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Scale effect in USLE and WEPP application for soil erosion computation from three Sicilian basins

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Abstract

Accurate estimation of soil erosion due to water is very important in several environmental contexts, such as the assessment of potential soil loss from cultivated lands and the evaluation of the loss of water storage capacity in reservoirs due to sediment deposition. Several studies have been carried out to build models suitable to quantify the results of erosion processes. These models, calibrated from experimental studies on plots or fields, have been applied at quite different scales. The aim of this paper was to present the results of the application of two soil erosion models, both spatially distributed, to three large Sicilian basins upstream of reservoirs. Each basin was subdivided into hillslopes, using three different classes of average area, in order to estimate the scale effect on the sediment yield evaluation. The first model was the empirical Universal Soil Loss Equation (USLE), and the other one was the physically based model of the Water Erosion Prediction Project (WEPP). A Geographical Information System was used as a tool to handle and manage data for application of the models. Computed sediment yields were compared with each other and with measurements of deposited sediment in the reservoir, and for these cases the WEPP estimates better approximated the measured volumes than did the USLE. Neither model appeared to be particularly sensitive to the size area of the hillslopes, at least within the range of values considered. This suggests that a finer subdivision, although it may better define the experimental conditions (plot or field areas) for calibration of models, may not result in a better estimate of erosion.

Keywords: Soil erosion; Universal Soil Loss Equation; Water Erosion Prediction Project; Geographical Information System; Scaling; Runoff; Watershed

1. Introduction

Soil erosion is a serious problem that stems from a combination of agricultural intensification, soil degradation, and intense rainstorms. Erosion may also be exacerbated in the future in many parts of the world because of climatic change towards a more vigorous hydrologic cycle. Many planning and management theories and formulas have been developed in order to reduce soil loss from basins and, as a result, sediment transport to hydrologic drainage networks.

This latter phenomenon has a great deal of importance in optimising policies for management

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of water resources, particularly when sediment is generated in such a way as to seriously reduce the capacity of reservoirs. Storage capacity of existing reservoirs is a valuable and non-renewable resource that must be protected from 'sediment danger' (Di Silvio, 1996), and which can be restored only through costly periodic dredging. It is therefore desirable to predict distributions of soil loss, sediment yield, and sediment deposition upstream of a dam in order to plan structural works and other means for reducing the problem.

In recent decades, models have been built (empirical, conceptual, or physically based) in order to represent and to quantify the processes of detachment, transport, and deposition of eroded soil, with the aim of implementing assessment tools for educational, planning, and legislative purposes (Renschler and Harbor, 2002). Since the phenomena are complex and depend on many parameters, calibration of models is difficult, especially because field data are usually not sufficient and relate to small spatial and temporal contexts.

Empirical models have been and are still used because of their simple structure and ease of application, but as they are based on coefficients computed or calibrated on the basis of measurement and/or observation, they cannot describe nor simulate the erosion process as a set of physical phenomena. The Universal Soil Loss Equation (USLE) is the most widely used empirical erosion model (Wischmeier and Smith, 1965). It estimates soil erosion from an area simply as the product of empirical coefficients, which must therefore be accurately evaluated. Original values of such coefficients were derived from field observations in different areas within the eastern part of the U.S., but they have been expanded with time using information gathered by researchers who have applied the USLE (and derived models) in different countries in the world (see, for example: El-Swaify and Dangler, 1976; Dissmeyer and Foster, 1981; reference list in Renard et al., 1997). When the USLE is applied, care must be taken in recognising the correspondence with cases already observed—when existing—in order to choose the correct value for the empirical coefficients. As a consequence, attention must be paid to the reliability of results when an application is made outside the range of experimental and calibration conditions.

Physically based models simulate the individual components of the entire erosion process by solving the corresponding equations; and so it is argued that they tend to have a wider range of applicability. Such models are also generally better in terms of their capability to assess both the spatial and temporal variability of the natural erosion processes. The Water Erosion Prediction Project (WEPP) is a physically based model that predicts soil loss and deposition using a spatially and temporally distributed approach (Foster and Lane, 1987; Nearing et al., 1989a; Flanagan and Nearing, 1995).

Any model for computing potential soil loss from an area must deal with a large number of variables, i.e. parameters concerning vegetation, management, soil, topography and climate. When available spatial data are geo-referenced and can be put in the form of maps, Geographic Information Systems (GIS) allow simpler and faster data and parameter management. Therefore, GIS can make soil erosion studies easier, especially when repeated applications of similar and complex procedures are required.

The aim of this study was the evaluation of the scale effect in the application of two models, the empirical USLE and the physically based WEPP model, to three Sicilian basins upstream of reservoirs, using a distributed approach. Each basin was subdivided into hillslopes, so that each of them was individually analyzed for erosion due to rainfall and runoff, and resulting areas could be considered hydraulically independent. ArcView GIS 3.1 (ESRI, 1996) was used as a tool to manage data and perform the computations as much as possible in an automated way, for the sake of both easing computation and obtaining a consolidated procedure that could be repeatedly followed for systematic inquiries.

2. The scale problem

Erosion spans a wide range of spatial scales that includes the simple plot for scientific study, the field scale for the interest of the single farmer, catchment scale for community level issues, and regional and national scales for policy-maker interests (Kirkby et al., 1996). Several monitoring studies on water erosion from arable lands have been conducted (Evans, 1993; Boardman and Favis-Mortlock, 1993).

