CLIMATE AGRESSIVENESS AND RAINFALL EROSIVITY

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ABSTRACT. – Climate aggressiveness and rainfall erosivity. The climate aggressiveness defines the extent to which elements of climate, their variability and interdependence affect a component of bio-pedo-geomorphological or human system. However, most studies analyze rainfall erosivity, namely the ability of rains to generate a significant erosional impact. There are two categories of rainfall evaluation methods: direct methods, which require a large consumption of time, financial and material resources, and indirect methods, less precise, but with the advantage of higher accessibility of meteorological data and better suitability for regional studies. This approach focuses on indirect methods in a brief presentation and argues the need to revise and updating of some indicators consecrated in Romania (eco-pedological indicator 99), given the substantial accumulation of climatic data and modernization of techniques for computer and complex spatial analysis. The arguments are based on indirect calculation of rainfall erosivity in eastern Romania.

Keywords: *rainfall erosivity, indirect methods, Eastern Romania.*

1. INTRODUCTION

Large amounts of rainfalls in a short period of time, namely heavy rains capable of generating a significant runoff on the ground, are a feature of climates with contrasting seasons or irregular rainfall, whether temperate or tropical. If the analysis of climate torrentiality or heavy rains, individually, is common in meteorology and climatology, climate aggressiveness and rainfall erosivity are less used terms. However, in technical-applied sciences, the use of these concepts is common. The climate aggressiveness defines the extent to which elements of climate, their variability and interdependence affect a component of bio-pedo-geomorphological or human system. The two approaches, although scientifically evolved especially in the last decades, retain essentially the basic meaning of words: diagnostic-descriptive, in the first case (lat. *torrens, -ntis* – flood water), of impact, in the second case (lat. *aggresio,-onis* – attack < lat. *aggredior,-gredi, -gressus sum* – to attack).

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Although climate aggressiveness may refer to thermal extremes and contrasts or to the impact of wind (in technical and constructions), the most commonly studies in geosciences are those relating to rainfall erosivity (aggressiveness), namely the ability of rains to generate a significant erosional impact. Obviously, this is a defining feature of climates characterized by irregular pluviometric regime, with rains having different pluviographic features (amount, duration, medium intensity, maximum intensity etc.).

Initiation of erosion depends primarily on the intensity of rainfall and the total amount of recorded precipitation. In the first case, rain intensity reflects the total kinetic energy of falling raindrops, which, by mass and speed, can cause destruction of soil structural aggregates (splash). In the second case, the amount of precipitation is important to infiltration/runoff balance. Erosion begins to manifest together with the exceeding retention capability of vegetation and soil infiltration capacity, developing in the form of sheet erosion, rill erosion or gully erosion.

Although the total amount of soil losses depends on many factors (declivity and slope length, soil erodibility, land use or existence of anti-erosion works), precipitations are the active factor of erosion, but highly variable in time and space. For this reason it is difficult to find a method or a universal expression of quantification, valid and enforceable in any climate conditions, no matter how common would be some of these expressions, especially since such efforts date back over almost a century.

The most accurate method for calculating rain erosivity is direct measurement of the amount of eroded soil within runoff plots. For example, splash cups (Ellison splash cup) have long been used for both the quantification of kinetic energy of rainfall and the detachability of soil particles by rainfall impact (splash erosion). Measurements of kinetic energy, however, have been difficult to operate in the field especially in remote areas, on steep slopes, and in forests since boundary conditions need to be controlled precisely (Scholten et al., 2011). The attention of scientific community increasingly focused on three methods for rainfall energy assessments:

- the acoustic principle in which the rain energy is translated into sound and into an electrical signal;
- pressure transducers which measure the strain induced by the impact of the rain drops;
- sensors which depend upon the direct conversion of impact into an electrical signal through the use of a piezoelectric crystal (Hudson, 1981).

However, direct methods require a large consumption of time, financial and material resources so that on the basis of research effectuated in the various points of the Globe, indirect relationships were computed.

Two types of equations have been developed in different regions of the globe, with results applicable to different scales of analysis, either locally or used for larger areas, even in adapted versions. The first category refers to indicators that rely on kinetic energy and intensity in a given period of rain: EI_{30} (Wischmeier, 1959), $H \cdot i_{15}$ (Stănescu et al., 1969), KE ≥ 25 (Hudson, 1971), AI_m (Lal, 1976) etc. The second category is represented by indicators based on hourly, daily or monthly values of rainfalls: Fournier (1960), Arnoldus (1980), Richardson et al. (1983), Renard and Freimund (1994), Diadato et al. (2005) etc.

