Erosivity factor in the Universal Soil Loss Equation estimated from Finnish rainfall data

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Continuous rainfall data recorded for many years at 8 stations in Finland were used to estimate rainfall erosivity, a quantity needed for soil loss predictions with the Universal Soil Loss Equation (USLE). The obtained erosivity values were then used to determine the 2 parameters of a power-law function describing the relationship between daily precipitation and erosivity. This function is of importance in erosion modeling at locations where no breakpoint rainfall data are available. The parameters of the power-law were estimated both by linear regression of the log-transformed data and by non-linear least-square fitting of the original data. Results indicate a considerable seasonal (monthly) variation of the erosivity, whereas the spatial variation over Finland is rather small.

Key words: precipitation, erosivity, USLE, Finland

Introduction

Rainfall is an important factor causing soil erosion in Finland. The terminal velocity of falling raindrops determines the kinetic energy for the detachment of soil particles. Early measurements of the terminal raindrop velocity were carried out by LENARD (1904) and SCHMIDT (1909). More refined measurements, using electric equipment, have been made by LAWS (1941) and GUNN and KINZER (1949). A high degree of correlation between drop size, and therefore terminal velocity, and rainfall intensity was found by LAWS and PARSONS (1943). The effect of rainfall intensity on soil detachment was formulated mathematically by WISCHMEIER and SMITH (1958) and connected to soil loss prediction by WISCHMEIER and SMITH (1978).

Several agricultural transport models, such as CREAMS (KNISEL 1980), its later extension GLEAMS (LEONARD et al. 1987) and EPIC (WILLIMAS et al. 1984), use the Universal Soil Loss Equation (USLE, WISCHMEIER and SMITH 1978) or its modifications for erosion calculations. The USLE contains a rainfall factor, which is based on the rainfall kinetic energy derived from breakpoint rainfall data (i.e. individual storms). However, in many cases breakpoint data are not available. Some models, such as CREAMS, provide an option to use daily rainfall amounts as input data to the model. In this case the rainfall factor is computed with a power-law relating daily precipitation to rainfall erosivity. This power-law has been derived from breakpoint data by LOMBARDI (1979). However, the parameters of this relationship are not universal, they depend on the geographical location and on the time of the year. The spatial dependence of the parameters of the power-law has been investigated by RICHARDSON et al. (1983) and HAITH and MER-

RILL (1987) for several locations in the United States. The influence of the resolution of the rainfall data on the erosivity calculations has been studied by WILLIAMS and SHERIDAN (1991).

The objective of this study was to estimate the parameters for the rainfall factor used in the USLE for each month of the warm season from breakpoint rainfall data collected at 8 stations in Finland.

Rainfall data

Continuous rainfall records from 8 stations (Fig. 1) were analyzed in this study for estimating the parameters for the rainfall factor used in the USLE. Seven of these stations are operated by the Water and Environment Research Institute and one - in Jokioinen - by the Finnish Meteorological Institute. The location and the number of years of record are given in Table 1.

Fig. 1. Location of the 8 stations with continuous rainfall measurements analyzed in this paper.

All rainfall gauges (pluviographs) used by the Water and Environment Research Institute have a Wild-type collector (500 cm^2 collector area with a Nipher-type windshield) with the opening 1.5 m above ground. The rainfall gauges are not protected against frost, and they are in operation only from the end of April to the beginning of November (depending on the location). In the northernmost station of Ranua frost and snowfall frequently occur in May and October, and therefore the number of observations in these months is low. The device draws the graph for one week on a single sheet of paper. The resolution of these graphs is about 15 minutes and about 0.1 mm. A more detailed description of the equipment is given in POSCH et al. (1992).

The pluviograph used by the Finnish Meteorological Institute in Jokioinen is a Belford-type collector (378 cm^2 ellipsoidal opening) with no windshield and 1.5 m above ground. The device is in operation throughout the year, and the protection against frost is maintained with NaCl. The pluviograms are drawn on a chart on a daily basis. The minimum resolution for rainfall depth is about 0.1 mm, but due to the daily basis of the chart the time resolution is better compared to the weekly charts used at the other stations.

