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Does WEPP meet the specificity of soil erosion in steep mountain regions?

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Abstract

We chose the WEPP model (Water Erosion Prediction Project) to describe soil erosion in the Urseren Valley (central Switzerland) as it seems to be one of the most promising models for steep mountain environments. Crucial model parameters were determined in the field (slope, plant species, fractional vegetation cover, initial saturation level), by laboratory analyses (grain size, organic matter) or by the WEPP manual (rill- and interrill erodibility, effective hydraulic conductivity, cation exchange capacity). The quantification of soil erosion was performed on hill slope scale for three different land use types: meadows, pastures with dwarf shrubs and pastures without dwarf shrubs. Erosion rates for the vegetation period were measured with sediment traps between June 2006 and November 2007. Long-term soil erosion rates were estimated by measuring Cs-137 redistribution, deposited after the Chernobyl accident. In addition to the erosion rates, soil moisture and surface flow was additionally measured during the vegetation period in the field and compared to model output. Short-term erosion rates are simulated well whereas long term erosion rates were underestimated by the model. Simulated soil moisture has a parallel development compared to measured data from April onwards but a converse dynamic in early spring (simulated increase and measured decrease in March and April). The discrepancy in soil water during springtime was explained by delayed simulated snow cover melting. The underestimation of simulated long term erosion rates is attributed to alpine processes other than overland flow and splash. Snow gliding processes might dominate erosion processes during winter time. We assume that these differences lead to the general simulated underestimation of erosion rates. Thus, forcing erosion processes which dominate erosion rates in mountainous regions have to be implemented to WEPP for a successful application in the future.

1 Introduction

Soil erosion is a major environmental problem in many parts of the world (Morgan, 1994; Walling and He, 1999; Wischmeier and Smith, 1978). Water-induced soil erosion in alpine regions is greatly influenced by land use and management as well as by climate, extreme topography and soil erodibility (Alewell et al., 2007; Simonato et al., 2002). The term “soil erosion” is used for sheet, rill, interrill and gully erosion as well as for landslides. Surface cover grassland, the land use type of interest in this study, does not have the typical rill and interrill pattern. Rough surfaces occur on the grassland and continuous rills downslope do not usually form. This is a major difference to soil erosion on cropland that typically features rills and interrills due to ploughing. Thus, in this study we focus solely on sheet erosion that is defined as erosion caused by surface water in unconcentrated flow.

Climate change has an enormous effect on the increase of thawing days in alpine regions (Appenzeller et al., 2008). Snowmelt is reported to occur earlier in spring due to rising temperatures (Laternser and Schneebeli, 2003). This indicates a higher amount of precipitation in the form of rainfall and surface flow in winter and spring with potentially increasing soil erosion during times of sparse or no vegetation cover (Fuhrer et al., 2006). From this point of view, it is essential to have a suitable method for the prediction of soil loss under a wide range of changing conditions for alpine regions.

The Water Erosion Prediction Project (WEPP) is a frequently used tool to simulate water erosion and sediment yield. WEPP has been tested and applied in various geographic locations across the United States (Huang et al., 1996; Laflen et al., 2004; Savabi, 1993), in Australia (Yu and Rosewell, 2001) and in Europe (Brazier et al., 2000; Gronsten and Lundekvam, 2006; Pieri et al., 2007; Raclot and Albergel, 2006). However, it has also been shown that on single investigations in the US und UK, the WEPP model performs better on the US plots (Brazier et al., 2000). After Brazier et al. (2000) this might be due to the fact that processes may not be as similar as expected. The application of WEPP in steep alpine environments, has been tested only once in the

Italian Alps by Simonato et al. (2002). The latter study resulted in a relatively good simulation of erosion rates compared to collected field data. However, hydrological parameters were not measured. Hence, the overall quality of the total model output could not be verified. For our study the WEPP model was chosen because it describes separately and in detail plot size, cattle trails, vegetation and fractional vegetation cover, precipitation amount and intensities, land use type and snow processes (snow accumulation and snow ablation). Thus, it covers many processes that are essential for alpine regions.

The objective of this study was to test whether the WEPP model is a suitable tool for soil erosion prediction for high alpine regions with snow influence and steep slopes. To appraise the influence of global warming on soil erosion amounts for changing land use conditions a useful soil erosion model for high alpine regions is urgently needed.

2 Materials and methods

2.1 Investigation area

The study area is located in Central Switzerland (Canton Uri) in the Urseren Valley (Fig. 1). The sub-catchment of the Furka Reuss has an area of about 30 km^2. The elevation of the W-E oriented mountain valley ranges from about 1400 m a.s.l. to about 2500 m a.s.l.

The mean annual rainfall from 1986 to 2008 is 1516 mm, mean air temperature is 3.1°C (Federal Office of Meteorology and Climatology MeteoSwiss, Zürich 2007). The valley is snow-covered from about November to April with the maximum snow height occurring in March (Ambuehl, 1961) and a mean annual snowfall from 1986 to 2008 of 448 mm. Surface water flow is usually dominated by snowmelt from May to June. Important contributions to the flow regime are early autumn floods.

The dominant land use types in the valley are meadow with hay harvesting near the valley bottom, and pasture further upslope. Dominant soils of the catchment classified after WRB, 2006 are podsols, podsocambisols, stagnosols and cambisols partly with stagnic properties. Vegetation shows strong anthropogenic influences due to centuries of pasturing (Kaegi, 1973). For a detailed description of the Urseren Valley see Meusburger and Alewell (2008).

2.2 Experimental plots

The experimental plots are situated at the south-facing slope at an altitude of 1550 to 1800 m a.s.l. (Fig. 1). Three different land use types with three replicates each were investigated. The land use types are meadow (m1, m2, m3), pasture with dwarf shrubs (paw1, paw2, paw3) and pasture without dwarf shrubs (pawo1, pawo2, pawo3). The slopes of all plots were in the range of 35°–39°. Soil textures of all 9 plots are listed in Table 1. The meadow vegetation is dominated by *Trifolium pratense* ssp. Partense, *Festuca* sp., *Thymus serpyllum* and *Agrostis capillaries*. Pasture with dwarf shrubs are dominated by *Calluna vullgaris*, *Vaccinium myrtillus*, *Festuca violacea*, *Agrostis capillaries* and *Thymus serpyllum*. Dominant plant species on pastures without dwarf shrubs are *Glubelaria cordifolia*, *Festuca* sp. and *Thymus serpyllum*.

