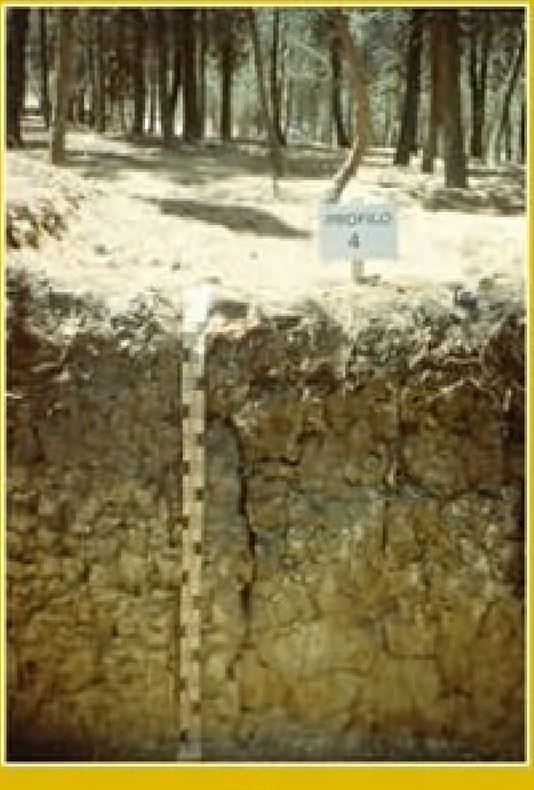
Manual of Methods for Soil and Land Evaluation



Editor

Edoardo A.C. Costantini

MANUAL OF METHODS FOR SOIL AND LAND EVALUATION

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Preface

This manual is revised from a text published in Italian (*Manuale dei metodi di valutazione dei suoli e delle terre*), which belongs to a series of publications about methods of agricultural analysis supervised by Prof. Paolo Sequi (Centro di ricerca per lo studio delle relazioni tra pianta e suolo, Rome) and formulated during the support activities of the National Observatory for Pedology and Agriculture and Forest Soil Quality of the Italian ministry of agriculture (Ministero delle politiche agricole, alimentari e forestali, Rome). The work was endorsed by the VI Commission for Soil Use and Conservation of the Italian Society of Soil Science.

The goal of the manual is to supply an operational tool for pedologists, agronomists, environmentalists, and all of the other specialists who carry out land evaluation for agriculture and forestry or, more generally, stakeholders and policy makers who make decisions at the local level based on the knowledge of the nature of soil. Discussion of the topics is not only technical and operational, but also in-depth and didactic; therefore, the text may also be used as a valid complement for students majoring in subjects that involve soil use, management and conservation. Such knowledge has gradually increased in recent years, thanks to research, experimentation and many programmes of pedological survey done on a detailed scale. In particular, the studies to determine land capability and suitability for cultivation have assumed an integrated and interdisciplinary character, involving aspects pertaining to environmental factors (soil and climate foremost), ecology, agro-techniques and genetics, and the transformation and analytic and organoleptic evaluation of products. Thus was born the concept of crop "vocation" for a land, superseding the concept of suitability. Crop "vocation" connotes qualitative excellence of the crop/land relationship, which is founded on the peculiarities of the land. The identification of crop vocation led to the development of "crop zoning", i.e., the subdivision of a land by its eco-pedological characteristics and the evaluation of crop response. Crop zoning is proving to be one of the most effective tools for making the most of product quality and typicality, which is universally accepted to be the best way to safeguard the rural landscape, especially in the Mediterranean countries.

It was not possible to discuss all of the soil and land evaluation methods in this manual; therefore, reference was made chiefly to experiments carried out in Italy, maintaining a methodology that reflects the indications of the international literature. As stated in the text, the literature offers a wide choice of possible soil and land evaluation methods, while knowledge of the relationships existing between the physical characteristics of lands, particularly those of soils, and the requirements of specific uses is limited. In this manual we have attempted a presentation of the state of the art on these relationships.

The introduction supplies an outline of methodological references, useful for orientation in the choice of the evaluation procedure to use, but also as a source of ideas for further research. Then there is a large collection of selected evaluations and commentaries on examples mostly drawn from Italy. These involve some of the most important applications of soil knowledge for general planning, for crop choice and crop zoning, for the evaluation of land suitability to slurry spreading, and for the reclamation and requalification of contaminated soils.

The formulation of the matching tables is the fruit of the collaboration of specialists from many different sectors, particularly agronomy and pedology. This collaboration is credited with having supplied an updated survey outline of the subject themes and an articulated and organic vision of the Italian and international frameworks.

Even though the manual does not have a rigid setup, each thematic chapter is organized in different sections that follow a common outline. The first paragraphs supply a wide agronomic picture that summarizes the characteristics of the species, cultivation techniques, and edaphic and agrotechnical requirements. The second series of paragraphs illustrate the functional factors of the soils and the environment with respect to the crop under examination, i.e., factors whose significant influence on agronomic results has been proved by research. Then follows a close examination of the indications that may be gleaned from the knowledge of the relationships that exist between soil nature and crop species.

Besides acknowledging all the contributors who made possible the publication of this manual, special thanks are due to Dr. Marcello Pagliai, former President of the Italian Soil Science Society and Director of the Research Centre for Agrobiology and Pedology, of the National Council of Research in Agriculture (CRA-Centro di ricerca per l'agrobiologia e la pedologia, Florence), who encouraged its publication, and to Dr. Elena Capolino, of the same research centre, for her invaluable contribution to the editing of the book.

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5. Soil Erodibility Assessment for Applications at Watershed Scale

Lorenzo Borselli,[1] *Paola Cassi*[1] and *Pilar Salvador Sanchis*[1]

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5.1. Introduction

The term "soil erodibility" indicates the aptitude of a soil, based on its properties, to be eroded by the following processes and exogenous agents: rainfall, runoff, mass movements and wind.

The concept of erodibility gained in importance during the last 50 years in the field of soil erosion modelling and applications of soil conservation. However, erodibility is a concept borrowed from geomorphological literature that was developed and adopted up to the beginning of the 20th century.

In this context, the concept of erodibility was often used to give a qualitative assessment of the effectiveness of various forms of erosion caused by exogenous agents such as water, ice and wind (Davis, 1909). It was used mainly by geologists and geographers for a long time and related to the processes most effective in the characterization of landform dynamics (Taylor and Eggleton, 2001; Turkington et al., 2005). It is easy to associate varying rates of erodibility to compactness of igneous and metamorphic rock masses compared to marls and clay shale, deeply eroded by gullies. Indeed, the effectiveness of different processes and geomorphic agents is directly linked to the characteristics of the bedrock in its state of weathering.