Table 1. Name, location and years of record of the rainfall stations used in this study.

Station	Location E	Location N	Height m a.s.l.	Years of record
Jokioinen	23°30'	60°49'	104	1966-1990
Vihti	24°26'	60°25'	65	1964-1990
Ranua	26°05'	66°10'	185	1976-1990
Savijoki	22°38'	60°36'	54	1972-1990
Löytäneenoja	22°16'	61°15'	40	1964-1990
Ruunapuro*	26°02'	62°31'	105	1963-1990
Sulvanjoki	21°41'	62°58'	15	1963-1990
Huhtisuonoja	28°41'	61°24'	112	1963-1990

* Data for 1964,1966,1968,1988 and 1989 is skipped due to malfunction of the sampling device.

The graphs have been digitized and combined to obtain the cumulative rainfall data for every summer half year, ranging from May to October. Rainfall events in April and November were included in the Jokioinen data, since most of the rainfall still comes as water during those months. The winter months (December-March) were skipped in this study because of the high probability of snowfall.

Due to the resolution of the equipment 2.4 mm d^{-1} = 0.1 mm h^{-1} was selected as the minimum depth and 15 minutes as a minimum duration of a rainfall event. In addition, 180 min was chosen as the minimum length of a gap separating two events (see POSCH et al. 1992).

Estimation of rainfall erosivity

The equation for computing rainfall energy E, for rainfall given by a continuous function in time t, is

$$(1)\quad E = \int_0^T e(t)\, i(t)\, dt$$

where e is the rainfall energy per unit rainfall, i is the rainfall intensity for the time differential dt and T is the duration of the rainfall. With Δt_k as the k-th part of the storm pluviogram for which a constant rainfall intensity i_k can be assumed, Eq.1 can be written in the discrete form

$$(2)\quad E = \sum_{k=1}^{p} e_k i_k \Delta t_k$$

where e_k is the rainfall energy per unit rainfall for the k-th increment and p the number of increments.

The unit energy e_k itself is a function of the intensity and, according to a regression equation by WISCHMEIER and SMITH (1958, 1978), it is given by

$$(3)\quad e = \begin{cases} 916 + 331 \log_{10} i & \text{for } i \le 3 \text{ in/h} \\ 1047 & \text{for } i > 3 \text{ in/h} \end{cases}$$

where the unit energy e has units of foot-tonsf/acre-inch and the intensity i is expressed in in/h (tonsf stands for ton force). US units are used here for simplicity and the conversion to SI units is given below. Eq.3 is based on rain drop size and terminal velocity measurements, and it is independent of the geographical location (LAWS and PARSON 1943, GUNN and KINZER 1949).

According to WISCHMEIER and SMITH (1958), the best single variable to predict rainfall erosivity of a single rainfall event is the product of the total rainfall energy E and its maximum 30-minute intensity I_{30}, i.e.

$$(4)\quad EI = E \cdot I_{30}$$

and it is the quantity EI which enters the soil loss calculations with the USLE. Since no data correlating soil loss and rainfall erosivity is available for Finland, Eq.4 is also used in this study.

Since breakpoint rainfall data is not always available, LOMBARDI (1979) (see also RICHARDSON et al. 1983) presented a simple power-law linking daily precipitation amount z and rainfall erosivity EI:

$$(5)\quad EI = az^b$$

In the USLE EI has to be in units of (100 ft-tonsf/acre)(in/h), and values of a=8.0 and b=1.51 were derived by regression analysis from 2700 data points from the United States, and these values are also coded in the CREAMS model.