2.3 Quantification of sheet erosion

2.3.1 Sediment traps

Sediment traps for erosion rate measurements were installed at each plot in July 2006 (Fig. 2). The sediment traps were installed using a geotextile which is fixed to the ground (Fig. 2). The construction was carried out based on Robichaud and Brown (2002). The sediment trap was extended by means of a v-shaped steel plane below the geotextile to concentrate and to measure the surface water flow (Fig. 2c). Material that flushed into the geotextile was taken every second to third week during the vegetation period from April to November. In addition, at one plot for each land use type (m3, pawo2, paw2), precipitation soil moisture and surface flow were measured continuously every 10 min. Precipitation was measured with tipping buckets (ECRN-50 rain gauge, DecagonDevices), soil moisture was measured with a EC-5 sensor, (DecagonDevices) and surface flow with a two-bowl tipping bucket, each bowl having 0.5 liter capacity (EnvironmentalProducts, 2006). Errors of measured soil moisture data are±2% due to laboratory testing. The measurement period of the sediment traps that was compared to WEPP simulations was from 2 April 2007 to 1 November 2007. The surface flow tipping bucket was installed at the outlet of the steel plate (Fig. 2d). All data were logged by means of an Em50 Data Logger (DecagonDevices). We assumed that field measurements with extended sediment traps to measure the surface water flow tends to underestimate the surface water flow. The underestimation is due to small gaps between soil and geotextile at the upslope edge of the sediment trap inlet. Surface flow might therefore partially trickle away. Because this difficulty has been suspected and anticipated, we installed the sediment traps in July 2006 one year before the beginning and comparison of measurements with WEPP simulations. The latter ensured the recovery of the soil edges and regrowth of the grass. Sediment traps are not suitable for winter conditions due to snow damages. For the comparison of the erosion measurements with sediment traps and the output of the WEPP simulations for the vegetation period the plots with included hydrological installations (m3, pawo2, paw2) were taken. This was done in order to identify whether the measured erosion can be compared to simulated erosion rates due to the same triggering processes (hydrology).

2.3.2 Cesium-137

As sediment traps provide information on short-term erosion for single vegetation periods, long-term information for soil erosion of all plots was obtained from Cs-137 measurements in autumn 2007. Cs-137 measurements for the determination of soil erosion rates since the fallout of Cs-137 (depending on the influence of Cs-137 sources for the investigation area) is a common method that was used many times before (Collins et al., 2001; Ritchie and McHenry, 1990; Schaub et al., 2009; Walling and He, 1999;

Zapata, 2003) Measured Cs-137 radiation concentrations in the valley are due to the Chernobyl accident in April 1986. After deposition Cesium-137 is strongly bound to fine particles in the soil. Movement via chemical and biological processes is greatly limited (Ritchie and McHenry, 1990). Redistribution is caused mainly by physical processes, where Cs-137 moves with transported soil particles (Ritchie and McHenry, 1990). We used a NaI scintillation detector for Cs-137 measurement. For the measurement procedure, the gamma spectrometer was placed perpendicular to the ground at a height of 25 cm and measured for 1 h. Boundary conditions, equipment declaration and the entire measuring procedure including error propagation are described in Schaub et al. (2009). A detailed description of the conversion of Cs-137 activities (given in Bq kg^{-1}) to erosion rates in t ha^{-1} a^{1} is given in (Konz et al., 2009). The Cs-137 measurements were carried out using three replicates at each plot. All measured Cs-137 activities refer to 2007. The error of the evaluation of Cs-137 is about 17.3% since the determination of the Cesium-137 peak position in the spectrum is subjective. Small changes in start and end position of the peak leads to a big variability in peak area. This error on peak area was determined by using the mean standard deviation of peak areas of 20 test spectra evaluated by five persons independently. Thus, error on peak area of every single measurement amounts 17.3% (Schaub et al., 2009). In addition to this error on peak area the heterogeneity of Cs-137 amounts at each plot was considered in the final Cs-137 value and thus in the erosion rates. The mean standard deviation due to the heterogeneity is 10.1% where the minimum standard deviation is 1.2% on m1 and the maximum standard deviation is 18.0% for paw2. The third error on Cs-137 based erosion rates is due the heterogeneity of soil porosity at each plot that has an influence on soil erosion amount. The mean standard deviation due to soil porosity is about 15%. A detailed descriptions as well as the discussion of the errors of the Cs-137 based erosion measurements can be found in Konz et al. (2009).

2.4 Description of WEPP

WEPP is a physically based simulation model (Flanagan and Livingston, 1995; Laflen et al., 1991) whose purpose is to describe basic mechanisms controlling erosion by water, including anthropogenic impacts such as irrigation, grazing and ploughing. The hillslope version of WEPP (please note that it differs from the watershed version) contains nine components: weather generator, winter processes, irrigation, surface and subsurface hydrology, plant growth, residue decomposition, soils and erosion. The plot size is variable in the model and can be adapted to our plot size. The determined vegetation as well as variable stocking rates and the cattle trails (variable configuration of slope intersections) can be transcribed by the model. Furthermore, the winter hydrology component is designed to simulate snow accumulation and density, snowmelt, and soil frost and thaw, all on an hourly basis. The snow accumulation routine predicts whether the hourly falling precipitation is rain or snow, as well as changes in snow depth and density. The melt component estimates the amount of snowmelt occurring for any given hour during the day. The frost component estimates the extent of frost development and thawing over the winter period as well as changes in soil water content and infiltration capacity of the soil during the winter period (Savabi et al., 1995).