These studies show that the specific mean soil loss rates from field-sized areas are much lower than those from plot-sized areas, stressing the importance of the scale.

Both empirical and physically based models have been applied at quite different scales. When the models are applied to large areas, either a lumped or a distributed approach can be used. In this latter case, the total area is subdivided into smaller units. Studies on scale effects in computing soil losses using an empirical equation (e.g. the USLE) for a large basin subdivided into small areas through a regular (square) mesh (Julien and Frenette, 1987), have utilised a correction factor for erosion estimates that decreases with the size area of grid cells. A grid size analysis (Julien and Gonzales del Tanago, 1991) showed that such a correction factor primarily depends on the average slope gradient and not on the spatial variability of the other factors in the USLE.

In another study, runoff and erosion of fine sediment was computed with the SWAT model (Arnold et al., 1993), which uses the NRCS curve number for runoff and the Modified USLE for soil loss estimates, for various subdivisions of an experimental watershed (Bingner et al., 1997). Results showed that, while runoff volume was not appreciably affected by the size of sub-watersheds, computed fine sediment yield was quite sensitive to it.

An analysis of sensitivity of the WEPP model to different resolutions and accuracy of three elevation data sets on the same area was carried out by Renschler and Harbor (2002), which indicated that coarser data overestimated erosion loss compared to high resolution data. Most interestingly, the results demonstrate that WEPP provided reliable results when only commonly available topographic data were used.

3. The USLE

The USLE (Wischmeier and Smith, 1978) allows one to estimate average annual soil loss for given natural and anthropogenic conditions. It was created as a support to soil conservation planning at the field scale. The USLE computes soil loss (in t $\mathrm{ha}^{-1}\ \mathrm{yr}^{-1}$) as the product of six parameters:

$$soil\ loss = R\ K\ L\ S\ C\ P \tag{1}$$

where

R (EI units, i.e. MJ mm $\mathrm{ha}^{-1}\ \mathrm{h}^{-1}$, where EI is the rainfall erosivity index) is the rainfall factor, computed on the basis of rainfall energy and the maximum 30-min intensity of a rainfall;
K (t $\mathrm{ha}^{-1}\ \mathrm{yr}^{-1}$ per unit R) is the soil erodibility factor, which is function of soil characteristics;
L (dimensionless) is the slope length factor, computed as $L = (\lambda_\mathrm{f}/22.1)^m$, where λ_f is the length in the runoff direction from the upstream point to the point where deposition begins on the hillslope and m an exponent (≤ 0.5), the value of which is a function of the average slope;
S (dimensionless) is the slope steepness factor, equal to $(0.43 + 0.3s + 0.043s^2)/6.613$, where s is the average slope along the main flow path;
C (dimensionless) is the cropping-management factor, that is function of land use type; and
P (dimensionless) is the erosion-control practice factor (usually contours, strip cropping, or terraces).

For field scale applications, local values of such factors can be obtained from diagrams and tables, which were originally developed after experimental research carried out at 49 sampling stations in 26 states of the USA, on the basis of data for more than 10,000 plot-years of erosion data from natural runoff plots (Wischmeier and Smith, 1978). As a general rule, such values are intended to assess soil loss at the same scale from which they were extracted.

The USLE has been widely applied at a watershed scale on the basis of a lumped approach (Williams and Berndt, 1972, 1977; Wilson, 1986; Griffin et al., 1988; Dickinson and Collins, 1998). GIS development, which reduces the time of analyses, has allowed for the application of USLE with a spatially distributed approach. Watersheds have been subdivided either into cells of a regular grid (Julien and Frenette, 1987; Julien and Gonzales del Tanago, 1991; Pilotti et al., 1996; Kothyari and Jain, 1997; Gabriele and Gaudio, 1998) or into units where a unique runoff direction exists (Kertész et al., 1995; Huszàr, 1999). Alternatively, by applying the USLE with a physically based approach, a catchment can be subdivided into hillslopes. Following a procedure recently proposed (Amore et al., 1998; Santoro et al., 2002) each hillslope can be further subdivided into homogeneous plots.

As the equation does not account for deposition phenomena along hillslopes, in order to assess sediment yield it is necessary to estimate the Sediment Delivery Ratio (SDR). In the scientific literature SDR is considered as a function of the slope (Kling, in Hadley et al., 1985; Kothyari et al., 1994; 1996) or, on the basis of a morphologic criterion, of the Probability Density Function (PDF) of the travel time, evaluated as a function of slope and slope length (Ferro and Minacapilli, 1995). In the present work, the authors use a new approach similar to this latter one, where the travel time is considered proportional to the ratio between the length of the path to the closest stream and a representative velocity, using the assumption of uniform flow and constant intensity rainfall (Santoro et al., 2002).

4. The WEPP model

WEPP (Flanagan and Nearing, 1995) is a continuous simulation model that is able to predict spatial and temporal distributions of net soil loss and deposition for a wide range of time periods and spatial scales. The Hillslope version computes erosion along a single slope profile, while the Watershed version can be used to assess soil loss at the catchment scale. In this latter case the watershed is idealised with multiple hillslopes, channels and impoundments.