The breakpoint rainfall data for the 8 stations described in the previous section has been used for computing both the rainfall erosivity and the daily rainfall depth. Rainfall events of less than 30 minutes duration have been omitted, since a 30 minute maximum intensity I_{30} cannot be computed for these events. Rainfall events extending over midnight were split into separate events with one ending at midnight, the other one starting at midnight; but the 30 minute maximum intensity of the whole event has been used for both. Furthermore - to be consistent with the derivation of the original equations - storms of less than 0.5 inch and separated from the previous rainfall by more than 6 hours have not been included in the computations, unless as much as 0.25 inch of rain fell in 15 minutes. Those rainfall events, i.e. non-intensive rain falling on dry soil, are reported to have only small erosive effect (WISCHMEIER and SMITH 1978). For the 8 Finnish stations treated in this paper this amounts to skipping 70-75% of the recorded rainfall events; however, it does not mean that all rainfalls below 0.5 inches are skipped (see also Fig. 2).

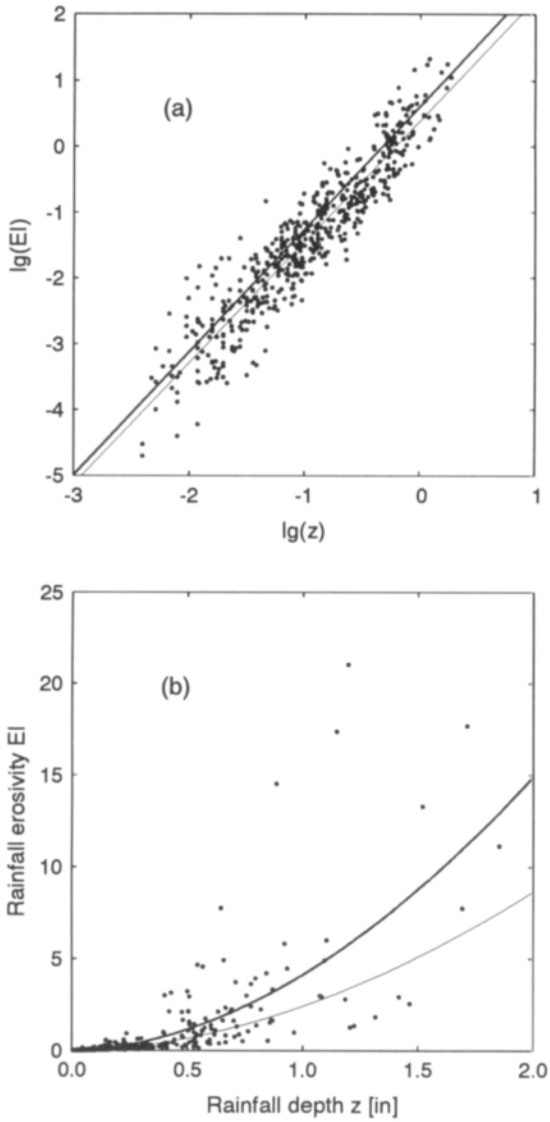

Fig. 2. Rainfall erosivity EI [(100 ft-tonsf/acre)(in/h)] as a function of daily rainfall amount [in] in Jokioinen (a) in double-logarithmic scale, (b) in normal scale. The thin line shows the least-square fit obtained by linear regression of the log-transformed data, and the thick line shows the least-square fit obtained by non-linear regression on the original data.

We assume that Eq.3 for computing unit rainfall energy also holds for Finland. Then the rainfall erosivity of a single storm is computed via Eq.4, and the daily rainfall erosivity is obtained by summing the erosivities of the individual rainfall events:

$$(6)\quad EI = \sum_{i=1}^{n} EI_i$$

where EI_i is the erosivity of the i-th storm and n is the number of rainfall events on that day. The daily erosivity values obtained in this way, together with the corresponding daily precipitation values, are then used to estimate the parameters a and b in Eq.5.