2.5 WEPP inputs

Four modules of the WEPP model can be modified by the user (delivering input information for the nine components that are described above). These four modules are climate (rainfall amount, duration and intensity of rainfall, wind velocity and direction, temperature, solar radiation and dew point temperature), slope, soil (albedo, initial water saturation, interrill and rill erodibility, critical shear parameter, hydraulic conductivity, cation exchange capacity and organic matter (Table 1) and management. For the climate description, field-observed precipitation, daily temperature, solar radiation and wind (velocity and direction) were used. The meteorological station from which the data were taken is located at the valley bottom (1400 m a.s.l.), whereas the investigation areas are at the south-facing slope (at about 1650 m a.s.l). Hence, temperature at single plots is slightly higher (0–2°C, depending on the sky cover) than at the valley bottom due to the angle of radiation. This difference was measured during 2007 and accounted for an air temperature increase of 1°C.

The soil properties soil texture, cation exchange capacity (CEC) and organic matter content were determined for the first 50 cm (0–10 and 10–50, Table 1) by laboratory measurements. Critical shear stress (τ_c), interrill erodibility (K_i), rill erodibility (K_r) and hydraulic conductivity were calculated based on equations of the WEPP User Summary (Flanagan and Livingston, 1995) depending on grain size analyses that were measured with 10 replicates at each plot (Table 1). An initial water saturation degree was set for all plots at 25% in January 2007, based on soil moisture measurements. As there is no rotation of management type and plant composition in this investigation area, one management type was assigned for each land use type, as well as one composition of plants for the entire period. The surface of grassland does not have the typical rill and interrill pattern due to rough surfaces that is leading to sheet erosion that is defined as erosion caused by surface water flow in unconcentrated flow. This process has been realized by adjusting the random roughness (range management file) to measured values in the field.

For the determination of a reasonable initialisation time, the year 2007 was run 20 times (leap years were considered). The model output is stable after around 5 to 6 years (Fig. 3). We took 10 years for the initialisation time for each run.

2.6 Sensitivity analysis and calibration

We performed a sensitivity analysis in evaluating the relative magnitudes of changes in the model response as a function of relative changes in the values of model input parameters. The input parameters were all changed within a range of±10% of the base case parameter values. This seemed to be a reasonable range that covers the known measurement errors of input data. The model was run with the base case parameter as a base scenario. The sensitivity parameter, S, is given by

$$S = [(O_2 - O_1) / O_{12}] / [(I_2 - I_1) / I_{12}] \quad (1)$$

where I_1 and I_2 are the least and greatest values of input used, respectively. I_{12} is the average of I_1 and I_2. O_1 and O_2 are the output for the two output values, and O_{12} is the average of the two outputs. The parameter S represents a relative normalized change in output to a normalized change in input, which allows a means of comparing sensitivities for input parameters which have different orders of magnitude. Detailed information about sensitivity analyses of the WEPP model are given by Nearing et al. (1990) and Tiscarenolopez et al. (1993). The sensitivity analyze in our study was done in order to appraise whether the parameters have the same sensitivity under steep mountainous conditions compared to the sensitivity analyses by Nearing et al. (1990) for lowland conditions.

For the calibration, there are generally two different ways to proceed. The first way is the automation of the input parameters (e.g. Baginska et al., 2003; Seibert, 2003) with suitable models like PEST (parameter estimation) to estimate parameters until the discrepancies between selected model outputs and a complementary set of measurement output is reduced to a minimum in the weighted least-squares sense. The second way, what we used, is that the calibration is conducted experience based (Konz et al., 2007). Thus, the initial model parameter set was estimated according to measured system characteristics (e.g. soil texture, climate parameter measurements, slope steepness, fractional vegetation cover), available data from literature (e.g. rooting depth) or was derived based on experiences from previous WEPP-applications to other basins (e.g. plant specific parameters).

3 Results and discussion

3.1 Model performance during the vegetation period

3.1.1 Erosion

Monthly measured erosion rates ranged from 0 to 4.4 kg ha^{-1} for meadows (m), from 1 to 68 kg ha^{-1} for pasture without dwarf shrubs (pawo) and from 1 to 11 kg ha^{-1} for pasture with dwarf shrubs (paw). Measured monthly erosion rates for meadows were up to 20 times higher than simulated erosion rates for the according time period, up to 200 times higher during single months on land use type pasture without dwarf shrubs and up to 50 times higher for pasture with dwarf shrubs (Table 2). The reason for this difference might be that whole conglomerations of soil pieces in the sediment traps with diameters up to 30 cm (Fig. 4) were observed regularly during field observations in 2007 mostly on the land use type pasture without dwarf shrubs. These "eroded" soil pieces can not be explained with the classical movement of soil particles trough overland flow and splash erosion but rather trough the steep site, where soil conglomerations are subject to gravity forcing. It can not be exactly determined how much of the eroded sediment in the trap has its origin in the "classical erosion". It was tried to subdivide the soil for weighing. This resulted in a fraction of soil from "classical erosion" of about 5–10% (Table 2). The highest difference of soil erosion amounts can be observed at the land use site pasture without dwarf shrubs. Reasons for this could be the extensive use of rangeland. Cattle destroy the soil matrix and amplify therefore the exposition to the formation of soil conglomerations. While meadows seem to be generally less susceptible than pastures to sheet erosion, dwarf shrubs obviously reduce sediment transport in the pastures. The latter is most likely due to the hindering effect of dwarf shrubs on the transport of soil particles over larger expanses, that has been shown with Cs-137 measurements in a previous publication (Konz et al., 2009).

Since the measured values of erosion rates are exceedingly low for "the classical erosion" (without conglomerations due to gravity forcing) such as 0.4 kg ha^{-1} for meadows in May (Table 2) the model simulates erosion rates in the same order of magnitude. Generally, low erosion values are very hard to predict with accuracy (Nearing, 1998).

Results of the sensitivity analysis are listed in the Appendix, Tables A1, A2, and A3. If the parameter is not sensitive (definition of S is listed and explained in Sect. 2.6 and Eq. 1) S is 0. The more sensitive the input parameter is the higher absolute value of S is reached. The highest S is reached for the input parameters radiation, wind velocity, minimum daily temperature, dew point temperature, peak rainfall intensity, daily precipitation and effective hydraulic conductivity. Nearing et al. (1990) reported the most dominant factors related to model response as precipitation, effective hydraulic conductivity, rill cover and rill erodibility. These results are mostly concordant with our results. However, peak rainfall intensity and sediment characteristics are not sensitive according to Nearing et al. (1990). This cannot be confirmed by our results. Other parameters like radiation have a major impact on processes like snow accumulation and melting. These parameters are also quite sensitive (Table A3) in alpine regions as shown in our analysis. Besides the sensitive parameters reported in earlier studies, specific parameters describing steep alpine environments such as slope and radiation are very sensitive and should be carefully determined for WEPP applications in alpine regions.