The model is composed of several components, taking into account climate, hydrology and water balance, plant growth with residue decomposition and agricultural practices, soil composition and consolidation. In particular, with regard to weather, WEPP can read climate data from two different input files: CLIGEN (Nicks et al., 1995) or BCDG, i.e. Breakpoint Climate Data Generator (Zeleke et al., 1999). Infiltration is estimated through the modified Green-Ampt equation for unsteady rainfall. The runoff, i.e., the difference between rainfall and infiltration rates, is routed over the land surface on the basis of kinematic equations. A steady state continuity equation is used to calculate the erosion rate as the sum of rill and interrill erosion amounts (Flanagan and Nearing, 1995).

Many examples of WEPP application may be found in the scientific literature, including: the influence of different soil uses on model results (Dedecek, 1984; Lindstrom et al., 1999; Reyes et al., 1999; Zangh et al., 1999); the calibration of some variables in situations different than those initially provided with the model, such as transport capacity in rill shallow water (Zartl and Huang, 1999) and erodibility parameters in rangeland (Nearing et al., 1989b; Dobrowoloski, 1994; Laflen et al., 1994); the calibration of parameters regarding infiltration and runoff processes (Bjorneberg et al., 1999; Duiker et al., 2001; Savabi, 2001); and the application to areas not included in the U.S. geographic territory (Klik et al., 1995; Ranieri et al., 1999; Zeleke, 1999; Bacchi et al., 2000; Santoro et al., 2002).

Studies on the effect of the scale of WEPP application are few. Renschler and Diekkruger (1999) implement a regionalisation method, which has the advantage of requiring a lesser amount of data and a significant reduction of calculation times. Reasoning that it is of limited value to apply a model to a scale different than the one for which it has been developed, they applied WEPP to a limited number of sample areas within a watershed. The interpolation of the results, gathered for hydrologically homogeneous areas, were then extended to the whole watershed.

Managing large quantities of data for WEPP application at the watershed scale is considerably simplified through GIS technology. Examples of GIS use (Savabi et al., 1995, 1996; Ranieri et al., 2002) concern only the evaluation of specific parameters to be used as input data for the model application. In order to allow the transfer of input data from a GIS to WEPP routines, a research group has worked to link WEPP and a GIS. In particular, Cochrane and Flanagan (1999) developed an interface between WEPP (the Watershed version), and ArcView GIS for small basins (0.59 to 29 ha), comparing the results obtained from the manual application of WEPP with those obtained using the interface, and studying the effect of the DEM resolution on the results from GIS-WEPP. There were no significant differences between the manual and the automated applications, and results obtained from different classes of resolution

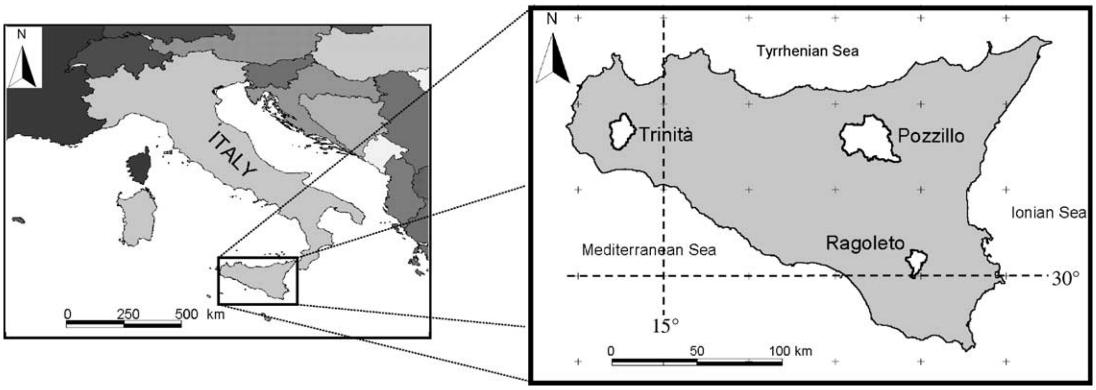


Fig. 1. Location of the three study areas, Sicily, Italy (the coordinates are referred to Lat/Long system).

were also not statistically different. Further development in techniques to automate applications of the model has resulted in GeoWEPP, a tool that allows the user to derive topographical input parameters (Renschler, 2003).

5. The study areas

Both USLE and WEPP were applied to three catchments in Sicily (Italy) upstream of reservoirs: Ragoleto, Trinità and Pozzillo lakes (Fig. 1). Their drainage area, soil use, and soil characteristics are listed in Table 1.

Ragoleto reservoir is located on the Dirillo River, in southern Sicily. The sediment volume in the lake, computed by comparison between the undisturbed land topography before dam construction (1962) and bathymetric measurements (taken in June 1972), was approximately 213,000 m^3 (Santoro et al., 2002); moreover specific dry weight of sediment in the lake, as measured from field samples, was approximately equal to 1350 $Kg_f\,m^{-3}$ (Amore, 1999). Trinità reservoir, on the Delia River, lies in western Sicily.