Following customary procedures, we first log-transformed the data (both z and EI) and estimated lg(a) and b by linear regression. This yielded highly significant correlations ($r > 0.90$ in all cases; see Table 2 and Fig. 2a). Due to the logarithmic transformation the parameter values obtained in this way emphasize small values and the influence of the more important but fewer high values is not reflected in the shape of the regression curve (see thin line in Fig. 2b).

Therefore, also a non-linear least-square minimization algorithm was employed for estimating the parameters a and b. The algorithm chosen is the so-called Levenberg-Marquardt method (PRESS et al. 1986). This method minimizes

$$(7)\quad \chi^2(a, b) = \sum_{i=1}^{N} (EI_i - az_i^b)^2$$

where N is the number of observations. As an example, the parameters obtained with this method for Jokioinen were used to plot the erosivity function in Fig. 2 (thick line). As can be seen, the resulting curves clearly differ from the one with parameters obtained by linear regression when plotted untransformed (Fig. 2b), whereas the log-transformed plot (Fig. 2a) would suggest that there is not much difference.

Most erosion models, such as CREAMS, have been developed in the United States and have incorporated the USLE formulated in the original US units. To facilitate comparison we present our re-

Table 2. Number of storms n, erosivity parameters a_{lin} and b_{lin}, estimated by linear regression from the log-transformed rainfall depth z and rainfall erosivity EI, and erosivity parameters a and b estimated by non-linear least square fit from the original data for the 8 rainfall stations for each month and the whole observation period. Also shown are the correlation coefficients r_{lin} for the log-transformed data and the correlation coefficient r for the untransformed data.

	n	a_{lin}	b_{lin}	r_{lin}	a	b	r
Jokioinen:							
Apr	65	0.83	1.61	0.94	0.65	1.37	0.90
May	40	2.62	1.85	0.93	2.95	1.51	0.74
Jun	40	3.36	1.86	0.93	5.09	1.53	0.59
Jul	68	3.93	1.78	0.95	5.27	2.20	0.81
Aug	69	4.06	1.86	0.95	3.98	1.30	0.71
Sep	73	2.02	1.67	0.93	3.06	1.62	0.72
Oct	79	1.55	1.71	0.93	2.45	2.12	0.82
Nov	120	1.08	1.70	0.93	0.99	1.49	0.87
ALL	554	2.42	1.84	0.93	4.14	1.85	0.69
Vihti:							
May	60	1.27	1.68	0.92	1.09	1.29	0.68
Jun	46	2.16	1.79	0.94	2.46	1.19	0.52
Jul	81	2.59	1.76	0.95	4.50	3.28	0.73
Aug	93	2.89	1.80	0.94	2.69	1.06	0.71
Sep	108	1.83	1.66	0.93	2.33	1.31	0.65
Oct	95	0.94	1.54	0.94	1.51	2.47	0.77
ALL	498	1.93	1.73	0.93	2.54	1.42	0.69
Ranua:							
May	44	1.03	1.58	0.95	0.98	1.52	0.88
Jun	47	1.43	1.52	0.93	1.70	1.28	0.80
Jul	47	1.85	1.67	0.95	1.34	0.84	0.74
Aug	53	1.64	1.60	0.92	1.47	0.79	0.55
Sep	45	1.16	1.75	0.93	1.33	1.56	0.83
Oct	19	0.81	1.62	0.96	0.84	1.68	0.93
ALL	255	1.44	1.66	0.94	1.39	1.09	0.69
Savijoki:							
May	59	1.11	1.62	0.95	0.79	1.29	0.86
Jun	58	2.01	1.73	0.94	3.64	1.65	0.62
Jul	75	2.87	1.82	0.97	3.40	1.53	0.78
Aug	79	3.37	1.74	0.95	3.97	1.30	0.64
Sep	63	1.39	1.65	0.93	2.10	2.81	0.80
Oct	48	0.87	1.54	0.94	1.01	1.50	0.79
ALL	382	2.12	1.75	0.95	3.26	1.65	0.68
Löytäneenoja:							
May	73	1.31	1.68	0.92	1.88	1.12	0.56
Jun	55	2.91	1.88	0.93	3.56	1.60	0.77
Jul	73	2.43	1.70	0.93	2.92	1.29	0.74
Aug	77	3.65	1.94	0.95	3.99	1.42	0.69
Sep	98	2.48	1.82	0.95	5.24	2.06	0.61
Oct	52	0.67	1.48	0.91	1.00	1.49	0.59
ALL	430	2.24	1.79	0.93	3.52	1.59	0.67
Ruunapuro:							
May	43	2.29	1.79	0.94	-	-	0.56
Jun	60	2.20	1.73	0.94	6.73	3.30	0.75
Jul	77	4.09	1.84	0.95	4.50	2.10	0.71
Aug	92	3.27	1.82	0.92	4.84	2.34	0.69
Sep	111	1.80	1.69	0.95	2.08	1.26	0.57
Oct	59	0.78	1.53	0.94	0.82	1.53	0.90
ALL	444	2.41	1.77	0.94	4.21	2.44	0.64
Sulvajoki:							
May	80	1.60	1.75	0.93	1.29	1.46	0.78
Jun	52	3.39	1.91	0.97	5.38	3.07	0.77
Jul	79	4.66	1.88	0.95	7.17	2.19	0.68
Aug	85	4.50	1.87	0.95	3.97	0.94	0.82
Sep	117	2.35	1.75	0.94	3.00	1.54	0.77
Oct	62	1.36	1.62	0.94	2.25	2.17	0.87
ALL	479	2.98	1.83	0.95	4.91	1.31	0.66
Huhtisuonoja:							
May	70	1.64	1.70	0.94	1.40	1.43	0.70
Jun	63	2.33	1.73	0.96	3.43	1.03	0.65
Jul	76	4.60	1.98	0.96	4.43	1.81	0.92
Aug	100	3.59	1.80	0.95	3.91	1.31	0.79
Sep	128	2.29	1.78	0.95	2.68	1.62	0.81
Oct	91	1.10	1.56	0.95	1.17	1.51	0.86
ALL	530	2.53	1.79	0.95	3.43	1.97	0.75