3.1.2 Hydrology

The hydrology (overland flow and soil moisture content) is simulated quite well during the vegetation period from April to October 2007 (Figs. 5 and 6). Simulated overland flow compares well with the measurements conducted overland flow seesaw for all land use types. By the way of example we discuss simulation results and measurements of the land use type meadow (Fig. 5). Slight overestimations of overland flow occur in May, June and August. The sediment traps with its equipment for overland flow measurement tends to underestimate the surface flow (see Sect. 2.3.1). Thus, the simulation bias falls within the expected error of the observed flow rates.

Interestingly, in July, September and October surface flow is observed but not simulated.

If field capacity of the soil is not exceeded water can infiltrate and form the soil moisture content. The dynamic of the observed soil moisture is reproduced well for all land use types (Fig. 6) from the end of April onwards and even very specific patterns of the soil moisture dynamics are simulated well for the land use type pasture without dwarf shrubs (pawo). Underestimation of about 5% during summer time can be observed for the land use types pasture with dwarf shrubs (paw) and meadows (m). Here again, the dynamics are reproduced satisfactory but the shift can be observed through out the entire vegetation period. A possible reason could be the overestimation of evapotranspiration with values of about 2.4 mm day^{-1} (maximum standard deviation±100%) for meadows and 3.2 mm day^{-1} for dwarf shrubs (maximum standard deviation±58%). Fecht et al. (2005) provided values of about 1.7 mm day^{-1} (maximum standard deviation±50%) for meadows and 2.8 mm day^{-1} (maximum standard deviation±45%) for dwarf shrubs. Significant discrepancies between measurements and observations of soil moisture both in terms of dynamics and absolute values can be observed in the end of March and beginning of April. Measurements and simulations show contradictory patterns with increasing simulated soil moisture and decreasing measured soil moisture (Fig. 6). Melting snow cover producing significant amounts of melt water dominates the hydrological processes of this period. Therefore, an accurate simulation of snow pack dynamics is crucial in alpine catchments. A detailed analyzes of the simulation performance of the snow accumulation and ablation processes was conducted based on snow measurements of the station at the valley bottom. Direct measurements at the investigation slopes were not possible due to the danger of avalanches. Figure 7a shows measured precipitation data in mm water column and if precipitation fell as snow, it is marked by grey shading. Figure 7b compares the measured snow depth at the valley bottom with the simulated snow depth of the land use type pasture with dwarf shrubs (paw2) because this investigation pot lies in the closest vicinity to the meteorological station. The observed snow depth was continuously declining from mid March to beginning of April and the entire snow pack vanished in the beginning of April (Fig. 7b). The simulation results show a similar decline of the snow pack with a delay of two weeks until total snow melt is over. Please note that the slopes are south exposed and should therefore become snow free even earlier than the valley bottom. The delayed melting creates additional water feeding the soil moisture content and therefore creates the continuous increase in soil moisture in all three land use types till mid April. Since the bias in soil moisture of simulation during March and April depends on the wrong snow accumulation and ablation process simulation, a detailed analysis with comparison of measured and simulated snow depth at the same site is necessary.

For that reason, the WEPP model was applied to an additional site were meteorological data were available as well as snow measurements. The meteorological station provides snow depth, and all required climatic input data at an altitude of 1980 m a.s.l. With this simulation it is exclusively intended to evaluate the performance of the winter routine. Please note that at this site no erosion data are available. The output of the winter routine for this additional investigation site is given in Fig. 8. The measured and simulated snow depth is in an acceptable agreement during the winter season till the beginning of April (Fig. 8). However, from April onwards it is significantly overestimated. Snow depth simulations are generally prone to uncertainty in density estimation and the water column of snow should be compared to measurements. Those data are not available and we therefore tend to show the snow depth data in order to assess the model performance. However, the WEPP model simulates melt water production only if the maximum snow density of 350 kg m^{-3} is exceeded. Therefore, we consider the snow depth data as useful proxy to evaluate the winter routine. WEPP strongly overestimates the duration of the snow ablation period and snow free conditions are delayed by one month. This causes additional melt water production and therefore overestimates the water availability in spring and early summer.

3.2 Long-term modeling

Mean annual erosion rates of WEPP outputs since 1986 were compared with Cs-137-based erosion data (Fig. 9). Simulated erosion rates of all 9 investigated plots were underestimated in comparison to Cs-137-based erosion rate data. A possible explanation for the observed deviations between simulated and measured erosion rates are snow processes during winter time that occur in the Urseren Valley but are not implemented in the model. From field observations it is known that upper soil layers are affected by erosion during winter and early spring time when snow movement and melting takes place (Fig. 10). However, the winter routine of the WEPP model consists of the snowmelt subroutine and a snow density calculation part, were snow depth and melting is calculated. The comparison of simulated snow accumulation and ablation is described in Sect. 3.1.2. Specific alpine processes like snow gliding, snowdrift and avalanches are not considered by the model and could thus lead to the described differences in the outputs. However, the comparison of simulated erosion rates during all vegetation periods (April till October) from 1986 to 2007 with simulated erosion rates including the whole years from 1986 to 2007 (Table 3) demonstrates that simulated erosion rates are also 30 (land use type m and paw) to 500 times (pawo) higher during winter time than during the vegetation period. These increased erosion rates during winter time (November till March) might result from erosion due to overland flow where vegetation is reduced and thus soil protection is lower. Generally, we found that the erosion during winter time dominates the high amounts of erosion rates that were measured due to Cs-137 method. Since the highest erosion rates were measured on slopes that are reported to have a quite high avalanche risk during winter time (m1, pawo3 and m3) it might be possible that those processes are dominant for high erosion rates. However, the influence of snow during winter time has to be investigated in detail in the future to give a clear statement of dominant processes that trigger high erosion rates in steep mountainous areas.

