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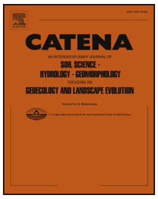

Evaluating the performance of different empirical rainfall erosivity (R) factor formulas using sediment yield measurements

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ABSTRACT

The study aims to evaluate the performance of nine empirical rainfall erosivity (R) factor formulas at the Venetikos River catchment, Northwestern Greece. The goal is to select the most appropriate one, for the accurate estimation of soil erosion. Since high temporal resolution precipitation data (required for the analytical calculation of the R-factor, based on the EI_{30} index) are only available at the Spilaio station, and for a shorter time period (1973–82) than the one the study focuses on (1965–82), a direct validation of R-factor (thus of the empirical equation used for its estimation) can't be applied. Consequently, an indirect validation is attempted considering the catchment's sediment yield, given the convergence between the respective observed and modelled time series. The former was based on field measurements provided by the Greek PPC (Public Power Corporation), while the latter on the (annual; multi-annual) implementation of RUSLE, once for every different R-factor approximation. Provided that all other factors (K, LS, C, P) remain unchanged, the model's relative results (of each application against all others) are only depended on the alternative R-factor values. Regarding the latter, the approximation (thus R-factor equation) that performed best was the one using the Renard and Freimund (1994) [F-based] formula, by displaying the smallest deviations (%) against the observed measurements. All approaches allowed identification of the most susceptible to erosion areas.

1. Introduction

Soil erosion is a major worldwide environmental problem, inducing severe impacts on agricultural productivity, water quality, infrastructure and the environment.

In Greece total annual soil loss is estimated at 150–300 × 10^6 t (Kosmas et al., 2001). The European Environmental Agency states that at Europe (without considering Russia) water erosion affects 105 × 10^6 ha of soil (16% of its total area), with the greater problems concerning Central Europe, Caucasus and the Mediterranean (Gobin et al., 2003). According to Panagos et al. (2015a), the mean soil loss rate in the European Union's (EU) erosion-prone lands (agricultural, forests and semi-natural areas) was found to be 2.46 $\mathrm{t\,ha^{-1}\,y^{-1}}$, resulting in a total soil loss of 970 × 10^6 t annually. Moreover, Borrelli et al. (2017) estimated (for 2012) an annual average soil erosion amount of 35.9 × 10^9 t worldwide. Overall, soil is being lost 10–40 times faster than it is renewed, a fact underlying the severity of the problem (Pimentel, 2006).

In sight of the above, the need to accurately simulate soil erosion (on-site effects) and sediment transport (off-site consequences) becomes essential for the proper implementation of land use measures and soil management strategies, based on the severity of the problem and the socio-economic characteristics of the targeted area. Towards that goal, considering moreover the difficulties met performing large scale (watershed; nationwide etc.) erosion field measurements, models of different accuracy and complexity (empirical, stochastic, deterministic) have been developed. The empirical ones {e.g. USLE (Wischmeier and Smith, 1978), RUSLE (Renard et al., 1991) etc.} are the most commonly used due to their low data requirements, computational speed and ease of use.

Regarding the phenomenon's mechanism, precipitation constitutes its driving force. According to Barfield et al. (1983), water erosion manifests when soil is exposed to the erosive powers of rainfall {detachment; the total volume of precipitation that reaches the soil surface and the kinetic energy of individual raindrops are equally considered, with the latter being affected by raindrop size and rainfall intensity (Gunn and Kinzer, 1949; Wischmeier et al., 1958)} and overland flow (detachment; transport). The parameter is expressed in the USLE and RUSLE models by the rainfall erosivity factor, having the most significant effect on erosion development potential (Renard and Freimund, 1994; Morgan, 2005). The R-factor is directly related to precipitation's specific characteristics like seasonality, depth, duration, extremes

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intensity and frequency, spatial distribution etc. {e.g. at Mediterranean regions, precipitation displays complex spatial and temporal variations (annual; seasonal; single rainfall event scale) with wide fluctuations from year to year (Renschler et al., 1999; Le Bissonnais et al., 2002), posing difficulties on predicting its distribution patterns (Safriel, 2007) and effect on erosivity (Ramos and Martinez-Casasnovas, 2006). At such regions, R-factor displays uneven distribution as well, being moreover volatile to the rainfall's random fluctuations}.

Several studies have been conducted at Mediterranean areas, adapting the analytical calculation of the R-factor, based on the EI_{30} index (De Santos Loureiro and De Azevedo Coutinho, 2001; Diodato, 2004; Boellstorff and Benito, 2005; Mikos et al., 2006; Onori et al., 2006; Angulo-Martinez et al., 2009; Meusburger et al., 2012; Panagos et al., 2016 etc.). Equally important was the effort to estimate R-factor at a European scale (Panagos et al., 2015b). Regarding the Greek region, the Panagos et al. (2015b, 2016) studies were based on high-resolution (30 min) pluviometric data, extracted from 80 stations nationwide {77 derived for the Hydroscope database (Sakellariou et al., 1994) and 3 from the Aegean University one} with a spatial distribution of approximately 1 station per 40 km × 40 km grid cell. Yet, in many countries worldwide, the scarcity of detailed precipitation data posed a serious problem regarding such approximation. That, combined with their difficult and time-consuming processing, led several researches to propose different formulas for its empirical estimation (Arnoldus, 1977; Lo et al., 1985 etc.), correlating it with more easily acquirable and manageable parameters like the total annual precipitation (P) or the Modified Fournier Index (MFI) which was developed by Arnoldus (1977). Each of these formulas is optimized for a certain location and there are no guaranties that it will be effective if applied elsewhere. In Northern Europe the R-factor is mostly estimated by the “Bavaria equation” (Rogler and Schwertmann, 1981), while in Southern Europe by the “Toscany equation” (Van der Knijff et al., 2000) equation. Both relationships are considered to approximate best the climate conditions of the corresponding areas, as well as those of the neighboring regions.