Table 1
Drainage area, soil use and soil characteristics of the study areas

Basin	Drainage area (km^2)	Soil use	Soil characteristics
Ragoleto	115	Meadow and pasture (49%) Olive grove (30%) Vineyard (18%) Other (wood, crop) (3%)	Submarine and subaerial lava flows Limestone Marly and clayly levels
Trinità	185	Vineyard (47%) Wheat (29%) Meadow and pasture (21%) Wood (3%)	Arenaceousclayly sequences Gypsum beds Limestones Claystones Sandstones Alluvial deposits
Pozzillo	570	Pasture (33%) Crop (32%) Crop with trees (9%) Wood (9%) Fruit trees (7%) Pasture with trees (5%) Other (vineyard, shrubs) (5%)	Marlyclay Marly limestone Sandylimestone Gypsumarenaceous sequences

The dam was completed in 1959. Sediment volume in the lake is known from a study carried out by Tamburino et al. (1989), according to which it was estimated to be 6.11 Mm^3 in 1982, and specific dry weight measured from site samples was 1440 $Kg_f\,m^{-3}$ on the average. Pozzillo reservoir, located in the eastern part of Sicilian territory, was created by damming the Salso River in 1958. High sediment transport has always caused difficulties in the operation of the lake. Sediment volume was approximately 26 Mm^3 in 1984 (Tamburino et al., 1989), which means a yearly average reduction of storage capacity of 0.69%, while specific dry weight from site samples was 1250 $Kg_f\,m^{-3}$ on the average.

6. Methods

For comparisons between model estimates and sediment volumes, the hypothesis was made that all estimated eroded material that reaches the stream network also reaches the outlet section (i.e. the transport capacity of the river was not limiting).

In order to provide the best comparison between the two models, input data were organised so as to have a common basis. In particular, basins were partitioned into hillslopes, and their geometric, geological and land use characteristics were defined and quantified before application of the models. Specific data for each model were then prepared separately, as needed, for each model.

6.1. Topographic data

First, contour lines within each basin were digitized from a topographic map at 1:50,000 scale (Istituto Geografico Militare ed. 1, 1970, 1971, 1974). Digital Terrain Maps (DTMs) were built with the GIS by using different values of cell area. Then, the hydrographic network in each DTM was constructed, through the appropriate GIS option, and compared with the one previously digitized from the maps of the areas. DTMs obtained with cells $25\times25\ m^2$ wide were chosen for all basins, those being the ones having the most similarity between the constructed hydrographic networks and the observed ones (Fig. 2). DTMs of the three basins are shown in Fig. 3.

Next, subdivisions were made using a morphological criterion, with the aim of obtaining hillslopes where a main flow direction could be clearly detected. To this end, a GIS routine, which identifies the flow direction, associated with local steepness, was used to detect ridges inside the basins separating adjoining hillslopes. By varying the degree of detail in such a step, different subdivisions for each basin were obtained. Three subdivisions for each basin were chosen: a fine one, a gross one and an intermediate one (compared to the total area, and thus different in each basin). For sake of completeness, it must be noted that the sub-area maps obtained directly from the GIS had to be 'cleaned' to eliminate very small and irregular areas that were not meaningful from a physical point of view. These areas were incorporated into nearby hillslopes according to local topography.

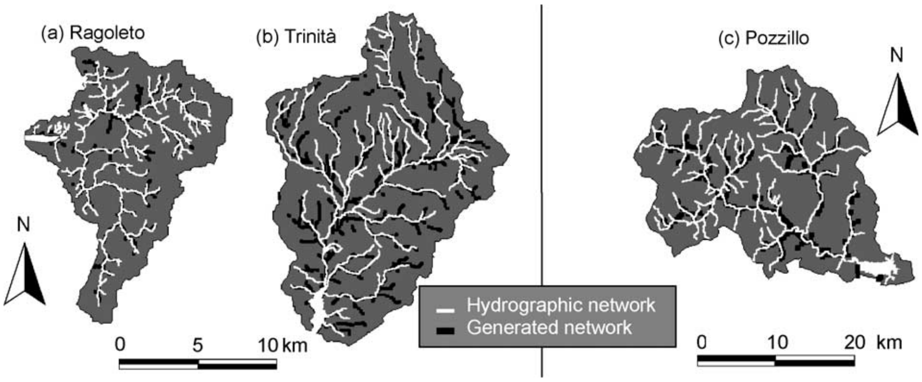


Fig. 2. Comparison between generated hydrographic networks and real ones.

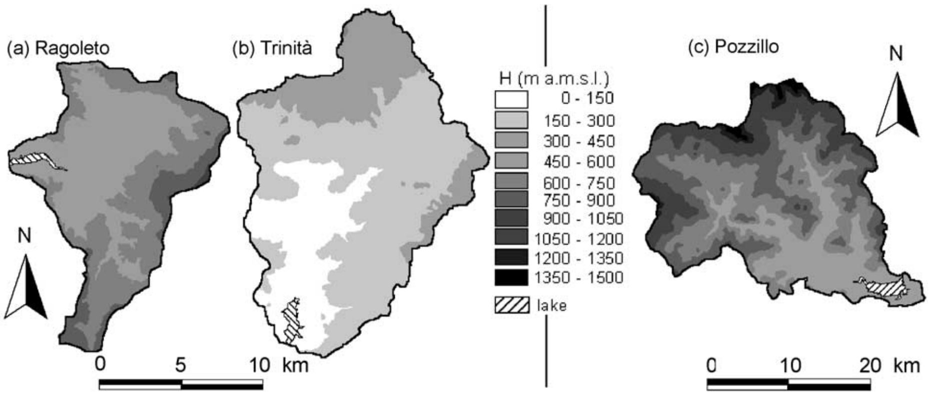


Fig. 3. Digital Terrain Models as reconstructed for the three considered basins.