2. INDICATORS BASED ON MAIN ELEMENTS OF RAIN

The major advantage of the indicators relied on rain elements is the high accuracy of the results, thanks to the use of direct values. In some cases, these ones regard the kinetic energy parameters (size and speed of raindrops), but in most cases they concern the total quantity of water and the average or maximum intensity of rain or of torrential core. However, discontinuous values in time and space are obtained, depending on the frequency of storm events and the density of measurement points. In Romania, there are about 160 weather stations, of which only 100 are automatic stations. Although the introduction of automatic stations is an obvious progress of the last two decades, their density is still very small. It is well known that heavy rains, with erosional activity, spread to elongated areas usually with small surfaces and widths that can fall below 2-3 km. In this case, most of the territory remains outside the permanent network of observations. Using radar to estimate rainfall amount, although it provides important information in terms of weather, has still an inadmissible margin of error to calculate real erosivity of rains, in order to estimate soil losses.

Some authors have established a direct correlation between drop diameter by volume and rainfall intensity (Laws and Parsons, 1943). Other studies, conducted in tropical climate, have shown that the relationship holds only for rainfall intensity bellow 100 $mm \cdot h^{-1}$ (1.67 $mm \cdot min^{-1}$). At higher intensities, greater turbulence makes larger drop sizes unstable (Hudson, 1963). Considerable variability consists because the relationship between the median drop size and rainfall intensity is not constant. Moreover, the drop size characteristics differ depending on the origin of rains: convectional or frontal rains, warm or cold fronts of a temperate depression etc. (Morgan, 2005).

Extremely important for assessment of erosion impact is the typology of heavy rains, determined by means of pluviograms. Frevert et al. (1955) separated four types of heavy rains depending on the position of core with maximum intensity: uniform, advanced, intermediate and delayed (Measnicov, 1975).

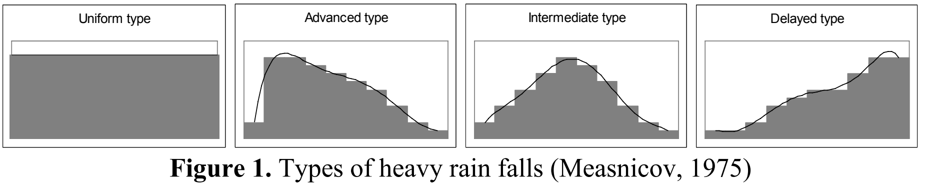

Figure 1. Types of heavy rain falls (Measnicov, 1975)

Uniform type involves a relatively constant intensity throughout the rain, but the frequency of this type is lower. Advanced type is characterized by a high intensity in the early period of rain. In this case, the discharge is relatively low and soils have a high capacity of infiltration. However, this type of rain can generate important runoff if the soil drainage water exceeded the capacity of the field due to earlier rains or if soil texture is fine or medium-fine. Intermediate type implies gradual increase and decrease in the intensity, the maximum value being recorded during the middle of the rain. Delayed type is characterized by an intensity that evolves upward, the maximum value being recorded at the end of rain. In this latter case, the runoff is more significant due to the reduction of soil infiltration capacity (Measnicov M., 1975, Stângă, 2009).

Chronologically, the first erosivity indicator considered sufficiently relevant and frequently quoted in the scientific literature (Moțoc M., 1975, Ioniță I., 2000) is the one proposed by Yarnell (1935). According to this criterion, a given rain has erosion efficiency if:

$$I \geq 0.254+5.08 \cdot t^{-1}, \text{ where:}$$

I – average rainfall intensity during the time t (mm/min.);
t – duration of torrential core (min.).

The minimum mean intensity required to a rain in order to ensure the erosion efficiency was calculated on the basis of Yarnell criterion and the duration of the torrential core *(tab 1)*.