In Greece, the detailed rainfall data problems {reliability (stations with non-functioning periods; not equipped with recording rain gauges of adequate temporal resolution), acquisition (availability to researchers; often dispersed between different agencies and overseers), spatial distribution (low gauging network density), time series length issues} along with the absence of an exclusive (developed especially for the Greek climate regime) empirical equation, led to the widespread use of the Van der Knijff et al. (2000) equation (Lykoudi and Zarris, 2002; Sigalos et al., 2010; Zarris et al., 2011 etc.). The latter estimates R-factor as a function of mean annual rainfall depth (P, mm) multiplied by a rating coefficient (“a”, dimensionless), ascribed with the value of 1.3 at most studies. The formula has suffered serious criticism since the R-factor is not directly analogous to P {their relationship depends on climatic, topographic, orographic etc. determinants, displaying spatial (and seasonal, among the dry and wet seasons) variability, following the respective trends of precipitation}, thus considered oversimplified (Kinnell, 2010). All and all, its choice was based on climatic relevance due to proximity as well as its satisfactory performance at such conditions. Flabouris (2008) attempted to localize this formula, by adjusting the “a” coefficient to the country's climatic conditions (the R-factor was analytically estimated, using precipitation measurements of high temporal resolution from 24 pluviometric stations nationwide – Greece was subsequently divided into four climatic zones and a different parameter value was ascribed to each). Yet, the small number of stations used (low gauging network density/inadequate distribution) poses issues concerning the proper description of the R factor's spatial variability.

Considering the above, the study aims to assess the effect of nine different empirical rainfall erosivity factor formulas (Arnoldus, 1977; Rogler and Schwertmann, 1981; Schwertmann et al., 1990; Renard and Freimund, 1994 [F-based]; Renard and Freimund, 1994 [P-based]; Van der Knijff et al., 2000; Ferrari et al., 2005 [exponential]; Ferrari et al., 2005 [linear]; Torri et al., 2006) on soil erosion. To that end, RUSLE was implemented (annually; multi-annually for the period 1965–82), once for every different R-factor approximation. Since high temporal resolution precipitation data (required for its analytical calculation) were only available at the Spilaio station (Maggina, 2003), and for a shorter time period (1973–82) than the one the study focuses on (1965–82), a direct validation of R-factor (thus of the empirical equation used for its estimation) can't be applied. Consequently, an indirect validation is attempted considering the catchment's sediment yield, given the convergence between the respective observed and modelled (per approximation) time series. The former was based on field measurements provided by the Greek PPC (Public Power Corporation), while the latter on the (annual; multi-annual) implementation of RUSLE per R-factor formula. Given the linear character of the model's equation, and provided that all other factors (K, LS, C, P) remain unchanged, the difference among the various applications results was only depended on the alternative R-factor values. Equations developed in non-European countries were included, in order to account for their localization and moreover to test whether they can be used in different climatic conditions.

Overall, the attempt to assess the effect of the rainfall erosivity calculation methodology on soil erosion simulation by comparing nine different empirical R-factor approximations, the implementation of RUSLE on a mountainous Mediterranean type catchment of complex (climatic, pedological, topographic, hydrologic, land cover) characteristics, the application on two time scales (annual, multi-annual; once per approximation; for a considerable 17 year period), the attempt to validate the empirical R-factor values against analytical ones and the validation of the modelled results against the catchment's measured sediment yield summarize the innovation of the present study.

2. Materials and methods

2.1. Study area and measurements

The Venetikos River catchment is a mountainous sub-basin of the Aliakmonas River, located at Northwestern Greece (Fig. 1). Its basic attributes are presented in Table 1.

A Digital Elevation Model (DEM) of the area was used, with a spatial resolution of approximately 50 m, in order to describe the local topography. The latter was created considering the corresponding topographic maps provided by the Greek Military Geographical Service, in a scale of 1:50000. Based on that, the watershed is characterized as mountainous (mean elevation of 1008.7 m, mean slope of 23.6%), displaying rough relief (steep slopes, cliffs etc.) at its western part and milder relief (limited lowlands; plains etc.) at its eastern part. It orients from West to East, having a “circular” shape. Its drainage is performed by a dense hydrographic network, developed due to the high precipitation (and snowfall) depth and intensity, conjuncted by the strong geomorphology (Fig. 1).

The land use delineation was based on the European CORINE (Coordination of Information on the Environment) Land Cover (CLC) Version 2000 classification (Table 2). Considering that, the basin is largely covered by vegetated areas (e.g. forests, woodland etc.), while the agricultural regions are less extensive, being located at the lowlands towards its outlet (Fig. 1). Overall, the land use map identified 14 different types of land cover.

The soil properties were described considering 24 soil samples provided by the Greek NAGREF (National Agricultural Research Foundation) and the EU through the LUCAS (Land Use/Cover Area frame Survey) topsoil database (Toth et al., 2013). All samples are sited within the basin's boundaries (Fig. 1). The latter refer to the soil's surface layer (EU) and horizon (NAGREF) with their depth ranging from 0 to 30 cm and 0 to 40 cm, respectively. The LUCAS samples have a density of around 1 per 199 km^2, forming a pan-European grid with a 14 km^2 cell size (Panagos et al., 2013).

The climate (and hydrologic regime) is of a typical Mediterranean