In the late 20th century, the great development of studies on soil erosion and experimentation in the field of soil conservation led to an extension of the erodibility concept also in soil science. The term "soil erodibility" was for the first time used by Middleton (1930).

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An important development in the concept of soil erodibility came about from the study and implementation of the extensive modelling of USLE (Universal Soil Loss Equation) (Wischmeier and Smith, 1978; Lafflen and Moldenhauer, 2003) and from other relevant works (Foster et al., 1981, 2002; Renard et al., 1997; Kinnell and Risse, 1998), which are implementations of the same basic conceptual modelling, which we name "USLE-TYPE".

The original qualitative concept of erodibility used by geologists and geomorphologists assumed a quantitative definition in soil science, through the parameterization of one or more soil characteristics (Bryan, 2000). In USLE-TYPE models, the erodibility mainly assumed an agronomic and soil conservation value. In a broad overview of the theory and modelling of the processes of soil erosion, the term "erodibility" has a major importance in the fields of geomorphology, hydraulics, agriculture and hydrology (Bryan, 2000).

Soil erodibility is not a physical quantity or measurable property like length, mass, or strength. It can be expressed qualitatively (high, medium, low) or quantitatively (a magnitude expressed numerically). In the first case, we proceed through comparison of the results of field or laboratory experiments on different soil exposed to the same erosion agent. In the second case, the soil erodibility can be expressed as an index, number or parameter defined as a coefficient of proportionality between a force, pressure, energy, linked to one or more specific processes or erosive agents. In this case, the numerical value that expresses the erodibility is closely related to a model to estimate the rate of soil erosion.

The use of a numerical parameter to express the soil erodibility is useful, especially in the modelling, but it is also limited because it is strictly linked to the model chosen to estimate erosion. Hence, a universal erodibility index does not exist.

There are various factors influencing soil erodibility. In the case of water erosion processes, soil erodibility is linked to the following:

1. The conditions of the state of aggregation and stability of aggregates during the first wetting (resistance to slaking)
2. Dispersivity of the clay fraction (chemical dispersion)
3. Resistance to surface shear stress (resistance to detachment operated by the rain drops and surface runoff)
4. The infiltration capacity and production of surface runoff
5. The tendency to formation of surface crusts (sealing)

According to Torri and Poesen (1997), the soil erodibility grows with increase in the characteristics listed in points 2 and 5 and may decrease with the characteristics listed in points 1, 3 and 4.

The soil response to the processes listed above is not constant but varies over time. For example, the initial soil moisture at the beginning of the rainfall has an important influence on the hydrological response and on the possibility of a process of slaking (disintegration and weakening of dry soil aggregates due to the matrix tensions developed with the first wetting) active in the early stages of the event. The components of erodibility are therefore highly dynamic over time (Torri and Borselli, 2000). For this reason, the time interval in which the erodibility is evaluated is crucial. Some processes described above operate on different time scales. Soil erodibility evaluated yearly has a different degree of complexity from erodibility evaluated on the basis of a single rainfall event.

The aims of this chapter are to provide the reader with a choice of criteria for assessing soil erodibility in a watershed context, to give an overview of the soil properties that mostly affect erodibility, and at the same time to provide some general guidelines on the various existing modelling approaches.

5.2. Models and Criteria for Soil Erodibility Assessment

The quantitative assessment of erodibility is necessarily linked to a modelling where this parameter is used to assess, within a predefined space-timescale, a potential rate of soil erosion through diffuse or concentrated erosion by water.

More than 80% of current soil erosion models (Doe et al., 1999; Merritt et al., 2003) use an explicit parameterization of erodibility through a coefficient of erodibility, sometimes with more than one (Foster et al., 1995; Misra and Rose, 1996; Rose et al., 1997; Laflen et al., 1997; Morgan et al., 1998).

The diversity of modelling techniques used, space-time steps, type of models (physical, conceptual, distributed, event-based, annual) makes uncertain a single soil erodibility characterization. Some models of soil erosion estimation cannot be applied at watershed scale. In this chapter, we will analyse the erodibility assessment criteria for models that have a higher number of applications, as for USLE-TYPE models.

5.2.1. The K Factor in USLE- TYPE Models

In USLE-TYPE models, the soil erodibility is derived from the study of the combined effect of rainfall and runoff.

According Wischmeier and Smith (1978) and Lafflen and Moldenhauer (2003), erodibility K factor is the rate of soil loss for unitary rainfall erosion energy as measured on a unit plot. The unit plot is 22.18 m long, has a 9% slope, and is continuously maintained in a clean fallow condition with tillage performed upslope and downslope.

In the international system (SI), K is expressed in Mg ha/h/MJ/mm (Foster et al., 1981) and the K values represent an integrated average of annual values of soil and soil profile reaction to a large number of erosion and hydrological processes. The data are collected over a long term (20 years).

The K values are identified using Wischmeier's nomograph (Wischmeier, 1971), then modified by Foster et al. (1981) and Rosewell (1993), in order to express K in SI units (Mg ha/h/MJ/mm). The nomograph in (SI units) is based on the following formula:

$$K=2.77\times10^{-7}(12-OM)M^{1.14}+4.28\text{x}10^{-3}(s-2)+3.29\times10^{-3}(p-3) \qquad (1)$$

where

$$M = T_f(100\text{-}C) \qquad (2)$$

and T_f is the soil fraction in percentage by weight between 0.002 and 0.1 mm (silt + very fine sand), OM is the organic matter (%), C is the clay fraction (%) (< 0.002 mm), p is a code indicating the class of permeability (Table 5.1), and s is a code for structure size, type and grade (Table 5.2) (Soil Survey Staff, USDA, 1951). The formula is applicable for a silt content not exceeding 70%. Note that the use of eq. 1 necessarily entails the use of classification and textural subdivisions into classes according to the USDA classification.

Table 5.1. Soil permeability classes (Soil Survey Staff, USDA, 1951).

Soil permeability classes	Permeability rates for the entire soil profile
1	Rapid, > 130 mm/h
2	Moderately rapid, 60–130 mm/h
3	Moderate, 20–60 mm/h
4	Moderately slow, 5–20 mm/h
5	Slow, 1–5 mm/h
6	Very slow, < 1 mm/h

Table 5.2. Soil structure classes (Soil Survey Staff, USDA, 1951).