Table 1. The minimum mean intensity of heavy rains (Yarnell criterion)

t (minutes)	5	10	15	20
I_{min}(mm/min.)	1.27	0.76	0.59	0.51
t (minutes)	30	45	60	90
I_{min}(mm/min.)	0.42	0.37	0.34	0.31

One of the most popular indicators is EI_{30}, which is the product of rainfall kinetic energy (E) and average intensity (I) of the maximum torrential core over 30 minutes (Wischmeier, 1959). The annual rainfall aggressiveness is calculated by summing the values obtained for all potentially erosive rains recorded during the year. The notoriety of this index is due to its use to calculate soil losses through the Universal Soil Loss Equation in (Wischmeier, Smith, 1978), the formula being maintained as such in the Revised Soil Loss Equation (Renard et al., 1997).

Based on the indicator proposed by Wischmeier (1959), Stănescu et al. (1969) used an indicator considered simpler and more suitable for the climatic conditions of Romania, indicator calculated as product of a heavy rainfall amount (H) and average intensity of torrential core calculated for 15 minutes (i_{15}): $H \cdot i_{15}$.

Hudson (1971) proposed an indicator, which takes into account the kinetic energy of rainfalls that cumulate over 25 mm of water per hour ($mm \cdot h^{-1}$). Lal

(1976) proposed another indicator (AI_m) calculated as product of daily precipitation amount and maximum intensity on short-term (I_m). Both equations have been adapted for the tropics and in the first case the author considered that only rains exceeding the mentioned threshold have an erosional impact. Uson and Ramos (2001) calibrated Wischmeier equation, considering representative time-segments of 5 minutes, instead of 30 minutes.

The kinetic energy of rainfall is usually used to quantify the ability of rainfalls to cause soil losses. Yet, this is not a parameter included in common meteorological measurements and that is why there were established correlations between kinetic energy and intensity of rain, based on measurements of velocity and particle size (Salles et al., 2000). There are many relationships in the scientific literature (e.g. volume-specific kinetic energy or time-specific kinetic energy), but different in form or statistical representativeness and sometimes adapted to specific climatic conditions. A general relation has the form (Morgan, 2005):

$$KE = 0.0895 + 0.0844 \cdot log_{10} I \quad (1)$$

3. INDICATORS BASED ON SUMS OR MEAN VALUES OF RAINFALLS

Indicators based on average or subsumed values of hourly, daily or monthly quantities of rains have the advantage of higher accessibility of meteorological data and better suitability for regional studies. However, statistical models and correction coefficients determined according to climatic conditions must be validated and the degree of approximation is higher than in the case of equation from the previous category. Although some indicators were used for mapping of global rain erosivity, they allow nevertheless only a first approximation of the parameter in question.

Fournier (1960) proposed an index based on monthly values of precipitations, initially to assess the potential for geological erosion on large areas and based on correlation with sediment load in the major rivers of Africa. Accessibility of monthly pluviometric data was a major advantage and Fournier index had a great success for worldwide surveys. It must be noted that the method has been used with good results in Tisa Plain and Moldavian Plateau (Ianoş, 2006, Stângă, 2009).

The general equation for calculation is:

$$FI = \frac{R^2 max}{Rmean} \quad (2)$$

where:
FI – Fournier index;
Rmax – rainfall of the wettest month;
Rmean – mean annual rainfall.

A modified version of this index has been used by Arnoldus H.M. (1980) in order to express more accurately the rainfall erosivity.

The general formula for annual values is:

$$MFI = \sum_{i=1}^{12} \frac{R_i^{\,2}}{Rm} \qquad (3)$$

or, for monthly values:

$$MFI = 12 \cdot \frac{R_i^{\,2}}{Rm}\text{, where:} \qquad (4)$$

MFI – the Modified Fournier Index;
Ri – the monthly rainfall;
Rm – mean annual rainfall.

The significance of obtained values is determined according to climatic features of the research area. For the continental temperate zone, this significance is as follows:

≤ 20: very low rainfall erosivity;
21-40: low rainfall erosivity;
41-80: medium rainfall erosivity;
81-120: high rainfall erosivity;
121-160: very high rainfall erosivity;
> 160: excessively high rainfall erosivity.

Oliver (1980) proposed, similarly, a Precipitation Concentration Index (PCI), having the next equation:

$$PCI = 100 \cdot \sum \frac{p^2}{P^2} \qquad (5)$$

Theoretically, the results range from values below 10 when the climate regime is uniform and up to 100, if all the rainfalls are concentrated in a single month.

