jacob, D., Göttel, H., Kotlarski, S.,Lorenz, P. & Sieck, K. (2008). Klimaauswirkungen und Anpassung in Deutschland - Phase 1: Erstellung regionaler Klimaszenarien für Deutschland (Climate impacts and adaptation in Germany – pase1: Development of regional climate scenarios for Germany).

KLIWA (2002). Langzeitverhalten von Starkniederschlägen in Bayern und Baden-Württemberg. Project report/summary. Available online at: http://www.kliwa.de/download/A113StarkniederschlaegeInternetArbeitsbericht.pdf. Visited on 13.05.2010.

Kuhn, S., Ernst, A. & Mauser, W. (2009). GLOWA-Danube-Szenarien (GLOWA-Danube-scenarios). In: GLOWA-Danube-Projekt (Ed.), Global Change Atlas, Einzugsgebiet Obere Donau, 1st Edition. Universität München (LMU), Dept. für Geo- und Umweltwissenschaften, Ch. 1.15, ISBN: 978-3-00-026548-8.

Léonard, J. & Richard, G. (2004). Estimation of runo critical shear stress for soil erosion from soil shear strength. Catena, 57, pp.. 233 - 249.

Ludwig, R., Mauser, W., Niemeyer, S., Colgan, A., Stolz, R., Escher-Vetter, H., Kuhn, M., Reichstein, M., Tenhunen, J., Kraus, A., Ludwig, M., Barth, M., Hennicker, R. (2003). Web-based modelling of energy, water and matter fluxes to support decision making in mesoscale catchments - the integrative perspective of GLOWA-Danube. Physics and Chemistry of the Earth 28 (14 - 15), 621 - 634.

Marke, T. (2008). Development and Application of a Model Interface to couple Land Surface Models with Regional Climate Models for Climate Change Risk Assessment in the Upper Danube Watershed. Ph.D. thesis, Ludwig-Maximilians University, Department of Geography, Munich.

Marke, T. & Mauser, W. (2008). SCALMET - A tool for bidirectional coupling of climate models with physically-based simulations of land surface processes. In: A. Borsdorf, J. Stötter, & E. Veulliet (Eds.) Managing Alpine Future Proceedings of the Innsbruck Conference October 15 - 17, 2007. Innsbruck.

Mauser, W. & Schädlich, S. (1998). Modelling the spatial distribution of evapotranspiration using remote sensing data and PROMET. Journal of Hydrology, 212, pp. 250 – 267.

Mauser, W. & Bach, H. (2009). PROMET - Large scale distributed hydrological modelling to study the impact of climate change on the water flows of mountain watersheds. Journal of Hydrology, 376(3 – 4), pp. 362 – 377.

Mauser, W. & Muerth, M. (2008). The Decision Support System DANUBIA. In: A. Borsdorf, J. Stötter, & E. Veulliet (Eds.) Managing Alpine Future Proceedings of the Innsbruck Conference October 15 - 17, 2007. Innsbruck.

Mauser, W., Prasch, M., & Strasser, U. (2006). Physically based Modelling of Climate Change Impact on Snow Cover Dynamics in Alpine Regions using a Stochastic Weather Generator. In: L. Oxley & D. Kulasiri (Eds.) MODSIM 2007 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, pp. 2138 - 2145.

Muerth, M. (2008). A Soil Temperature and Energy Balance Model for Integrated Assessment of Global Change Impacts at the Regional Scale. Ph.D. thesis, Ludwig-Maximilians University, Department of Geography, Munich.

Nash, J.E. & Sutcliffe, I.V. (1970). River flow forecasting through conceptual models part I - A discussion of principles. Journal of Hydrology, 10, pp. 282 - 290.

Olsson, J. (1998). Evaluation of a scaling cascade model for temporal rainfall disaggregation. Hydrology and Earth System Sciences, 2(1), pp. 19 - 30.

PESERA (2009). PESERA: Pan-European Soil Risk Assessment. http://eusoils.jrc.ec.europa.eu/ESDB_Archive/pesera/pesera_download.html. Visited 02.11.2009.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.A., & Yoder, D.C. (1996). Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook 703, USDA-ARS.

Salmi, T., Määttä, A., Anttila, P., Ruoho-Airola, T. & Amnell, T. (2002). Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen's slope estimates Publications on air quality [31]. Finnish Metorological Institute, Publications on air quality 31.

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

Todini, E. (2007). A mass conservative and water storage consistent variable parameter Muskingum-Cunge approach. Hydrology and Earth System Sciences, 11(5), pp. 1645 - 1659.

Vanapalli, S.K., Fredlund, D.G., Pufahl, & W., C.A. (1996). Model for the prediction of shear strength with respect to soil suction.. Canadian Geotechnical Journal, 33, pp. 379 - 392.

von Werner, M. (1995). GIS-orientierte Methoden der digitalen Reliefanalyse zur Modellierung von Bodenerosion in kleinen Einzugsgebieten (GIS-oriented methods of digital terrain analysis for modelling of soil erosion in small catchments). Ph.D. thesis, Freie Universität Berlin.

Waldmann, D. (2010). Large-Scale Process-Oriented Modelling of Soil Erosion By Water in Complex Watersheds. Ph.D. thesis (accepted), Ludwig-Maximilians University, Department of Geography, Munich.

Waldmann, D. & Mauser, W. (2008). Temporal disaggregation of precipitation data for modelling soil erosion in landuse change scenarios. In: Borsdorf, A., Stötter, J., Veulliet, E. (Eds.), Managing Alpine Future Proceedings of the Innsbruck Conference October 15 - 17, 2007. Innsbruck.

Wicks, J. M. & Bathurst, J. C. (1996). Shesed: a physically based, distributed erosion and sediment yield component for the SHE hydrological modelling system. Journal of Hydrology 175, 213 –-238.

Wirsig, A., Krimly, T., Stoll, M., Dabbert, S. (2006). Landwirtschaft (Agriculture). In: GLOWA-Danube-Projekt (Ed.), Global Change Atlas, Einzugsgebiet Obere Donau, 1st Edition. Universität München (LMU), Dept. für Geo- und Umweltwissenschaften, Ch. 1.15, ISBN: 978-3-00-026548-8.