• Size	• Type	• Class
• Fine	• Platy, prismatic, • angular blocky, • subangular blocky,	• 4
• Medium	• Platy, prismatic, • angular blocky, • subangular blocky,	• 4
• Coarse	• Platy, prismatic, • angular blocky, • subangular blocky	• 4
• Very Coarse	• Platy, prismatic, • angular blocky, • subangular blocky	• 4
• Fine	• Granular	• 1
• Medium	• Granular	• 2
• Coarse	• Granular	• 3
• Very coarse	• Granular	• 3

The soil permeability class value can be predicted through a qualitative assessment following the original criteria of the USDA manual (Soil Survey Staff, USDA, 1951: 168-170), here represented in Table 5.1. Note that the classes of permeability in subsequent editions of the USDA manuals are changed. However, the nomograph was developed using as reference the 1951 edition.

To use eq. 1, we need to know the fraction between 0.002 and 0.1 mm. If the fraction less than 0.1 mm is not measured directly, it must be obtained through interpolation of the size distribution curve (Nemes et al., 1999). To overcome this element of uncertainty, some authors (Loch and Rosewell, 1992; Rosewell, 1993; Loch et al., 1998), suggest the following relationship, based on several tests on Australian soils for the estimation of M in eq. 1, be used to extend this relationship to all soils as well as the well-aggregated soils and soils with high clay content:

$$M\,(\%) < 0.125 \text{ mm} \tag{3}$$

The authors also suggest that, in addition to eq. 3 for the assessment of M, the following modification be considered to estimate the *K* factor:

$$K_m = \frac{K}{d_s - 1} \tag{4}$$

where K_m is the modified *K* values, d_s is the wet density of sediments expressed in Mg/m^3, which is also assessed by the following relationship (Loch and Rosewell, 1992; Loch et al., 1998).

$$d_s = 1.462 + 0.048(1.03259^x) \tag{5}$$

where *x* is the percentage of soil fraction greater than 0.02 mm.

According to Loch and Rosewell (1992) and Loch et al. (1998), eqs. 3 and 4 should be used as an alternative to the classical methodology (eqs. 1, 2) and always in the case of soils with high clay content, or strong aggregation (e.g., vertisols or soils with high structural stability).

Equations 1 and 2 have a broad range of application, especially with the proposed changes (eqs. 3, 4, 5), but there are also other pedotransfer functions and pedoalgorithms for *K* assessment.

5.2.2. Other Pedotransfer Functions and Pedoalgorithms for Calculating K *Factor (Applicable to Models USLE-TYPE)*

The Revised Universal Soil Loss Equation model (RUSLE, Renard et al., 1997) uses the *nomograph* expressed by eq. 1. To get a more general application, however, other authors have proposed some changes in the calculation of *K*. The RUSLE model manual (Renard et al., 1997) contains an alternative equation for estimating *K* based on a global set of experimental data (255 soils). Only soils with skeleton less than 10% were considered. The value of *K* expressed in international units (Mg ha/h/MJ/mm) is estimated using the following equation:

$$K = 0.0034 + 0.0405 e^{\left[-0.5\left(\frac{\log_{10} dg + 1.659}{0.7101}\right)^2\right]} \tag{6}$$

where *dg* is the geometric mean particle diameter (mm), calculated as indicated by Shirazi and Boersma (1984):

$$dg = e^{\left[0.01 \sum f_i \ln m_i\right]} \tag{7}$$

where f_i is the particle size fraction as a percentage and m_i is their average diameter (mm).

This equation is presented in RUSLE for general use as an alternative to eq. 1. The eq. 6 is useful when the data for estimating *K* factor by the Wischmeier-Foster approach are not available. Note that the evaluation of *K* factor obtained by eq. 6 does not take into account the possible effects of organic matter content. Furthermore, the high value of the coefficient of determination obtained by the authors for eq. 6 is due to the fact that eq. 6 is derived by means of a non-linear regression between the average values of *K* for different values *dg*. In practice, considering the actual dispersion of original data set, we obtain a real value of the coefficient of determination that is extremely low.

Trying to develop a more integrated and comprehensive approach, Torri et al. (1997, 2002) proposed an alternative method, which requires also the organic matter content, derived from a large data set on 240 global soils with a skeleton fraction less than 10%.

The alternative wording proposed for the calculation of the *K* factor, expressed in international units (Mg ha/h/MJ/mm), is as follows:

$$K = 0.0293\left(0.65 - Dg + 0.24Dg^2\right)e^{\left\{-0.021\frac{OM}{C} - 0.00037\left(\frac{OM}{C}\right)^2 - 4.02C + 1.72C^2\right\}} \quad (8)$$

where C is the fraction of total clay content, OM is organic matter as a percentage, and D_g is logarithm of the geometric mean of the particle size distribution, which can be directly calculated according to Shirazi et al. (1988):

$$Dg = \sum f_i \ \log_{10}\left(\sqrt{d_i d_{i-1}}\right) \quad (9)$$

where f_i is the mass fraction of particles in the class with range of diameters d_i and d_{i-1} (in mm). If only three main textural components of soil (sand, loam and clay) are available, the argument of square root in eq. 9 can be calculated as in Table 5.3.

Table 5.3. Calculation of parameter Dg in the case of three basic textural components.

Textural component	**d$_i$ (mm)**	**d$_{i-1}$ (mm)**	**d$_i$d$_{i-1}$**	$\log_{10}\left(\sqrt{d_i d_{i-1}}\right)$
clay	0.002	0.00005*	0.0000001	−3.5
loam	0.05	0.002	0.0001	−2
sand	2	0.05	0.1	−0.5

* *Conventionally for the lower limit of clay particles is equal to 0.00005 (mm) (Shirazi et al., 1988).*

When only the data of the textural classes as a percentage (sand (S), loam (L) and clay (C)) are available, D_g can be calculated by the following simplified formula:

$$Dg = \frac{-3.5C - 2.0L - 0.5S}{100} \quad (10)$$

or directly estimated by the diagram in Fig. 5.1.

A comparative study of pedotransfer functions (6, 8) conducted over a large database of 190 Italian soil profiles (Francaviglia et al., 2003) indicated that these two pedotransfer functions are almost equivalent and have the same areas of uncertainty in the estimation of *K*.