Long term evapotranspiration for the Urseren Valley are 552.7 mm per year from 1973 till 1992 (HADES, 2007), which is comparable to a mean value of 568.7 mm of the WEPP simulation for the same time period for all investigation plots. This indicates that WEPP is able to predict long term evapotranspiration in a reliable order of magnitude. However, the uncertainty due to the proportion of different land use types in the valley is not considered within the WEPP simulations.

4 Conclusions

This WEPP application was the first comparison between high temporal resolute field installations (erosion, soil moisture, and surface flow measurements) and WEPP simulations in subalpine areas. The study was done in the framework of seeking adequate methods for the prediction of erosion under different grassland conditions in alpine systems. We distinguished between short-term erosion prediction for a single vegetation period, compared to sediment trap data and long-term erosion prediction, compared to Cs-137 data for nine investigation plots.

Because of the uncertainties of simulated winter processes, including snow height and development, temporal snowmelt and water amount distribution, we conclude that WEPP is not a useful tool for alpine regions where winter processes seem to have a great influence on the water balance and erosion processes. WEPP underestimated erosion rates for the long time period from 1986 till 2007 by a factor of 10 to 100. Though erosion rates of the vegetation period turned out to account little to the entire erosion rates of the whole year, the model was able to simulate the erosion rates during the vegetation period in a comparable order of magnitude. Simulated soil moisture and overland flow during the vegetation period was simulated well as well. Therefore, special alpine processes have to be investigated as it is not yet clear what processes are triggering those hight erosion rates and implemented to the WEPP model in order to provide simulation of erosion under changing land use and climate conditions. Generally, the comparison of WEPP simulations with our measurements (sediment traps as well as Cs-137) improved the understanding of Alpine erosion processes. Winter processes seems to be important drivers of alpine erosion. Thus, WEPP might be a useful tool to differentiate between confounding factors of erosion in alpine systems.

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Table 1.

a. Soil parameter for the three investigated meadows (grain size analyses are given in % weight of fine-grained soil <2000 μm). The maximum standard deviation is 10% for grain size analyses, 9.5% for organic matter, 4.8% for pH-value, 5% for fractional vegetation cover and 4.5% for slope steepness (for all three Tables 1a, b and c).

	m1		m2		m3	
depth [m]	0–0.1	0.1–0.5	0–0.1	0.1–0.5	0–0.1	0.1–0.5
sand (63–2000 μm) [%]	31.9	3.1	23.8	22.1	37.2	34.1
silt (2–63 μm) [%]	42.3	3 9.8	45.5	4 3.9	41.4	33.6
clay (<2 μm) [%]	13.7	16.1	1 5.3	13.8	16	12.6
organic matter [%]	12.9	6.7	12.2	6.1	12.8	6.4
pH-value	5.0	na	4.4	na	4.5	na
fractional veg. cover [%]	92		95		90	
slope [°]	39		36		39	

b. Soil parameter for the three investigated pastures without dwarf shrubs.

	pawo1		pawo2		pawo3	
depth [m]	0–0.1	0.1–0.5	0–0.1	0.1–0.5	0–0.1	0.1–0.5
sand (63–2000 μm) [%]	24.6	24.3	25.2	22.1	27.4	28.2
silt (2–63 μm) [%]	38.2	37.8	32.4	34.6	30.1	31.4
clay (<2 μm) [%]	12.1	14.6	11.3	11.8	10.9	11.2
organic matter [%]	12.6	6.3	12.8	6.4	12.2	6.1
pH-value of soil	17.1	na	7.3	na	4.6	na
fractional veg. cover [%]	65		62		67	
slope [°]	38		8		35	

c. Soil parameter for the three investigated pastures with dwarf shrubs (paw).

	paw1		paw2		paw3	
depth [m]	0–0.1	0.1–0.5	0–0.1	0.1–0.5	0–0.1	0.1–0.5
sand (63–2000 μm) [%]	23.1	27.0	22.6	25.9	28.6	31.5
silt (2–63 μm) [%]	52.3	49.8	55.7	47.9	49.3	52.2
clay (<2 μm) [%]	8.7	8.5	9.5	7.6	11.2	10.1
organic matter [%]	11.9	6.1	11.9	6.0	12.2	6.1
pH-value of soil	4.3	na	4.4	na	4.5	na
fractional veg. cover [%]	77		73		79	
slope [°]	38		38		35	

na=not available

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Table 2. Monthly measured (meas.) and WEPP-simulated (simul.) erosion rates (kg ha-1) for the vegetation period April to November 2007 for the investigated three land use classes meadow, pasture without dwarf shrubs and pasture with dwarf shrubs. About 90% of all measured erosion rates is caused by gravity forcing. Erosion values that are assumed to result from "classical erosion rates" (overland flow and splash erosion) are given in brackets behind the erosion values. For pawo it is assumed to be even more than 95%.

	land use type					
	m3		pawo2		paw2	
	meas.	simul.	meas.	simul.	meas.	simul.
April	0(0)	0	39(<1.9)	0	1(0.1)	0
May	4.4(0.4)	0.2	44(<2.2)	0.3	8(0.8)	0.2
June	1.3(0.1)	0.1	22(<1.1)	0.2	5(0.5)	0.1
July	0.5(0.05)	0	68(<3.4)	0	11(1.1)	0
August	1(0.1)	0	62(<3.1)	0.3	3(0.3)	0
September	0(0)	0	2(<0.1)	0.1	3(0.3)	0
October	0(0)	0	1(<0.05)	0	1(0.1)	0

Table 3. Comparison of simulated erosion rates 1986–2007 during the vegetation periods (April–October) and simulated erosion rates including the whole year (January–December) from 1986–2007. Erosion rates are given in $\mathrm{t\,ha^{-1}}$.

	land use type					
	m3		pawo2		paw2	
	vegetation period	complete period	vegetation period	complete period	vegetation period	complete period
1986–2007	0.005	0.154	0.04	20.9	0.14	4.4

Table A1. Sensitivity analyses with±10% of parameter for initial range management of pasture without dwarf shrubs.

parameter	units	[1]base case parameter value	sensitivity of mean annual erosion (S)
initial frost depth	m	0.1	0.00
average rainfall during growing season	m	0.885	0.00
initial residue mass above the ground	kg m×$^{-2}$	0.1	0.12
initial residue mass on the ground	kg m×$^{-2}$	0.05	0.02
random roughness	m	0.2	–5.25
initial snow depth	m	0.3	0.00
depth of secondary tillage layer	m	0.1	0.00
depth of primary tillage layer	m	0.2	0.00
interrill litter surface cover	0–1	0.1	0.95
interrill basal surface cover	0–1	0.6	0
rill litter surface cover	0–1	0.1	–0.97
rill basal surface cover	0–1	0.6	–0.43
total canopy cover	0–1	0.6	–5.19

[1] The definition of base case is explained in Sect. 2.5 and 2.6.