Fig. 4 shows the maps of the hillslopes in the three basins, and Table 2 shows their number and the corresponding average areas. It should be stressed that such maps were obtained with a purely morphological criterion (i.e. based only on topography) and are therefore independent of any other characteristic (such as geology, vegetation, hydrology, or anthropogenic intervention) of the basins. Also, note that the scale of hillslopes corresponding to the finest subdivision for the Pozzillo basin and the coarsest ones for the Ragoleto and Trinità basins can be considered the same.

6.2. Soil and land use data

Existing information on texture classes of soil were transformed into digital data, obtaining a georeferenced soils map for each basin. Cartographic data on land use (Fierotti, 1989) were used to obtain a digital map for each basin, which constituted a starting configuration. Each map was adjusted using field observations, which showed little variations with respect to the older, cartographic information. Such small variations occurred only within small areas, and on the basis of this information, it was assumed that no significant changes in land use occurred within the time periods considered for model runs.

6.3. Hillslope input data

For each basin, morphological subdivisions (see Fig. 4) were superimposed on the soil map and the land use map, so that each hillslope was ultimately characterised by shape, topography, soil, and land use. Thus, nine sets of hillslopes (three for each basin) were obtained. For each of them, sediment yield from the basin was computed as the sum of all values estimated on each hillslope, both with the USLE and the WEPP model.

6.4. USLE application

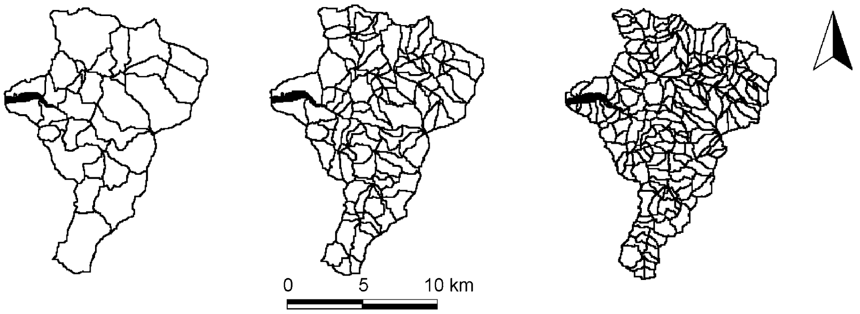
In order to correctly apply Eq. (1) on each hillslope, proper values of all factors had to be chosen. Values of soil erodibility factor K, related to soil type, were taken from tables (ARS, 1975, in Basso, 1995), based on geologic characteristics available from the digital geological map of the areas. In particular, each class of soil was associated with the proper value of K, obtaining a map whereby a specific value of that factor corresponded to each field.

Similarly, a digital map related to the cropping-management values (C factor) was built, by marking each land use type as indicated in USLE tables (ARS, 1975, in Basso, 1995).

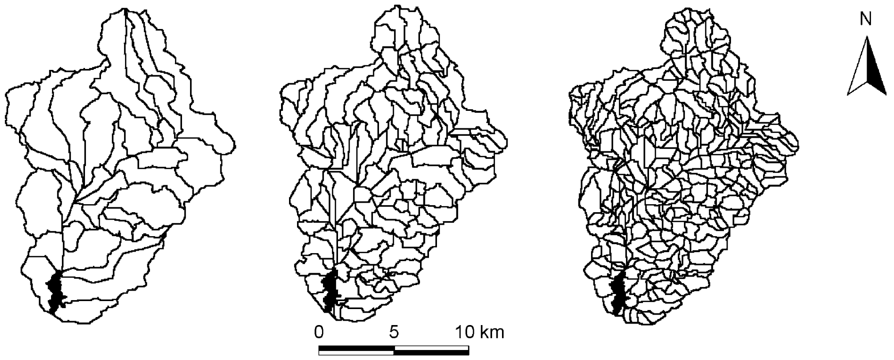
Distribution of the rainfall factor R was obtained from the isoerodent map built for Sicily at a scale of 1:500,000 (Ferro et al., 1991). The isoerodent contours for each basin's area were digitized and a value of R, obtained by average weighed with distance from the closest isoerodents, was assigned to each basin.

Due to the absence of erosion-control works in the basins during the time periods considered, erosion control factor, P, was set equal to one everywhere.

(a) Ragoleto



(b) Trinità



(c) Pozzillo

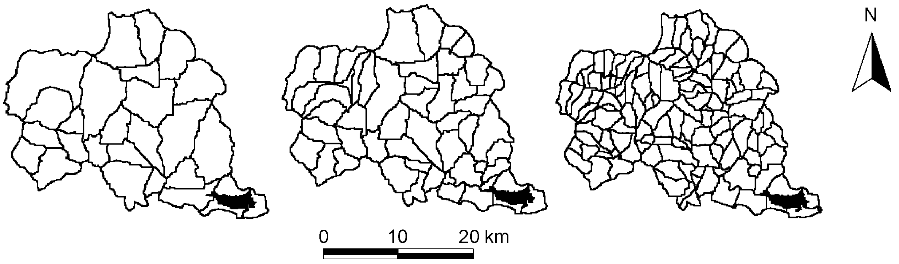


Fig. 4. Morphological subdivisions, as considered for the three basins.

Fig. 5 shows K, C, and R maps for the three basins, as obtained from the above described procedures.

Topographic factors L and S for the hillslopes were obtained as follows: on the basis of slope map, maximum slope paths were traced using Autocad© and imported into the GIS which computed their length and slope.