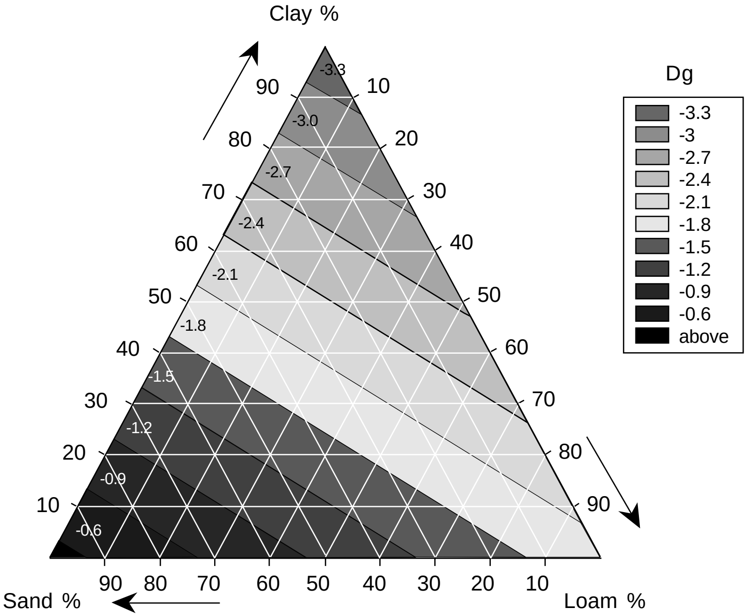


Fig. 5.1. Ternary diagram for the estimation of the parameter D_g (logarithm to the base 10 of the geometric mean of the particle size distribution) used in eq. 8.

The same study also involved a test of the procedure based on a pedoalgorithm based on fuzzy logic implemented in software FUZKBAS (Torri et al., 1997; http://www.fi.cnr.it/irpi/software.htm). The latter procedure, as revealed by Francaviglia et al. (2003), shows more interesting results and the best way to discriminate and differentiate the *K* values in the soil database analysed.

In the software FUZKBAS (Torri et al., 1997), the *K* value is evaluated with the same input parameters of pedotransfer function in eq. 8 and the output is a distribution of values of *K* around a reference value, hence not a single value of *K*. *K* value is given as a fuzzy variable for a given soil type (Torri et al., 1997). The analysis with fuzzy techniques of the global database values of *K* is certainly an improvement over a traditional statistical analysis, but does not provide a definitive result.

Salvador Sanchis et al. (2008) extended the analysis of soil erodibility global databases to soils with rock content (skeleton + rockiness) > 10% in volume, increasing the dataset to a total of 334 soils.

Salvador Sanchis et al. (2008), examining the new enlarged dataset, noted that the climate and rock content have the greatest influence on the *K* factor. Figure 5.2 shows the main groups into which the database is subdivided and highlights the difference of various populations based on the climate classification: cool continental climate (Df, Cf) or warm climate/tropical/Mediterranean (A, Cs,) following the Koppen-Geiger classification.

Note that this diversification based on climate is present in both soils with rock content < 10% and soils with rock content > 10%.

The major evidence is that the soils developed in continental climate have an erodibility that is double that of the soils developed in warm climate.

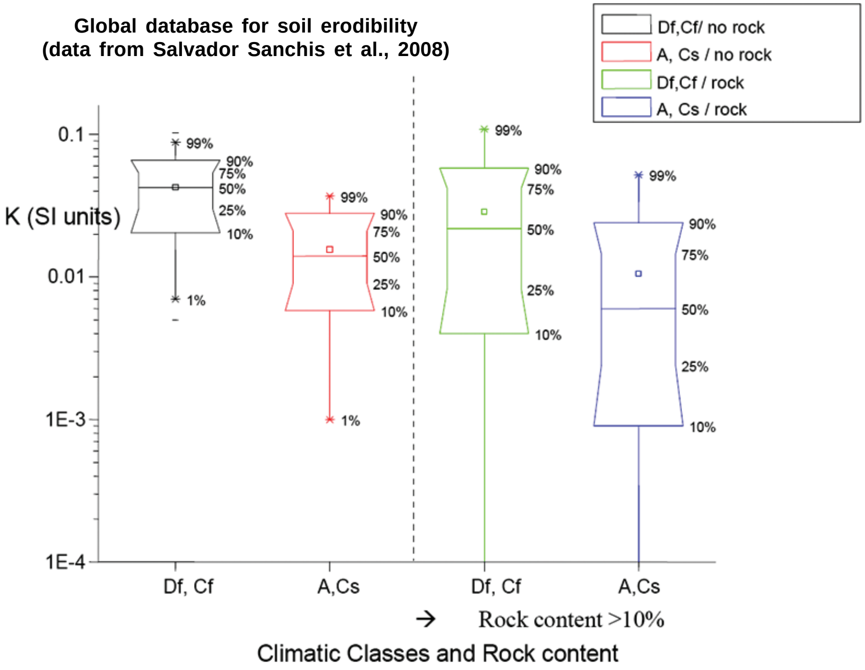


Fig. 5.2. Box and Wiskers plot of soil erodibility values distributions measured for various groups of climatic class following Koppen-Geiger climate classification and rock content %: left < 10%, right > 10%.

A new technique and a specific software are developed to generalize the non-deterministic method for estimating *K*. The new software KUERY1.2 (http://www.irpi.fi.cnr.it/software.htm) (2005) makes it possible to query the database and obtain a statistical distribution of values of *K*, corresponding to given values of soil properties. The input data of KUERY1.2 are climate classification, percentage of total rock content (R), percentage of organic matter content, logarithm of geometric mean of the particle size distribution (D_G) (Shirazi et al., 1988), the logarithm of geometric standard deviation of geometric mean of the particle size distribution (S_g).

In the new procedure, the S_g parameter, which is the logarithm of geometric standard deviation, already defined by Shirazi and Boersma (1984) and Shirazi et al. (1988), is calculated with the following equation:

$$S_g = \sqrt{\sum f_i \left[\log_{10}\left(\sqrt{d_i d_{i-1}}\right) - D_G\right]^2} \tag{11}$$

If only the data of the textural classes in percentage (sand (S), loam (L), clay (C)) are available and D_G is calculated by eqs. 9–10, S_g can be calculated using the following equation:

$$Sg = \sqrt{\frac{\left[C(-3.5 - Dg)^2 + L(-2.0 - Dg)^2 + S(-0.5 - Dg)^2\right]}{100}} \tag{12}$$

In the application of this procedure, it is necessary to know for each soil the climatic class, and in relation to the surface horizons parameters to know D_g. S_g *OM,* and *percentage rock content* (*R*).