Diodato et al. (2005) calculated monthly rainfall erosivity starting from RUSLE model on the basis of the equation bellow:

$$EI_m = 0.1174 \cdot \left(\sqrt{m} \cdot d^{0.82} \cdot h^{1.18}\right) \qquad (6)$$

where:
EI_m – monthly erosivity index (MJ mm ha^{-1} h^{-1});
m – monthly precipitation amount (mm);
d – monthly maximum daily rainfall (mm);
h – monthly maximum hourly precipitation amount (mm).

Given the frequent difficulty to obtain hourly rainfall data, Bellocchi and Diodato (2009) simplify this relationship, reaching the following form:

$$EI_m = 0.0400 \cdot \left(p^{0.35} \cdot d^{0.60} \cdot (d \cdot \alpha_m)^{0.70}\right) \qquad (7)$$

where:
α_m – seasonal scale-factor in function of the month. This is calculated for each month (1-12) with the relation bellow:

$$\alpha_m = \left\{1 - 0.30 \cdot \cos\left[2\pi\left(\frac{m}{26 - m}\right)\right]\right\}^2 \tag{8}$$

Coefficients in equation were calibrated for the central-southern Italy (Campania and Basilicata).

Hoyos (2005) used semestrial rainfall data to calibrate EI_{30} indicator through statistical regression, differentiated for the dry season, respectively rainy season in tropical regions of the Colombian Andes.

As a general model, the most equations for predicting rainfall erosivity have the form:

$$R = a \cdot \sum P_d^b \tag{9}$$

where:
P_d – daily rainfall;
a and b – coefficient, respectively exponent depending on climatic conditions (Richardson et al., 1983).

4. DISCUSSION

Erosivity depends on the characteristics of each rain, mainly on the intensity, duration and moment of the torrential core. These peculiarities depend largely on genetic conditions of each rain individually, so that generalizations involve some errors, sometimes impossible to be removed by calculation.

The success of indicator Ei_{30} actually created a direction of research to identify new and better indicators, adapted to different climatic conditions. However, on the one hand, the desire for continuous improvement of these indicators or creating new ones was not always accompanied by satisfactory results, especially in terms of their validation. On the other hand, in some countries, for economic reasons or from a "scientific reticence" is not very easy to operate any correction or improvement of well-known and consecrate indicators and methodologies. In Romania, the best known is the eco-pedological indicator 99 from the Methodology of Soil Surveys Elaboration - MSSE, edited by the Institute of Pedological and Agrochemical Researches in 1987 (fig. 2). Values in the map are grouped in three classes: low erosivity (0.067-0.100), moderate erosivity (0.127-0.144) and high erosivity (0.167-0.207). Obviously, setting a single benchmark (mean value) for a large area has an applicative importance, supporting practitioners in pedology and soil erosion.

Accumulation of climate data over the last 25-35 years, especially in the current climate changes necessarily requires a revision of this indicator. Moreover, current techniques of calculation and spatial analysis allow a significant improvement of results. We don’t have climate data for the whole country, but at least on the basis of logical correlations, draws the attention the same value of erosivity (0.127) for the Plain of Someş, Romanian Plain, but also for the Gurghiu

Mountains or Harghita Mountains. Moreover, this value is intermediate to those which characterize the neighboring regions Tutova Hills and Fălciu Hills.

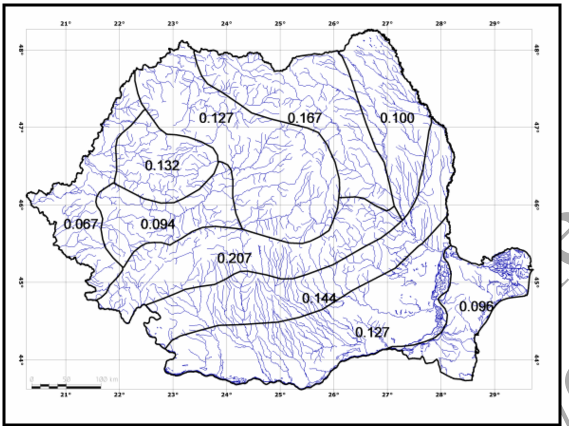

Figure 2. Rainfall erosivity according to MSSE (1987)