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Table A2. Sensitivity analyses with±10% of parameter for range management of pasture without dwarf shrubs.

parameter	units	[1]base case parameter value	sensitivity of mean annual erosion (S)
change in surface residue mass	–	0.5	3.34
coeff. leaf area index	–	2	3.36
change in root mass coeff.	–	1	0.00
parameter value for canopy height	–	2	0
c:n ratio of residue and roots	–	29	–3.34
standing biomass	$kg \times m^{-2}$	1	0
frostfree period	integer	191	–0.02
projected plant area coeff. for grasses	–	0.5	0.00
average canopy diameter for grasses	m	0.1	0.00
average height for grasses	m	0.25	0.00
number of grasses along a 100 m transect	integer	1000	0.00
minimum temp. to initiate growth	°C	5	5.02
max live biomass	$kg \times m^{-2}$	0.6	–0.13
plant drought tolerance factor	0–1	0.1	0.00
minimum amount of biomass	$kg \times m^{-2}$	0.3	3.255
root biomass in top 10 cm	$kg \times m^{-2}$	0.1	0.00
fraction of live and dead roots	–	0.2	0.00
minimum temp. to initiate senescence	°C	–15	0.00

[1] The definition of base case is explained in Sect. 2.5 and 2.6.

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Table A3. Sensitivity analyses with±10% of parameter for soil (*)and climate (**) of pasture without dwarf shrubs. Changes of the output lower than 1% are defined as slight, changes in the output between 1 and 50% are defined as moderate and changes higher than 50% of the base case scenario is defined as high.

parameter	units	[1]base case parameter value	sensitivity of mean annual erosion (S)
initial saturation level*	%	20	0.00
interrill erodibility*	$\mathrm{kg\times s\times m^{-4}}$	4379760	0.00
rill erodibility*	$\mathrm{m\times s^{-1}}$	0.0506	0.69
critical shear*	Pa	3.2372	−1.95
eff. hydr. conductivity*	$\mathrm{mm\times h^{-1}}$	3.8989	−5.01
sand*	%	25.2	−1.52
clay*	%	16.4	−3.39
organic matter*	%	12.8	0.00
CEC*	meq×100 g−1	14	0.00
daily precipitation** (mean daily value)	mm	3.5	4.99
precipitation duration**	h	0.5	−3.65
time to peak intensity**	–	0.25	2.90
peak rainfall intensity**	–	3	−5.02
maximum daily temperature**	°C	4.5	0.00
minimum daily temperature**	°C	−1.6	−5.00
radiation**	$\mathrm{l\times d^{-1}}$	170	4.96
wind velocity**	$\mathrm{m\times s^{-1}}$	6	4.90
wind direction**	deg	100	0.00
dew point temperature**	°C	−2.3	−4.90
slope angle**	°	42	3.18
grazing	cow/ha	10	0.00

[1] The definition of base case is explained in Sect. 2.5 and 2.6.

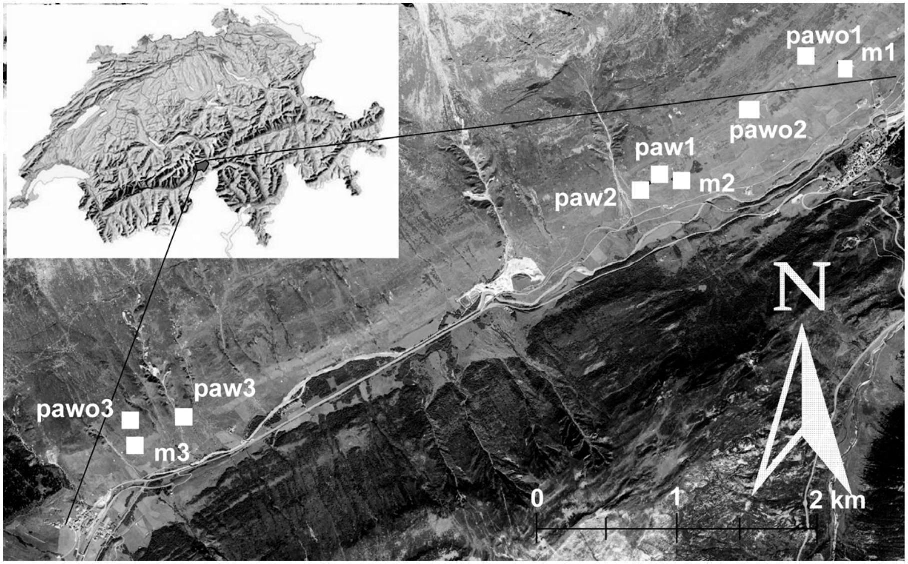

Fig. 1. The Urseren Valley in central Switzerland and location of the investigation sites with three land use types: meadow (m), pasture without dwarf shrubs (pawo) and pasture with dwarf shrubs (paw).

Fig. 2. **(a, b)** Sediment trap after Robichaud et al. (2002) and **(c)** extended version under construction in the Urseren Valley (2006) with a steel plate to concentrate the surface flow. The steel plate was finally attached to the upper boundary of the filled trench where the geotextile gets out of the trench. **(d)** Completed sediment trap for erosion measurement at land use type meadow (m3).