The complete frequency distribution of *K* values and its statistical parameters (mean, standard deviation, median, and various quantiles) are derived from the basic input D_g. S_g, *OM,* and *percentage rock content* (*R*). An analysis of *K* values frequency distribution allows us to choose the more representative *K* value for a given soil. This procedure is shown later in the example of application at watershed scale, using also additional information on the soil characteristics that are not usually taken into account in the *K* evaluation. Figure 5.3 shows an example of output of the synthetic pedoalgorithm KUERY 1.2.

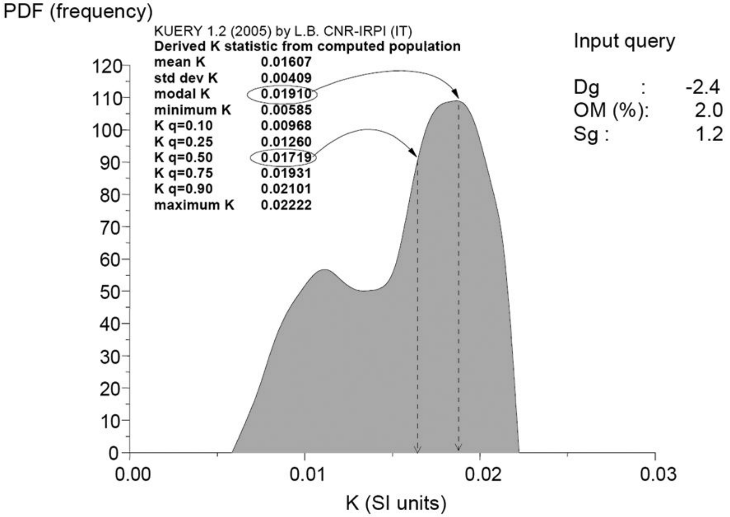


Fig. 5.3. Distribution of possible values of *K* for a soil located in the warm Mediterranean climate group. The probability density distribution (PDF) refers to a soil with rock content less than 10%, $D_g = -2.4$; OM = 2%, $S_g = 1.2$ in a warm and/or Mediterranean climate.

5.2.3 Seasonal Variation of Soil Erodibility

The seasonal variability of *K* value within the year is also considered in USLE and RUSLE models. This variability can be seen on a monthly basis (Rhernad et al., 1997), calculating up to 12 different values depending on the soil moisture content and freezing and thawing cycles.

Usually a corrective coefficient to the mean annual *K* value is calculated by the following equation:

$$K_{mr} = \frac{K_m}{K} \tag{13}$$

where K_{mr} is the ratio between the monthly erodibility K_m and the mean annual *K* value.

The change in erodibility is taken into account using seasonal correction factors, which are strongly influenced by the thermo-pluviometric behaviour of the weather station considered

(Zanchi, 1983; Mutchler et al., 1983). Zanchi (1983, 1988), examining a data set of 169 rainfall events between December 1977 and August 1983, found a very different trend for each month of the year. The best interpolation of experimental data was obtained with the following equation:

$$K_{mr}=1+0.9\cos(0.532t) \tag{14}$$

where t is the month, which is expressed by a number (January = 0.5, February = 1.5, etc.), and the argument of cosine is expressed in radians.

A new, more general approach has been developed from Salvador Sanchis et al. (2008) using a dataset from three locations: Minnesota (USA), Mississippi (USA), Tuscany (Italy) and four different soils.

The new method performs calculation of an index based on the average cumulative temperature of the month starting with the lowest average temperature.

$$T_U=\frac{1}{T_{\max}-T_{\min}}\sum_{M_0}^{M}T_J\ ,\ T_J>0 \tag{15}$$

where:

T_U is a dimensionless index related to the average cumulative air temperature;

T_{max} (°C) is the highest mean monthly temperature;

T_{min} (°C) is the lowest mean monthly temperature;

M_0 is the numerical integer index of the month with the lowest value of average air temperature;

M is the numerical integer index of the month for which T_U is calculated (it varies from 1 to 12);

J is a numerical integer index of the month considered, which varies between M_0 and M;

T_J (°C) is the average temperature of the month J.

Using this definition, K_{mr} can be calculated using the following equation:

$$K_{mr}=4.75\cos\left[0.373\ln\left(3.223T_U\right)\right]+\frac{24.1}{14.0-T_U}-4.83 \tag{16}$$

Please note that if calculated values of K_{mr} are $< 10^{-3,}$ K_{mr} must be equal to 0.

5.2.4. General Consideration on Model for Soil Erodibility Assessment

The uncertainty is evident in all the *K* factor assessment processes, because there are model and parametric uncertainties at the same time. The last type of uncertainty in particular is mainly due to the level of spatial-temporal representativeness of the soil parameters assumed locally for *K* evaluation.

The choice of the model used for *K* estimation has key importance. The application of a single pedotransfer function gives an incomplete evaluation of *K* values, because there is no equation that can interpolate trends, as the global database shows. Pedoalgorithms are valid alternatives because, using basic soil parameters, they estimate the complete frequency distribution of possible *K* values. The use of pedoalgorithm KUERY 1.2 will be shown in the examples of application. The next section will describe the additional soil features that could be a complement and help in K assessment.

5.3. Assessment of Soil Erodibility: Integrations from Erosion Features and Soil Additional Characteristics

All the pedotransfer functions previously presented allow an immediate estimate of soil erodibility for modelling USLE-TYPE on an annual basis, and other developments make it possible to achieve a dynamic assessment of seasonal average values for *K*.

However, the pedotransfer function for estimating the *K* factor from the basic characteristics is unable to consider many other important characteristics that have strong influence on soil erodibility.