In cases resulting in K or C values that were not unique within the hillslope area as determined by the topographic analyses, a further subdivision was made so as to obtain homogeneous sub-areas on which to apply the USLE. In such cases, the original hillslope was either to be divided into parallel units (when the new border followed approximately the main flow direction) or into areas in series (when the new border was approximately orthogonal to the main flow direction). In the former case, slope length factor, L, of each sub-area was set equal to the value of the original hillslope. In the latter case, a different evaluation of L was necessary for each area in

Table 2
Characteristics of the hillslopes obtained using a morphological criterion

Basin	Number of hillslopes	Average area of hillslopes (km^2)
Ragoleto	34	3.37
	122	1.01
	235	0.49
Trinità	38	4.93
	122	1.52
	298	0.63
Pozzillo	27	20.79
	52	10.80
	128	4.38

the series. In this case, however, the new length factor of the lower of the two hillslopes could not coincide with the physical length λ_f of the area in the runoff direction, because upslope flow enters the area with a velocity greater than zero, nor it can be set equal to the distance from the upstream point, as the flow operates (i.e. erodes) only on the geometric length of the area.

In the present work, a methodology was used (Santoro et al., 2002), in which L_i in the *i*th area in a series (starting from the top) is computed under two hypotheses: (i) it is a function of the distance from the upstream point; and (ii) eroded soil from a homogeneous hillslope must have the same value when calculated both globally on the total area between the top of the hillslope and the *i*th area, and when calculated as the sum of the eroded quantities from each of the *i* areas. Following this procedure, L_i could be computed as

$$L_i = \frac{k_i^m \lambda_{f_i}^m}{22.1^m} \tag{2}$$

where

$$k_i^m = \left(\frac{\sum_{j=1}^{i} \lambda_{\mathrm{f}_i}}{\lambda_{\mathrm{f}_i}}\right)^m \left(\frac{\sum_{j=1}^{i} A_j}{A_i}\right) - \left(\frac{\sum_{j=1}^{i-1} \lambda_{f_j}}{\lambda_{f_i}}\right)^m \left(\frac{\sum_{j=1}^{i-1} A_j}{A_i}\right) \tag{3}$$

and A_i is the *i*th area.

For each area in a series, the slope steepness factor *S* was computed with reference to its average slope in the runoff direction. Hillslope input data were at this point ready for USLE application both for the homogeneous and non-homogeneous hillslopes. With regard to SDR, an approach was used (Santoro et al., 2002) that allowed for correspondence to the Probability Density Function of *l*/*v*, where *l* is the runoff path to the closest river and *v* is a uniform flow velocity on the hillslope computed under the hypothesis of constant rainfall intensity. In the most general case, which includes also the possibility for an area to belong to a series on a hillslope, SDR$_i$ for the *i*th area in a series turns out to be proportional to the PDF of l_i/v_i, being in turn:

$$v_i \propto \left[\left(\frac{l_i \sum_{j=1}^{i-1} A_j}{A_i}\right) + \frac{l_i}{2}\right]^{-0.4} s_i^{-0.3} \tag{4}$$

As a result, a rather complete GIS database was created both in the form of maps and as a set of tables, each associated with an area of the final hillslope subdivisions, containing information on topography, soils, land use and cover management, and climate.

In order to obtain the total sediment yield, soil loss from each area was multiplied by its, respective, SDR. Yearly average sediment yield P_s was thus assessed by means of the expression

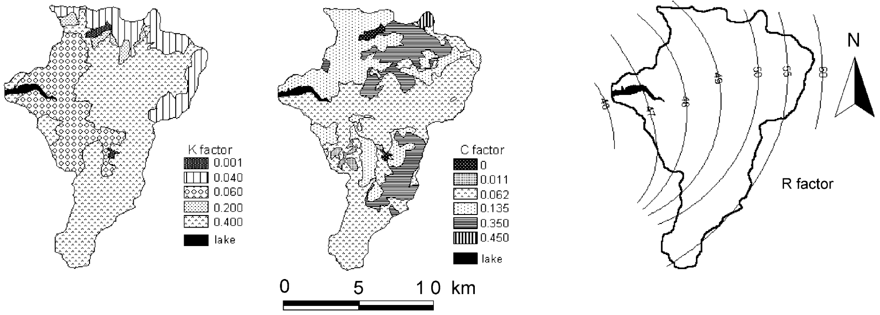
$$P_\mathrm{s} = \sum_{i=1}^{N} R_i K_i L_i S_i C_i P_i A_i \mathrm{SDR}_i \tag{5}$$

6.5. WEPP application

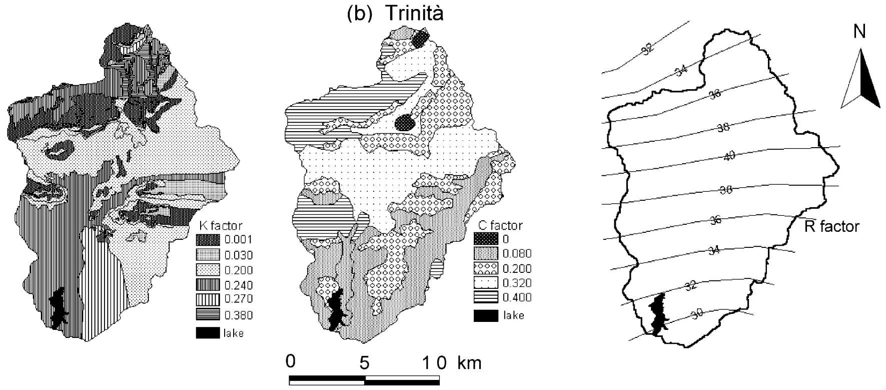
The Hillslope version of the WEPP model (Flanagan and Nearing, 1995) with its Windows-based Graphical User Interface was used in this study. In order to run the model, it was necessary to prepare four different input files regarding climate, topography, soil and land use, for each of the three basins.