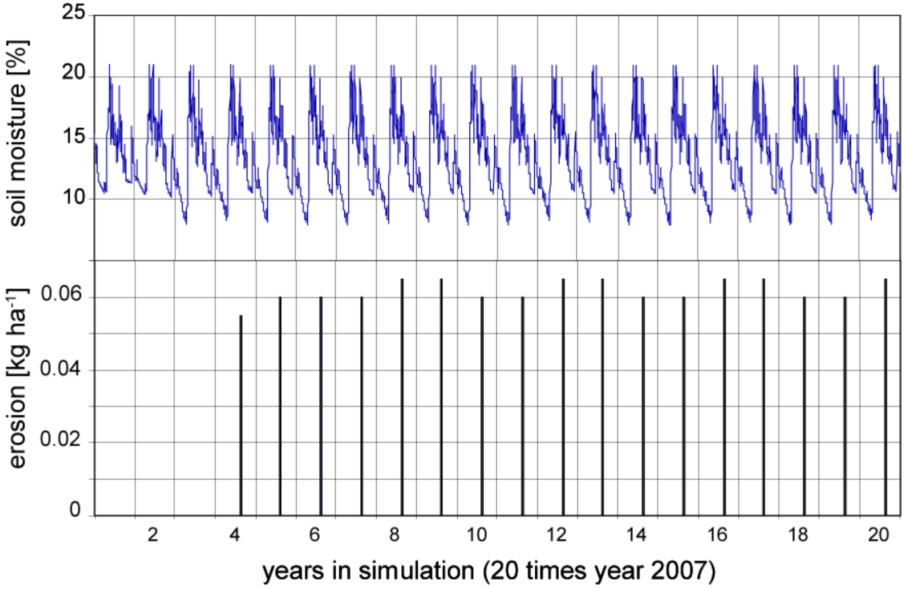

Fig. 3. Initialization of the WEPP model for the land use type meadow for 20 times 2007. The same year was taken 20 times instead of a time series in order to identify the stabilization of the water amount and erosion processes independent of the variability of water amount from precipitation.

Fig. 4. Soil erosion during the vegetation period 2007. Large pieces of soil were collected in the sediment traps ranging from 1 to 30 cm.

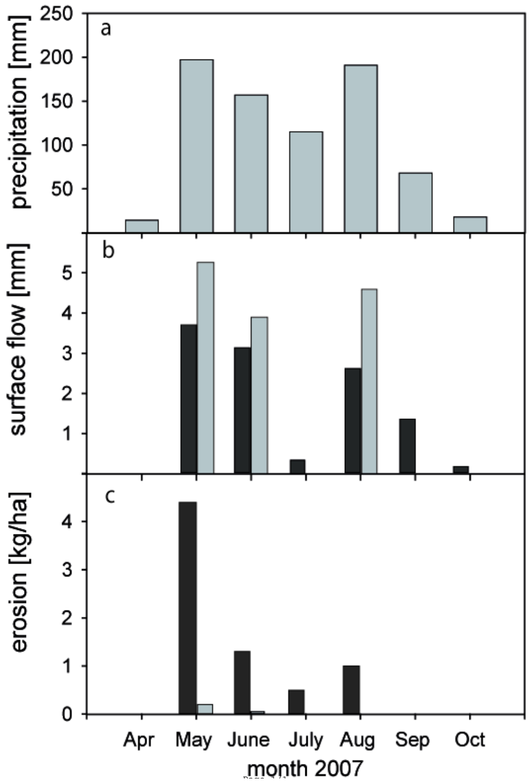

Fig. 5. Measured monthly precipitation **(a)** with measured (black) and WEPP-simulated (grey) surface flow **(b)** for meadow m3 and measured (black) as well as simulated (grey) erosion rates **(c)** from April to November 2007.

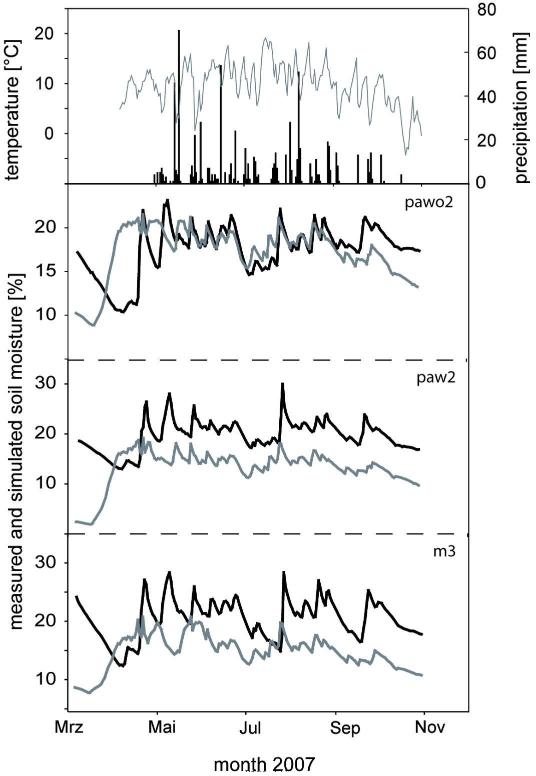

Fig. 6. Measured daily precipitation (black) and mean air temperature (upper figure), measured (black) and WEPP-simulated (grey) soil water content for April to November 2007 for all three land use types pasture without dwarf shrubs, pasture with dwarf shrubs and meadow for the first 35 cm.