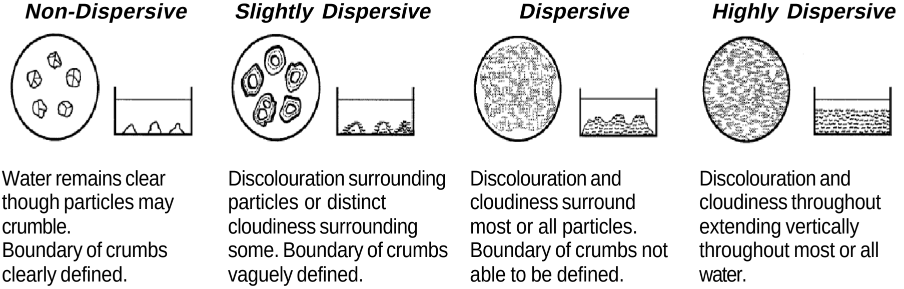
At field scale, we can observe processes of degradation of the soil characteristics that are directly related to erodibility: sealing, crusting, dispersivity. All these phenomena are always linked to a low soil structural stability (Valentin and Bresson, 1992) and can have a strong impact on soil erodibility (Robinson and Phillps, 2001). The *K* values global database, used by several authors to derive different pedotransfer functions, refers to very different soil type, geographic area and climate and the information required for *K* assessment is limited. For example, it does not require information on the potential structural stability and/or dispersivity. Nevertheless, these properties are readily observable in field: qualitative characteristics of soil erosion and re-deposition, and texture and thickness of the depositional structure.

The dispersion of the soil particles is closely related to the chemical characteristics of the circulating solutions and clay mineral constituents (Sumner, 1993; Agassi et al., 1994). There are many tests to assess the dispersion potential (dispersivity) (Vacher et al., 2004). One of the most rapid and well-known is the "crumb test" (Emerson, 1967).

The test can assess the degree of dispersivity of some soil aggregates placed on a Petri-plate with deionized water. A visual analysis of the behaviour of clods after wetting with deionized water is sufficient to give an assessment of the potential of soil dispersivity.

The crumb test can be performed as follow (Fig. 5.4, DNR, 2005):

- Place five air-dried soil crumbs, each about 5 mm diameter, in a squat beaker or glass jar containing 100 ml deionized water.
- Add the soil to the water, not the water to the soil.


Non-Dispersive

Water remains clear though particles may crumble. Boundary of crumbs clearly defined.

Slightly Dispersive

Discolouration surrounding particles or distinct cloudiness surrounding some. Boundary of crumbs vaguely defined.

Dispersive

Discolouration and cloudiness surround most or all particles. Boundary of crumbs not able to be defined.

Highly Dispersive

Discolouration and cloudiness throughout extending vertically throughout most or all water.

Fig. 5.4. Crumb test: visual appraisal and identification of class of soil dispersion potential (from DNR, 2005).

- Let stand without shaking for at least 1 h.
- Note the turbidity of the solution. If the solution is clear, then little trouble from dispersion can be expected.
- Examine the interface between the soil sample and the water. If there is a cloud at this interface, it is indicative of a dispersive soil.

A criterion to assess the soil dispersion potential is the concentration of the major cations of soluble salts in the soil (Na, K, Ca and Mg), and derived or associated parameters: ESP (exchangeable sodium percentage), SAR (Sodium adsorption ratio), EC (electrical conductivity) (Sherard et al., 1976; USDA-SCS, 1991; Sumner, 1993; Bell and Walke, 2000). One of the most interesting parameters related to the soil dispersion potential is the ESP. Many authors suggest conditions of soil dispersion with ESP values higher than 4% (Sherard et al., 1976; USDA-SCS, 1991; Sumner, 1993; Bell and Walker, 2000), and sometimes with values even lower (Barre et al., 2004; Sotelo, 2005). However, the value of ESP is not sufficient by itself to express the soil dispersion potential (Sumner, 1993; Bell and Walker 2000; Vacher et al., 2004). A promising method to identify soils with dispersion potential is one proposed by Barre et al. (2004), which uses ESP and the *Loveday-Pyle* index (LPI), derived from the dispersion test of Emerson (2002) (see Fig. 5.5). This diagram shows five classes with decreasing dispersion from 1 to 5. Classes 4 and 5 do not have dispersive behaviour. In class 4, in cases of high ESP values, the high content of carbonates prevents dispersion.

Soil aggregate stability is also checked by analysing the response to mechanical and/or electrochemical stress. This method is widely used to determine the potential ability of soil to change its state of aggregation (structural collapse) and the consequent promote mobility of fine sediments, which is strictly related to soil erodibility (Le Bissonais, 1996; Le Bissonais and Le, 1996; Le Bissonnais and Arrouays, 1997; Barthès and Roose, 2002; Legout et al., 2005). Several tests have been proposed for soil aggregate stability assessment (Imeson and Vis, 1984;

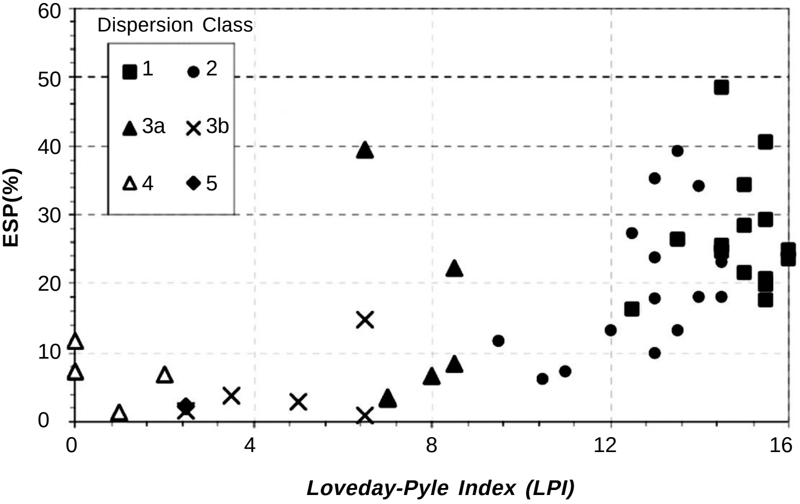


Fig. 5.5. Loveday-Pyle Index (LPI) vs ESP indicating the various classes of dispersion (from Barre et al., 2004).

Kemper and Rosenau, 1986; Le Bissonais, 1996). In all these works, the authors clearly highlight the importance of the stability test to estimate the potential aptitude of soil to be eroded. An example of how the various indices of aggregates stability are linked to soil erodibility, as derived from systematic observations in the field, can be found in Barthès and Roose (2002).

If additional features are known, for crusting potential, dispersivity, and low structural stability, a reliable *K* factor can be better estimated.