For climate, the input processing program CLIGEN was used, as recommended for WEPP. To this end, three thermo-pluviometric stations were chosen within and near each basin in order to assign the relevant area for each station through the Thiessen polygons method. For each station, daily rainfall data and maximum and minimum temperature data over a 30-year period were collected and digitized.

(a) Ragoleto



(b) Trinità



(c) Pozzillo

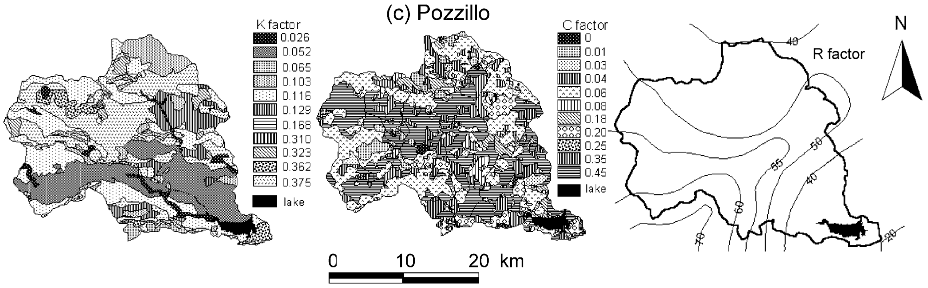


Fig. 5. Soil erodibility factor, *K*; cropping-management factor, *C*; and rainfall factor, *R*, maps for the three basins.

With regard to the slope file, hillslope geometry (slope orientation, length, width, steepness) was obtained, as explained above, through the GIS. In particular, the width *B* of each hillslope was considered constant over the entire slope profile, as WEPP works on the basis of rectangularly shaped areas. The non-uniformities on a hillslope are simulated in WEPP using strips with homogeneous characteristics, better known as Overland Flow Elements (OFE's), which correspond to the same sub-areas in series already considered in the USLE application.

With regard to the soil input file, percentages of sand, clay and rock were obtained on the basis of geological and lithological maps. Organic Matter and Cation Exchange Capacity (CEC) were obtained partly from literature data (Flanagan and Livingstone, 1995) and field data (Amore, 1999). Effective Hydraulic Conductivity (K_e) was computed internally by the WEPP model on the basis of sand and clay contents and CEC. The Interrill Erodibility (K_i), the Rill Erodibility (K_r) and the Critical Hydraulic Shear (τ_c) were computed as suggested in WEPP User Summary (Flanagan and Livingstone, 1995). In particular, as regard to K_r, its value had to be adjusted each time the hillslope had a length greater than 100 m, to meet the condition for this parameter to be correct in WEPP simulations. Slope lengths longer than 100 m result in over-prediction of erosion by WEPP (Baffaut et al., 1997). The Initial Saturation Level was set equal to 50–75% on the basis of soil water content estimated at the beginning of the first year of the entire period of simulation. The Soil Albedo parameter was estimated through the Baumer equation (Flanagan and Livingstone, 1995).

For the plant/management files, some existing files (for pasture and wheat) were used, but it was necessary to create new ones for vineyards, olives and forests, which are not included in the default WEPP dataset. In particular, vineyards and olives input files were built using unpublished field data from the NSERL—RUSLE archives, field data regarding Sicilian environment (La Malfa, 1999) and literature data (Rossi, 1954; Giorgini, 1958; Bruni, 1971; Weaver, 1976; FAO, 1977; Rallo, 1989; Mullins et al., 1992; Leonard and Andrieux, 1998). For forest areas, the input file was built on the basis of data from the original database for running WEPP in forest conditions (Elliot and Hall, 1997). Each WEPP run provided sediment yield for one year through the continuous simulation of the erosion and deposition processes on each hillslope.

6.6. Computation of porosity

Using field data on specific dry weight of sediments, porosity in each lake was computed as a function of the known specific dry weight and the specific solid weight of sediments, which was assumed to be equal to 2,650 $\mathrm{Kg_f\,m^{-3}}$.

6.7. Volumes estimates

Sediment yield, as estimated by both the USLE and the WEPP models, was provided in units of $\mathrm{t\,ha^{-1}\,yr^{-1}}$. In order to perform a valid comparison with measured volumes, estimated volume of sediment in each reservoir was computed by multiplying estimated sediment yield by the relevant basin area and by the proper number of years, and dividing the result both by the specific solid weight of sediments and by the term (1-porosity).