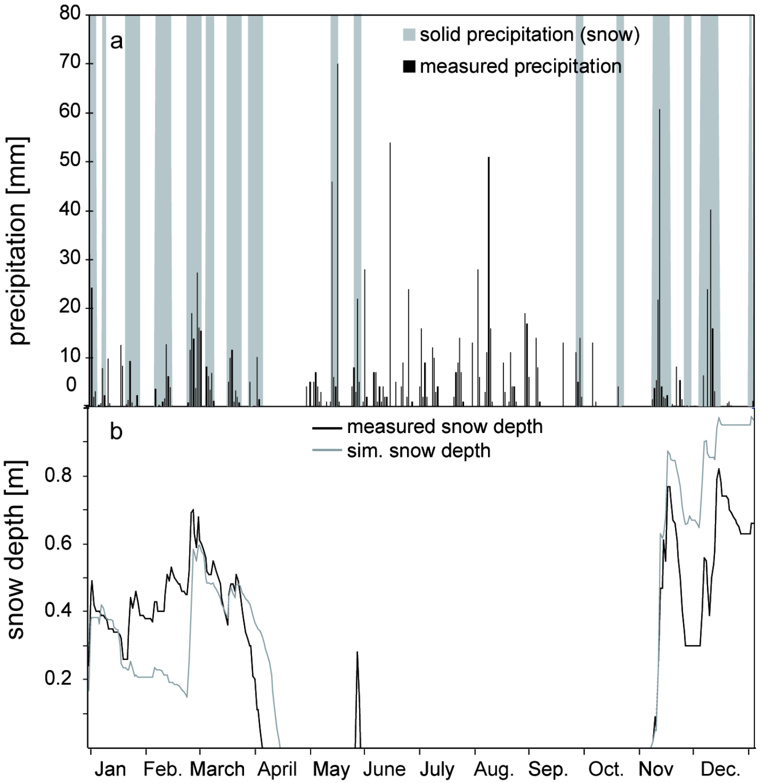

Fig. 7. Verifying the accumulation and ablation of the WEPP model: **(a)** Total precipitation with the proportion of snow fall (grey background), **(b)** measured and simulated snow in depth the Urseren Valley.

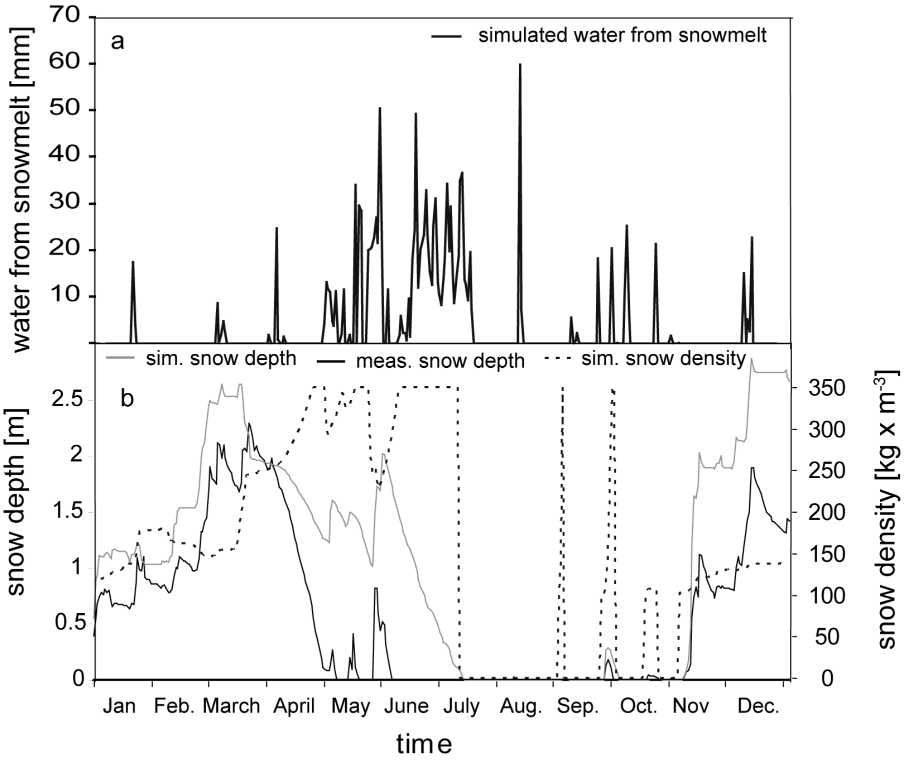

Fig. 8. Simulated water from snowmelt **(a)** and simulated and measured snow depth comparison **(b)** in the Urseren Valley at a meteorological measuring station above the investigation sites with an elevation of 1980 m a.s.l. If the snow density of 350 kg m^{-3} is reached water from snowmelt can be produced by the model.

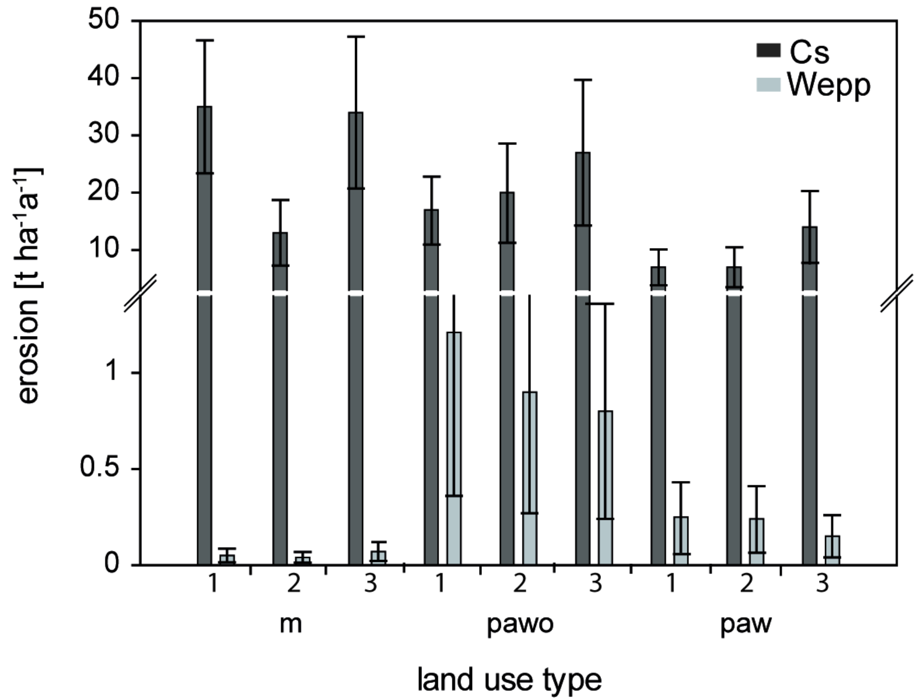

Fig. 9. Mean annual erosion rates of WEPP simulation compared to Cs-137-based erosion rates of all investigation plots for the period 1986–2007. Cs-137 error bars are due to manually analysis of gamma spectra (17%), the heterogeneity of each single plot (n=3; mean standard deviation 10.1%) and uncertainty of soil porosity. WEPP errors are due to the consideration of maximum standard deviations of measured input parameters.

Fig. 10. Investigation site m1 after winter time. This picture gives an impression of the possible influence of snow and "snow gliding" processes during winter time on erosion processes.