These soil characteristics are extremely useful to evaluate erodibility at watershed scale from basic information derived from a soil database integrated with field observations. The process of assessing the K value following the pedoalgorithm KUERY 1.2 can be used to define an expected frequency distribution of K values, obtained through a statistical analysis of *K* values calculated for soils with similar characteristics. For a practical application, however, it is necessary to use a single value of K. With additional information on the aggregate structural stability or dispersion susceptibility, the *K* value to be used within the expected frequency distribution of K values can be selected (Fig. 5.3). The choice can be made with the knowledge of additional properties. For example, in case of clear conditions of structural instability or dispersion, the choice can be addressed more to the 75th or 90th percentile than to the median or modal values. The choice of the highest percentiles of K values distribution takes into account the possibility of high erodibility values in the presence of an additional factor that indicate a major aptitude to erosion (lower aggregate stability, high dispersion potential). An example of this procedure is provided in the next section.

5.4. Soil Erodibility Maps: an Application

The elements for the production of soil erodibility maps at watershed scale are illustrated in Fig. 5.7. It is necessary to produce a reliable soil erodibility map, which requires a detailed soil

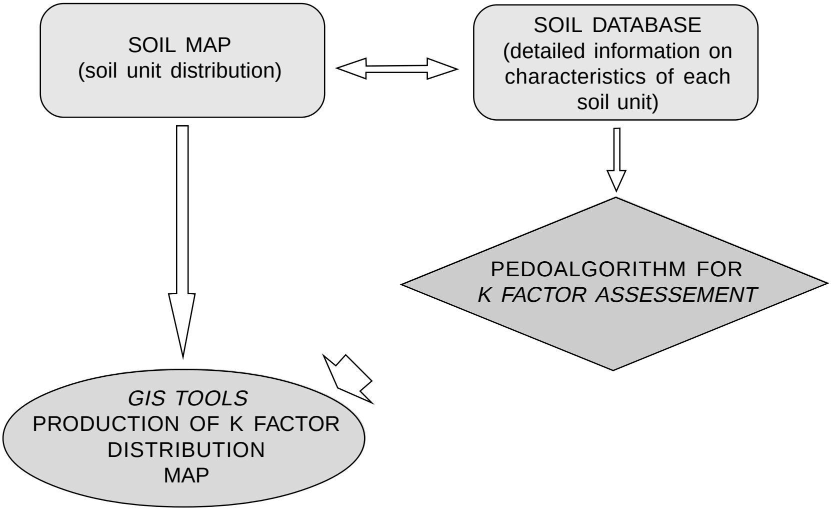


Fig. 5.6. Elements for the production of maps of soil erodibility at watershed scale.

map (at least 1:25,000) and databases with all the relevant properties of each soil unit mapped.

Two other key elements are related to elaborate a soil erodibility map: a pedoalgorithm for estimating the *K* factor for each soil map unit and GIS tools for spatial distribution of K values within the basin according to existing soil units (Fig. 5.6).

In this process, the bond soil unit/reference profile/K value is the key point of the whole system. This bond is a strength point when for each soil unit there is a sufficient number of observations that define the fundamental properties of the unit. The absence of an adequate number of observations, in proportion to the scale of the map, is a weak point of the process of associating the properties of a soil profile to a soil cartographical unit.

The following is an example of the process of mapping the *K* factor at watershed scale.

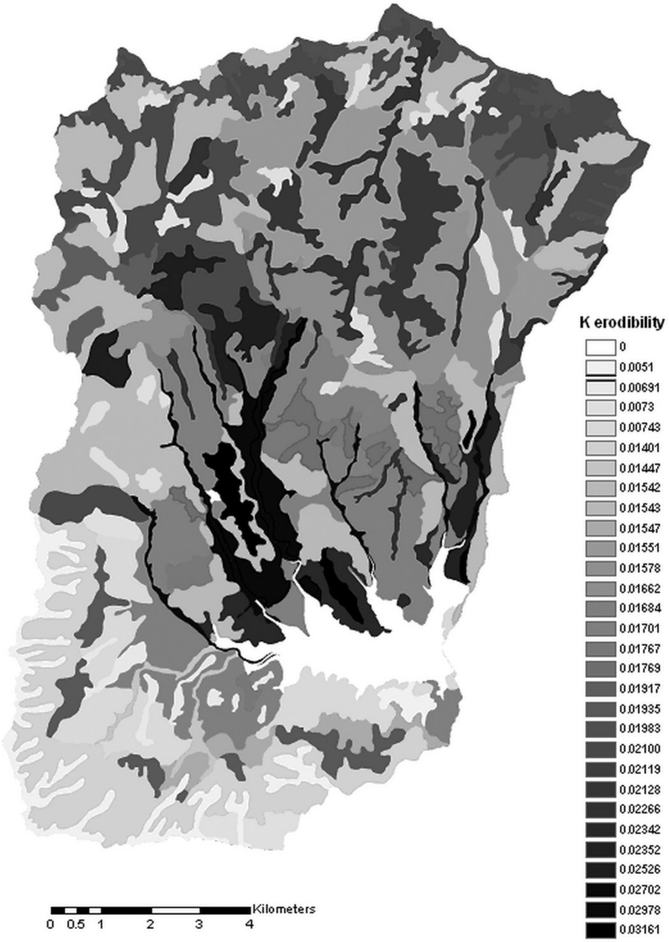


Fig. 5.7. Distribution of soil erodibility values in the Bilancino Basin.

The map was developed in 14 months from 2003 to 2004 with the objective of studying the primary source areas of sediments in the Bilancino basin (Mugello, Tuscany, BABI project, Borselli et al., 2004). In the absence of a soil map at the scale needed, a soil map at scale 1:25,000, functional to estimate the *K* factor for each soil unit, was produced.

The pedoalgorithm KUERY 1.2 was subsequently applied using the soil unit information and new analytical data. Table 5.4 shows the important parameters for the *K* assessment for four different soil units. Units 23 and 25 refer to soil with rock content lower than 10%, while units 13 and 19 refer to soil with rock content higher than 10%. The climate group is temperate/hot/Mediterranean for all the units (Cs).

All data in Table 5.4 refer to the A and Ap horizons of the unit reference profiles.

The pedoalgorithm KUERY 1.2 provides the frequency distributions (PDF) of the *K* values for each unit. The distributions of the *K* values have a free form, so we used a non-parametric statistical characterization. In the table are listed the modal values of *K* and of the following quantiles of the frequency distribution: 0.1, 0.25, 0.5, 0.75, 0.9 respectively (see also Fig. 5.3)

Table 5.4. Parameters relevant to the application of pedoalgorithm KUERY 1.2 for the assessment of erodibility of some soil units. The figures refer to the A or Ap horizons of reference profile identified for each unit.