7. Analysis of results

Soil loss estimates were computed for each basin for the corresponding time spans that allowed for comparisons to the available data on sediment volume in the reservoirs. In particular, USLE estimates and WEPP runs covered a 9-year period for the Ragoleto basin, a 22-year period for the Trinità basin, and a 25-year period for the Pozzillo basin. Table 3 reports the values of volume in the lakes computed by

Table 3
Computed sediment yield as function of average area of the subdivision and measured value of deposited sediment

Basin	Porosity	Average hillslope area (km^2)	USLE sediment yield (Mm^3)	WEPP sediment yield (Mm^3)	USLE computed volume (Mm^3)	WEPP computed volume (Mm^3)	Measured sediment volume (Mm^3)
Ragoleto	0.50	3.37	0.432	0.483	0.864	0.966	0.213
		1.01	0.434	0.532	0.868	1.064	
		0.49	0.341	0.464	0.682	0.928	
Trinità	0.46	4.93	0.781	2.232	1.446	4.133	6.100
		1.52	0.668	2.222	1.237	4.115	
		0.63	0.565	2.251	1.046	4.169	
Pozzillo	0.53	20.79	7.320	17.733	15.574	37.730	25.960
		10.80	8.160	17.642	17.362	37.536	
		4.38	7.660	17.985	16.298	38.266	

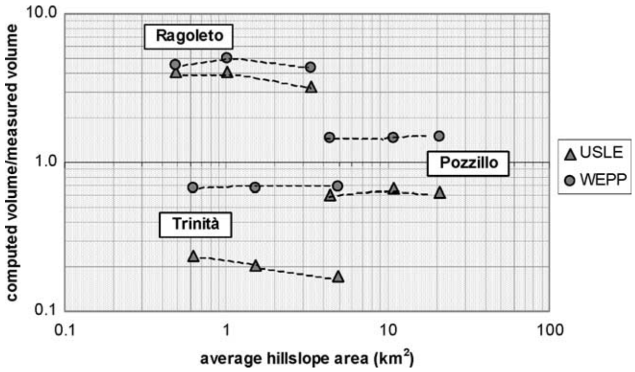


Fig. 6. Ratio between computed and measured volumes vs. subdivision size.

applying the two models to the basins, together with the measured values of deposited sediment.

Results are also shown in Fig. 6, where the ratio between computed and corresponding measured volume in the reservoir is plotted versus the average size of the sub-areas within each basin.

7.1. Effect of area size

Both models appeared to be relatively insensitive to the average size of the areas. Variations in WEPP predicted values were insignificant from a practical point of view, while USLE estimates varied slightly more, although not in a systematic manner (Table 3).

Considering that the watersheds are characterised by different patterns in distributions of soil type and land use (relatively homogeneous in the Ragoleto basin, more variable in the Trinità basin, and highly mixed in the Pozzillo basin, see Fig. 5), the fact that the models' results do not change significantly with hillslope size is encouraging: both models are able to deal reliably with soil and land use variability in the basins. Moreover, it can be observed that: (i) both models were applied to areas with slope lengths longer than those from which models were developed; (ii) average values of hillslope areas and lengths in the runoff direction for each subdivision are comparable for the two smaller watersheds, but very different for the Pozzillo basin, which had a much larger area; and (iii) steepness varied significantly among the three basins. Based on these results, it appears that finer detail in representation of these basins does not improve the prediction capability of the models.

7.2. Model performance

As a general result, in the examined cases WEPP model estimates were always larger than USLE ones. In particular, sediment deposited in Ragoleto reservoir was overestimated by a factor varying between three and five with both models at all of the scales applied; the sediment amount in Trinità reservoir was remarkably underestimated with the USLE (by a factor of 0.2) and little underestimated with the WEPP (by a factor of 0.7); and sediment volume in Pozzillo reservoir was underestimated by the USLE (by a factor of 0.6) and overestimated by the WEPP (by a factor of 1.4). From the results of the present study, a trend can be detected: the greater the amount of eroded sediment, the smaller were the relative errors that resulted with both USLE and WEPP models. Greater relative prediction error at lower erosion rates on the plot scale is a well documented phenomenon, related in part to naturally greater coefficients of variation of erosion at lower erosion rates (Nearing, 1998; 2000; Nearing et al., 1999). The result is also reasonable since a given absolute error by either of the models will result in a greater relative effect on the lesser erosion value.

8. Conclusions

Two models, the empirical USLE and the physically based WEPP, were applied with distributed approaches through a GIS to three large Sicilian basins located upstream of Ragoleto, Trinità and Pozzillo reservoirs in order to estimate soil erosion due to water. The aim was twofold: to compare computed values with measures of deposited sediment in the reservoirs, and to investigate whether and how the detail of subdivision affected the total computed soil loss from each basin.

Each model was applied to hillslopes that were obtained by subdividing the basins on the basis of three different classes of average area using a morphological criterion based only on local topography.

As far as scale effects are concerned, neither model is sensitive to the size area of the hillslopes within the considered range of values. With regard to this result, it is worth pointing out that the considered watersheds are different in their distribution of soil and land use, as well as in the size and average steepness of the sub-areas used. Results suggest that a finer subdivision, even though better approximating the experimental conditions (plot or field areas) originally used to develop the models, is not necessarily needed for a better estimate of eroded soil.

As regard to computed values of deposited sediment, in general, WEPP model estimates were always larger than USLE ones. In particular, USLE and WEPP computed sediment volumes in the Ragoleto lake are comparable and both significantly higher than the measured value, which was fairly small. Sediment volume in the Trinità lake is underestimated with both models, but WEPP estimate is much closer to the measured value than the USLE one. Errors on computed volume in the Pozzillo lake, where the highest amount of deposited sediment was measured, are comparable with the used models, being USLE estimate smaller than the measured one and WEPP estimate higher.

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