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Adjustment of a weather generator to represent actual rain erosivity in the northern Black Forest – Germany

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ABSTRACT

To estimate the impact of highly erosive precipitation on existing and planned forest infrastructure we deem the Forest Service WEPP Interfaces, based on the Water Erosion Prediction Project (WEPP), feasible.

As a first step towards testing WEPP and especially the implemented weather generator CLIGEN for conditions in Germany we evaluated the application of CLIGEN to calculate rain erosivities from generated time series. CLIGEN parameters were taken from time series of up to 17 years with 10-minute resolution from three sites in the Northern Black Forest, southwestern Germany. We assessed a rain kinetic energy function for this region from field measurements with a laser disdrometer to compare CLIGEN performance using the local function to using common kinetic energy functions.

We showed that running CLIGEN with unaltered input parameters is not suitable to model climatic conditions and erosivity indices in the Northern Black Forest. R-factors from unaltered model runs deviated extremely from observed R-factors, resulting in just one third of observed values. Model performance and parameter uncertainties do not benefit much from the use of a site specific kinetic energy function. Differences in model errors and sensitivities compared to a well-established kinetic energy function remain negligible. However, model output was improved by empirical calibration of input data. Virtual best parameter sets for best model results could be identified.

To reproduce observed rain erosivities the input parameters of CLIGEN have to be manipulated to model a precipitation regime where daily precipitation amounts and maximum precipitation intensities are higher at a lower number of rainy days.

We also identified the input parameters to which the model is most sensitive to when manipulated, i.e. precipitation amount and frequency, and maximum peak precipitation. These parameters are especially important when implementing future climate change scenarios.

1. Introduction

Soil erosion in forest ecosystems is a problem rarely discussed in European Forestry (Borelli et al., 2016). It is assumed that stable forest ecosystems are not prone to soil loss. Also rain erosivities are low and practices promoting erosion like clear cuttings are rare. However, studies from North America under soil, vegetation and management conditions comparable to Western and Central Europe have shown that up to 90% of sediment delivered from forested watersheds derive from logging infrastructure (Grace III, 2003).

Under the perspective of a changing global climate an increase in extreme weather phenomena is expected. For instance, in Southwestern Germany the occurrence of heavy rain storm events in the winter half-year where logging operations usually take place increased by 5% to 40% in the period from 1931 to 2005 (KLIWA, 2008). To estimate the impact of highly erosive precipitation on existing and planned forest infrastructure several equations and models are available.

As an approach to forest related erosion scenarios we deem the Forest Service WEPP Interfaces (Elliot et al., 2000) most feasible. The interfaces are based on the Water Erosion Prediction Project (WEPP, Flanagan and Nearing, 1995), developed in the United States, and facilitate the application of WEPP to forest specific problems like erosion from forest roads or disturbed forests. Forest practices and soil properties in North America can be considered at least in parts comparable to those in Central Europe. Hence it would be desirable to make the FS WEPP technology available to forest specialists here.

To provide WEPP with the necessary climate input data the model is shipped with the built-in stochastic weather generator CLIGEN (Nicks et al., 1995). CLIGEN produces time series of daily values of precipitation patterns, temperature, radiation, wind, and dew point

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temperature. The weather generator can be driven with climate files containing parameters which all but one describe the annual distribution of that parameter on a monthly basis. Future climate scenarios and their impact on soil erosion only evolve to their full potential after a certain period. It is necessary to have a model that can supply weather data of desired length, e.g. several decades or centuries, of which CLIGEN is capable.

While the WEPP model has experienced global acceptance and was subject to many studies CLIGEN has been tested only in few applications outside of the US. Among those are studies from Australia (Yu and Rosewell, 2001; Yu et al., 2000), Brazil (Favis-Mortlock and Guerra, 1999; De Maria et al., 2001), the UK (Favis-Mortlock, 1994; Brazier et al., 2001), Korea (Kim et al., 2009), and Taiwan (Fan et al., 2013). Even if these studies consider local CLIGEN performance as sufficient, we were not satisfied with our findings when beginning the work for this study and those of other studies from Germany (Al-Mukhtar et al., 2014).

Three basic assumptions underlay CLIGEN: (1) on a day where precipitation occurs there is only one storm with a maximum duration of 24 h, (2) this storm has a single peak pattern, and (3) the storm can be described by a double exponential function. This simplified representation of internal storm patterns is a limitation to CLIGEN. Storms generated by CLIGEN are described by 4 daily parameters: precipitation amount, storm duration, peak intensity and the time to peak intensity. WEPP uses these 4 parameters to disaggregate storms into more complex patterns via a double exponential function. For single day events with one single peak this representation may be sufficient. But the complexity of events with multiple peaks or durations > 24 h is underrepresented. Climatic regions like the Black Forest have a certain percentage of relatively uniform and extensive precipitation events, in some cases lasting over more than one week. Due to large cumulated precipitation quantities and temporary saturation of soil pores (Morgan, 2005) these events might still generate surface runoff and become erosive. For those situations the simplified representation in CLIGEN might not suffice.