Unit no.	**23**	**25**	**13**	**19**
Classification (WRB98)	**Profondic Luvisols**	**Gley-Dystric Cambisols**	**Eutri-Skeletic Cambisol**	**Gley-Dystric Regosols**
Textural class(USDA)	**FS**	**F**	**FL**	**AL**
Clay %	18	24	23	40
Loam %	31	32	60	45
Sandy %	51	44	17	15
Rock content %	< 10	< 10	50	26
OM %	1.5	1.35	3.5	2.5
D_g	−1.505	−1.7	−2.09	−2.375
S_g	1.3	1.2	0.944	1.047
K (SI units)	***K* values**			
K (modal)	0.02967	0.02292	0.00384	0.01693
$K_{0.10}$	0.01297	0.015	0.00286	0.00667
$K_{0.25}$	0.0188	0.01911	0.00327	0.01221
$K_{0.50}$	0.02616	0.02352	0.0051	0.01547
$K_{0.75}$	0.03006	0.02776	0.01144	0.01842
$K_{0.90}$	0.03161	0.02979	0.0144	0.01977
K (used)	*0.03161**	*0.02352*	0.0051	0.01547

**We use the 0.9 quantile because horizon A and Ap has ESP > 4.*

In the case of unit 25, 13 and 19, the final value used is the median (quantile 0.5). In the case of unit 23, since the value of the ESP was 6%, we used the 0.9 quantile because of the probable dispersive behaviour of A horizon.

For the whole basin (150 km^2), in most of the units we used the median value of the *K* distribution. Only in 6 of 29 units we used the 0.9 quantile due to the assumed dispersive behaviour (ESP > 4) of A and Ap horizon.

Figure 5.7 is a map of the distribution of *K* values in the entire watershed estimated from benchmark soil parameters associated with each soil unit. The darker portions show higher soil erodibility values and the white portion shows the Bilancino reservoir surface.

The benefits of a detailed soil map are evident from comparing the previous existing GIS representations for the distribution of soils of the Mugello and their estimated erodibility.

In a previous work on the same watershed (Cassi, 2002), due to lack of soil maps, the erodibility was estimated by extrapolating data from lithological characteristics of the substratum and on two *K* values calculated experimentally in two soils in the area of Mugello (Zanchi, 1988).

The comparison of the two erodibility maps, the Cassi (2002) map and the map derived with the KUERY 1.2 methodology (Borselli et al., 2004), both developed in a raster resolution 10x10 m, evidences the obvious limits of the methodology for estimating the *K* factor on the basis of lithology alone. The distribution of soil units obtained of the soil map in the BABI project has a low correspondence to the division into lithological units, consequently leading to a different distribution of *K* values.

The *K* values derived from lithological map underestimate the soil erodibility up to 80% in northern and central areas near the ridge and central valley areas surrounding the Bilancino reservoir (mainly in units associated with different soil orders of terraces), and overestimate up to 250% in areas of the southern ridge of the watershed (Fig. 5.8).

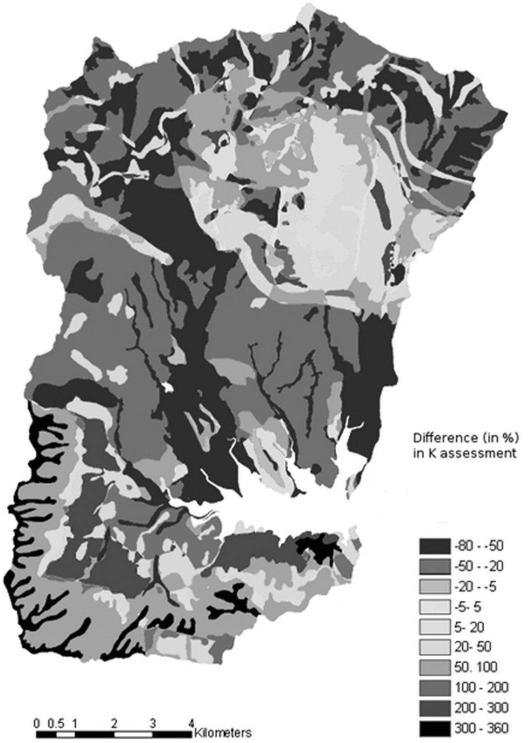


Fig. 5.8. Map of the difference between *K* derived from lithologic map and *K* derived from soil map.

These data were obtained through a calculation of the difference in percentage between the *K* values derived from lithological map (Cassi, 2002) and the *K* derived from soil map (Borselli et al., 2004).

These results give clear evidence how low is the correspondence between data derived from lithology and those derived from soil, and how great may be the error in the extrapolation of erodibility values, bound to the physical and chemical properties of soil (texture, organic matter, rock content), from lithological characteristics that provide none of these data.

The algorithms and rules that make it possible to estimate soil erodibility from physical and chemical characteristics of various soil horizons are consolidated techniques of soil science and of soil conservation modelling. The erodibility values of a particular lithology, on the other hand, are largely subjective and not supported by any database of measured values, as are the values of soil erodibility (Torri et al., 1997).

5.5. Guidelines for Assessing Soil Erodibility

From the application at watershed scale we understand the importance of soil map cartography and a soil database appropriate for the purposes of charting a soil erodibility map that is reliable and based on current scientific knowledge. Estimation based only on lithological information or geological map generally has poor reliability and, as the example above indicates, could lead to large over- or underestimates of the *K* value. However, maps of soil erodibility from inadequate maps (geological map at 1:100,000 or lower scale) or from unsuitable scale (soil map of Italy 1:1,000,000) have been widely produced in the past. These practices should be discouraged.

An acceptable compromise between cost and benefits is a soil map at 1:25,000 scale. The knowledge gained about the soils in a given region, the sensitivity and the experience may, however, represent key elements of the estimate of *K*.

The guidelines for assessing erodibility at watershed scale can be summarized in the following points:

- Availability of adequate soil mapping and an organized soil database.
- For each soil unit in the soil database, selection of the physical-chemical soil parameters necessary for the selected pedotransfer function or pedoalgorithms for *K* factor estimate.
- Where available, use of additional information on phenomena related to structural instability and dispersivity potential of the soil.
- The lack of information does not justify the use of alternative map type (geological maps or insufficiently detailed soil maps) from a technical and scientific point of view.
- The use of lithological characteristics alone for the estimation of soil erodibility has no scientific basis and therefore should be rejected.

Acknowledgements

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