The Fournier Index and Modified Fournier Index were calculated for several weather stations in Eastern Romania: Focşani, Galați, Adjud, Tecuci, Bârlad, Bacău, Roman, Vaslui, Iaşi, Cotnari, Piatra Neamț, Rădăuți, Suceava, Botoşani, Dorohoi and Darabani. Although the power function multiply the role of monthly rainfall, it is obvious that, even in the simplest form, rainfall erosivity does not vary only directly proportional to monthly rainfall and inversely proportional to the annual amount of rainfall. However, the results seem to be conclusive since for Bârlad station, a very good correlation was established (Stângă, 2009) with soil losses under fallow and maize derived from runoff plot measurements within the Țarina Valley-Perieni, very close to Bârlad (Ioniță, 2000) (fig. 3). It must be noted that the considered reference period is from May to October, interval for which there have been measurements of monthly erosion.

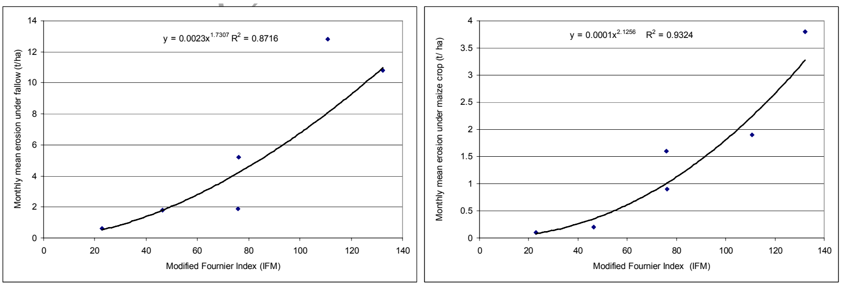

Figure 3. Monthly mean erosion under fallow and maize (t/ha, Perieni) and the MFI at Bârlad (Stângă, 2009)

Starting from the results obtained for 12 stations, there is very clear that erosivity varies with altitude and latitude: Galați: 44.1; Tecuci: 45.9; Bârlad: 50.0; Adjud: 52.9; Vaslui: 52.4; Bacău: 58.4; Roman: 55.5; Iaşi: 57.1; Piatra Neamț: 67.2; Botoşani: 58.8; Suceava: 66.o; Rădăuți: 68.5. The coefficient of correlation between altitude and erosivity is not exceptional, but statistically significant (fig. 4).

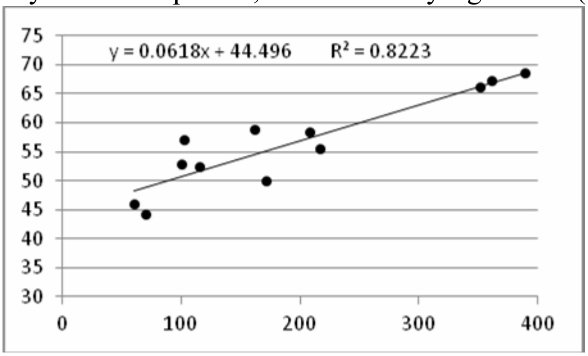

Figure 4. Correlation between altitude (horizontal axis) and rainfall erosivity (vertical axis) in Eastern Romania

Based on the above classification (equation no. 4), the entire region is characterized by medium rainfall erosivity (MFI = 41-80). From this point of view, things are different from eco-pedological indicator 99, according to which most of the Moldavian Plateau is characterized by low rainfall erosivity (0.100). Some of our previous studies have already shown that, at least for Tutova Hills, the 0.100 value seems undersized (Stângă, 2009).

To emphasize the existing differences in the Moldavian Plateau, the class of medium erosivity was divided into three subclasses: moderate-low erosivity (MFI ≤ 55), moderate erosivity (MFI = 56-65), moderate-high erosivity (MFI > 65) (fig. 5). Furthermore, differences appear in the recording of maximum MFI. For stations in S-SE, maximum erosivity is recorded in June (Galați, Tecuci, Bârlad, Adjud, Vaslui, Iaşi), while for stations in the N-NW, it is recorded in July (Bacău, Roman, Cotnari, Piatra Neamț, Botoşani, Suceava, Rădăuți). This shows a gap of about a month of critical erosion season, set to be between 15-20 May and 15-20 July (Ioniță, 2000). In terms of our results, it appears that maximum erosivity is recorded in May-June in Covurlui Hills, Plain of Elan River, Tutova and Fălciu Hills, the western part Central Moldavian Plateau and southern part of Jijia Plain. One month later (June-July), there is maximum erosivity in the central-northern Hilly Plain of Jijia, Siret corridor and Suceava Plateau, in accordance with the dynamics of air masses and latitudinal difference of thermo-convective processes generating heavy rains. The mean annual erosivity regime for Eastern Romania and two extreme stations (Galați and Rădăuți) is shown graphically in fig. no. 6.