Note: The dash '--' means that the data did not allow non-linear estimation of the erosivity parameters.

sults in the same units. However, because of the gradual adoption of SI metric units also in the United States, we shall present the factors for converting the rainfall erosivity EI to the metric system.

Indicating the use of metric units by the subscript m, Eq.5 reads:

$$(8) \quad EI_m = a_m z_m^{b_m}.$$

The conversion between US units and metric units is carried out by appropriate factors, i.e.

$$(9) \quad z_m = \alpha z \quad \text{and} \quad EI_m = \beta EI.$$

Expressing the rainfall depth in mm we get α=25.4; to convert EI, expressed in (100ft-tonsf/acre)(in/h), to the metric unit of (MJ/ha) (mm/h) yields a conversion factor of ß=17.02 (FOSTER et al. 1981). Inserting Eq.9 into Eq.8 gives the following formulae for b_m and a_m:

$$(10) \quad b_m = b \quad \text{and} \quad a_m = \frac{17.02}{25.4^b} a.$$

Results and discussion

The breakpoint rainfall data of the 8 stations described above have been used to estimate the rainfall erosivity parameters a and b in Eq.5 by regressing the daily rainfall amounts with the erosivity computed by Eqs.2-4, and results both for the linear and non-linear regression are presented in Table 2. This was done separately for each month and the whole observation period at each station.