Yu (2002) presented a method focusing on modeling daily rain erosivity expressed as EI_{30}-values of the Revised Universal Soil Loss Equation (RUSLE, Renard et al., 1997) from daily CLIGEN precipitation output. The author derives a double exponential function for each day by using the generated parameters for precipitation amount, duration of a storm, peak intensity and the time from the beginning of a storm to its peak. This double exponential function is identical to the one used in the WEPP model itself to depict daily rainfall patterns. EI_{30}-values are then calculated by integrating the unit energy function from RUSLE over the double exponential storm pattern. In this study we apply this method as a first step towards evaluation of CLIGEN performance for the Northern Black Forest, possibly making CLIGEN and hence FS WEPP available in the future to application in this region. Furthermore, EI_{30}-values can form the basis to RUSLE itself, a model which also might produce satisfactory results for easy assessable topographic conditions like forest roads. Maps of EI_{30}-values, or the closely related R-factor, are readily available in Germany (Sauerborn, 1994). According to those maps erosivity in Germany, expressed as RUSLE R-factor, rarely exceeds 1500 MJ mm ha^{-1} h^{-1} yr^{-1} and is usually well below (compare Fig. 1). These comparably low values are a consequence of rather low precipitation intensities in extensive rain events with low mean precipitation intensities, which are typical for the climate. Arguably the R-factor might be unsuitable for those climatic conditions and there is doubt if functions from (R)USLE established in the United States are valid for climatic conditions at differing locales (Kinnell, 1980; McIsaac, 1990). For example antecedent soil moisture indices might locally be better predictors to describe imminent soil erosion events. Still, in this study we decided to include EI_{30} in our method for two major reasons: Firstly, this erosivity index is, despite its possible limitations, widely accepted by public authorities and professionals in Germany as a tool to assess erosion risks in agriculture, and is taught in both academic and job training contexts. To further address those doubts we want to evaluate, if a local function for the Black Forest is needed. Secondly, the index is mathematically well defined and hence a sound target function for comparison and benchmarking of the performance of a weather generator.

The main focus of this study is to present a framework to evaluate the potential of CLIGEN application as part of erosion prediction concepts in Central Europe with the help of the method proposed by Yu (2002). In this we attempt to clarify the following questions:

1. Is CLIGEN suitable to model climatic conditions and erosivity indices in the Northern Black Forest?
2. Is it necessary to find and apply a local rain kinetic energy function instead of standard functions from differing climates, and does this improve the method of Yu (2002)?
3. How sensitive is each input parameter to empirical manipulation and how do sensitivities affect e.g. implementation of future climates?
4. Can model output be improved by limited empirical manipulation of input data?

In this study we addressed the suitability of CLIGEN to model climatic conditions and erosivity indices in the Northern Black Forest by applying the method proposed by Yu (2002) to data from 3 sites in the region. Then we compared model output to erosivity indices directly derived from pluviograph data. To evaluate the necessity and possible benefits of a local rain kinetic energy function the indices were calculated using common kinetic energy functions and a local function which was established from rain kinetic energy measurements from a field campaign. To evaluate the sensitivities of CLIGEN input parameters the parameter sets of the 3 sites were stochastically varied and the output of model runs driven by the derived parameter sets were benchmarked against observations with two goodness of fit (GOF) parameters. To address the question if model output can be improved by empirical manipulation only those model runs were evaluated where modeled mean annual precipitation did not pass a threshold of 5% deviation from observed annual precipitation. From these runs sets of virtual best parameters were established which might be used as a workaround to obtain better estimates of erosivity using CLIGEN.

2. CLIGEN functionality and history

The development of CLIGEN is rooted in weather generators used in the EPIC (Erosion-Productivity Impact Calculator, Williams et al., 1984) and SWRRB (Simulator for Water Resources in Rural Basins, Arnold et al., 1990) models. The model version used in this study is CLIGEN v5.3 (Meyer et al., 2002; Zhang and Garbrecht, 2003; Meyer et al., 2008). The algorithms used in CLIGEN are provided in great detail in the aforementioned studies and the documentation of older model versions (Nicks et al., 1995).

Rain-related input parameters to CLIGEN are provided in a parameter file which consists of monthly values for mean, standard deviation and skewness coefficient of rain amount on a day where precipitation occurs, the monthly mean maximum 30-minute rainfall intensity, and the probabilities of a wet day following a wet day and a wet day following a dry day. Also represented by 12 values is an empirical cumulative distribution of the time to peak ratio, i.e. CLIGEN assumes that time to peak does not vary seasonally and so the distribution applies to the entire year.

Precipitation occurrence is modeled based on a first-order, two-state Markov chain. The conditional probabilities of a wet day following a wet day $P(W|W)$ and a wet day following a dry day $P(W|D)$ define the probability of a day where precipitation occurs $P(W)$. For a time series of desired length CLIGEN generates 4 daily precipitation variables: precipitation depth P in mm, duration of a rain event D in hours, peak storm intensity i_p, and the time from the beginning of the storm to its