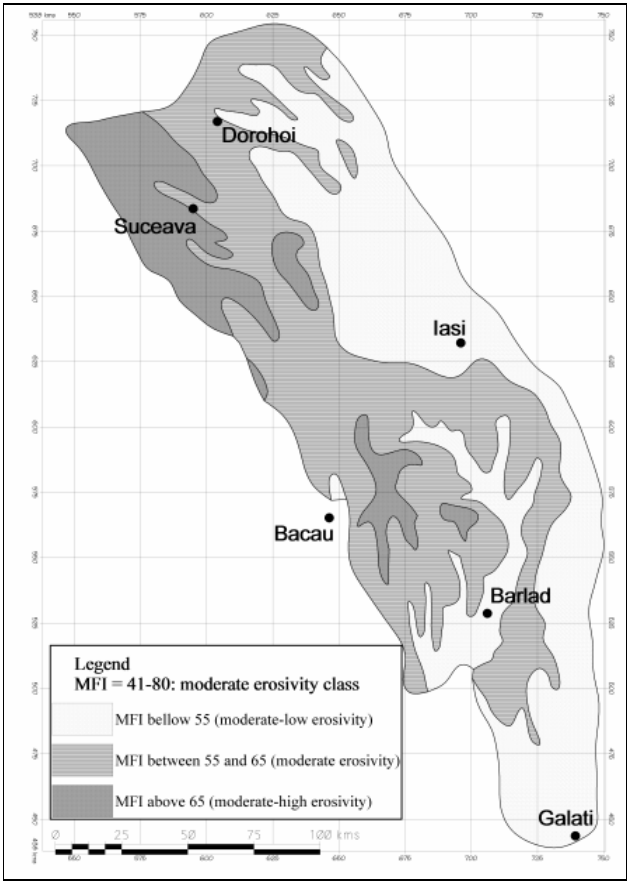

Figure 5. Rainfall erosivity in Moldavian Plateau (MFI)

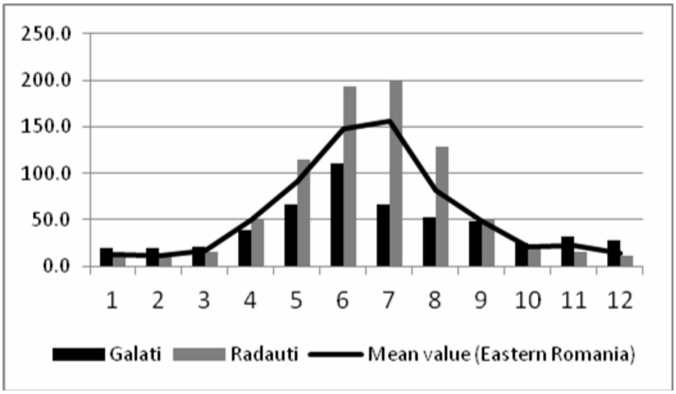

Figure 6. Annual rainfall erosivity regime in Eastern Romania (MFI)

4. CONCLUSIONS

Climatic aggressiveness is most often approached in terms of rainfall erosivity. Direct studies are expensive and most frequently are used indirect methods of computation based on the elements of rain, or on subsumed or average of hourly, daily or monthly rainfall. The first category offers greater accuracy, the second category have the advantage of higher accessibility of climate data. However, both require proper calibration and validation based on direct measurements, but also constantly updating, with the accumulation of ever longer string of climate data and modernization of calculation techniques. Precisely in this perspective and based on indirect calculations performed in Eastern Romania, the author argues the need to review some well-known indicators as eco-pedological indicator 99 from the Methodology of Soil Surveys Elaboration.

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