The parameters a_{lin} and b_{lin} were obtained by linear regression of the log-transformed data, showing high positive correlation (r>0.90 in all cases). The exponent b_{lin} is spatially and seasonally rather uniform, varying from 1.48 to 1.94. This is in good agreement with the value of 1.81 used in the CREAMS model and derived from US data (LOMBARDI 1979, RICHARDSON et al. 1983). The proportionality factors a_{lin} range from 0.67 to 4.66 in Finnish conditions, and are considerably lower than those obtained for US conditions (8.0 in the CREAMS model; see also RICHARDSON et al. 1983). This means that the functional dependence of the erosivity on the daily rainfall amount in Finland and the United Sates is very similar, whereas the absolute erosivity values are at least twice as high in the United States, implying the same amount of rain is more erosive there (more intense storms, i.e. "hard rains", DYLAN 1966).

As already pointed out in the previous section, taking logarithms of the data gives little weight to the (less frequent) high values, which are those of interest in erosivity estimations (see Fig. 2). Therefore we estimated the parameters a and b by minimizing the sum of the true squared distances, and the obtained values are reported in Table 2. As an example, the resulting erosivity functions (Eq.5) are displayed for each month in Jokioinen (Fig. 3a) and for the whole observation period for all stations in Fig. 3b. The exponents b are of the same magnitude as the ones obtained by linear regression (b_{lin}), but more varying (0.79-3.30). The multipliers a are even more variable and range from 0.65 to 7.17, and are generally higher than a_{lin}.

Tests with the CREAMS model adapted to Finnish conditions, using erosivity parameters derived from Finnish rainfall data, gave better results than using the US parameters (REKOLAINEN and POSCH 1993). Therefore, in this CREAMS version monthly values for the parameters a and b can be input by the user, and this allows the application of this model in locations with different rainfall characteristics.

Regarding the seasonal variation of the parameters, it can be seen from Table 2 that the values for a are clearly higher during the summer months (Jun-Aug) compared to May and the fall months (see Fig. 3a for Jokioinen). This seasonal variation is less pronounced for the exponents b. This implies that the storms during the summer months are more erosive, reflecting the higher intensity of convective storms, which occur more often during summer. The spatial variability in erosivity is small, with the exception of the northernmost station of Ranua, where the erosivity is lower than in the other stations (Fig. 3b), possibly due to less thunderstorms in Lapland (Atlas of Finland 1987).

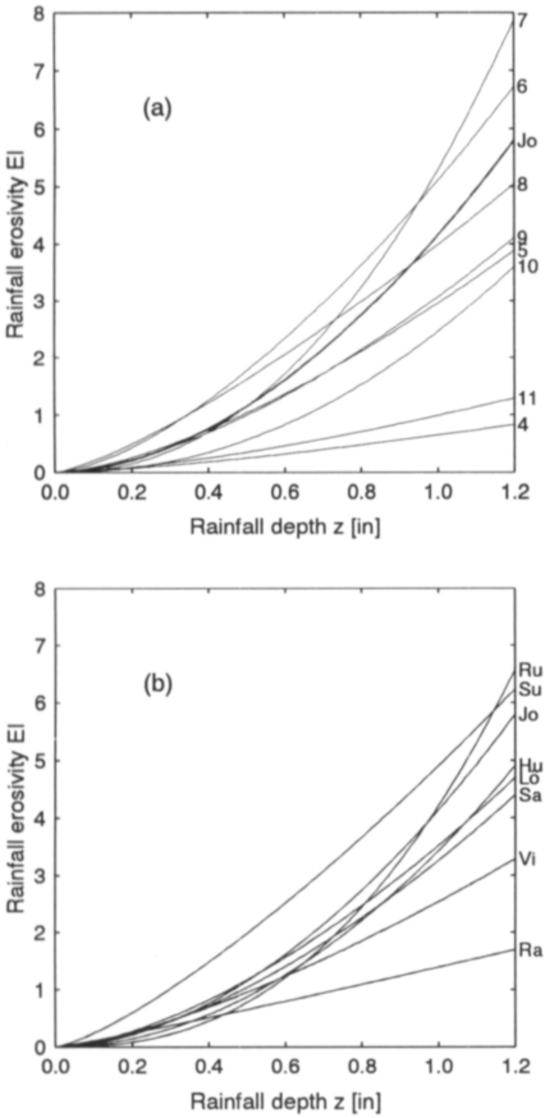

Fig. 3. Least-square fitted power-laws (see Eq.5) for computing daily rainfall erosivity EI [(100 ft-tonsf/acre)(in/h)] as a function of daily rainfall amount [in]. (a) for the months April-November (4-11) and the whole observation period (Jo; thick line) in Jokioinen, (b) for the whole observation period at the 8 stations.

Only a few data is available for April and November, and these indicate that erosivity is low in those months. No data is available for the winter months December to March, and in addition one would have to know if the precipitation falls as rain or snow in order to estimate their erosive impact. In Southern and Central Finland, where most of the agricultural fields are located, the proportion of snow as percentage of total precipitation varies from 30 to 40% (Atlas of Finland 1987). However, it is not only the amount of snow which determines its erosive impact, but also the speed of thawing. These factors have to be taken into account when estimating the overall erosion in Finland.

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SELOSTUS

Sateen eroosiovoiman arviointi Suomessa

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Vesien- ja ympäristöntutkimuslaitos

Suomessa sade on tärkeä maa-aineksen eroosion aiheuttaja. Sateen eroosiovoima on yksi määräävistä kertoimista USLE-yhtälössä (Universal Soil Loss Equation), joka formuloitiin laajaan havaintoaineistoon perustuen USA:ssa ja jota käytetään edelleen laajalti eroosion arvioinnissa. Sateen erosiivisyyskerroin USLE:ssa perustuu sateen kineettiseen energiaan, joka arvioidaan yksittäisten sadetapahtumien ominaisuuksien avulla. Tällaista sadanta-aineistoa ei ole kuitenkaan saatavilla yhtä laajasti kuin päivittäistä aineistoa. USLE:n ja siihen perustuvien lukuisten eroosiomallien laaja käyttö vaatiikin sateen erosiivisyyden arviointia päivittäisen sadantatiedon avulla.

Päivittäisen sadannan ja sateen eroosiovoiman välinen riippuvuus on kuvattu USA:ssa potenssiyhtälönä. Tämän potenssiyhtälön kertoimet eivät ole yleismaailmallisia, vaan riippuvaisia maantieteellisestä sijainnista ja vuodenajasta. Tässä tutkimuksessa arvioitiin Suomessa kahdeksalla havaintoasemalla kerätyn jatkuvan sadanta-aineiston perusteella päivittäisen sadannan ja sateen eroosiovoiman välisen potenssiyhtälön kertoimet.

Potenssiyhtälön $EI=az^b$, jossa EI on sateen eroosiovoima ja z on päivittäinen sademäärä, kertoimet estimoitiin logaritmimuunnetusta havaintoaineistosta lineaarisen regression sekä muuntamattomasta aineistosta epälineaarisen algoritmin avulla. Lineaarisesti estimoidun yhtälön eksponentin b havaittiin vastaavan hyvin USA:ssa havaittuja, mutta yhtälön kertoimen a todettiin olevan huomattavasti alhaisemman. Tämä viittaa siihen, että sateiden eroosiovoima on Suomessa selvästi pienempi kuin USA:ssa.

Potenssiyhtälön kertoimissa havaittiin selvää ajallista vaihtelua siten, että kesäkuukausien sateiden erosiivisyys oli selvästi muita kuukausia korkeampi. Tämä johtuu todennäköisesti konvektiivisten sateiden suuremmasta osuudesta kesällä muihin vuodenaikoihin verrattuna. Sen sijaan eri havaintoasemien välillä ei havaittu suuria eroja lukuunottamatta pohjoisinta, Ranualla sijatsevaa asemaa, missä sateiden erosiivisyys oli selvästi muita asemia pienempi. Tämä johtuu mahdollisesti ukkossateiden vähäisemmästä määrästä Lapissa Etelä- ja Keski-Suomeen verrattuna.