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Spatially varied soil erosion under different climates

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Abstract The spatial variability of the factors of the universal soil loss equation is examined on the mediterranean basin of Conca de Tremp covering 43.1 km^2 in Spain. The evaluation of the rainfall erosivity R and the soil erodibility K is relatively straightforward and spatially-averaged values of these parameters can be applied to the entire basin. Conversely, the spatial variability of annual soil erosion losses on large basins depends primarily on the factors L, S, and C describing topographic, vegetation and land use parameters. A grid size analysis of soil erosion losses from the Conca de Tremp basin under mediterranean climatic conditions in Spain shows excellent agreement with the earlier results on the Chaudière basin in Canada. It is concluded for both basins that unbiassed estimates of soil erosion losses are obtained for grid sizes less than about 0.125 km^2. The analysis of the Conca de Tremp basin validates the use of the grid size factor proposed by Julien & Frenette (1987). It is also found that the grid size factor primarily depends on the average slope gradient which decreases with increasing grid size or drainage area. On the other hand, the grid size factor does not depend on the spatial variability of the factors R, K, L and C.

Variabilité spatiale de l'erosion des sols sous différents climats

Résumé Les variations spatiales des facteurs de l'équation universelle de pertes de sol est examinée sur un bassin méditerranéen en Espagne. Sur le bassin de la Conca de Tremp, couvrant 43.1 km^2, on démontre que la variation spatiale des paramètres d'agressivité des pluies R et d'érosivité des sols K justifie l'utilisation de valeurs moyennes sur les bassins versants. Par contre, la distribution spatiale des pertes de sol annuelles dépend essentiellement du relief, de la végétation et de l'utilisation des sols. Ainsi, les parametres L, S et C doivent être évalués soigneusement bien que les méthodes actuelles soient plutôt subjectives. Une analyse de l'influence de la dimension des mailles sur les calculs d'érosion superficielle du bassin de la Conca de Tremp en climat

discussion until 1 June 1992

méditerranéen, en Espagne, corrobore les résultats antérieurs obtenus sur le bassin de la rivière de la Chaudière, Canada. L'analyse des deux bassins démontre que les calculs non-biasés de de pertes de sol sont obtenus pour des mailles de taille inferieure à environ 0.125 km^2. L'analyse du bassin de la Conca de Tremp confirme la validité du facteur de maillage de Julien & Frenette (1987). Ce facteur de maillage dépend principalement de la réduction de pente moyenne des bassins en fonction de la superficie drainée. Par contre, le facteur de maillage ne dépend pas de la distribution spatiale des facteurs *R*, *K*, *L* et *C*.

INTRODUCTION

The extent of erosion, specific degradation and sediment yield from drainage basins relates to a complex interaction between topography, geology, climate, soil vegetation, land use and manmade developments. Sheet and rill erosion induced by raindrop impact and surface runoff constitute major components of erosion losses and sediment yield from large basins. The well-known universal soil loss equation (USLE) revised by Wischmeier & Smith (1978) computes long term average soil losses from surface runoff. Eventually, the USLE is intended to be replaced by the revised USLE (Renard & Simanton, 1990), or the water erosion prediction project (WEPP) (Lane *et al.*, 1988; Lane & Nearing, 1989), in an attempt to incorporate recent advances in surface hydrology, soil erosion and computer technology. The USLE proposed by Wischmeier & Smith (1978) remains widely used on small areas. The USLE is also likely to remain the simplest method available to undertake soil erosion studies on large basins. Extensive use at a larger scale has been reported by Williams & Berndt (1972), Boyce (1975), Renfro (1975), Frenette & Julien (1986) and Lee & Camacho (1986). Applications to large areas involve lumping of several parameters describing vegetation, soil types and topography. Discretization of drainage basins under a small grid usually satisfies the conditions of homogeneity over a grid area. On the other hand, it introduces additional complexities in the calculation of slope and runoff length, and the approach requires large data bases not commonly available.

An extensive grid size analysis on the Chaudière Basin in Canada by Julien & Frenette (1987) showed that grid sizes up to 0.125 km^2 can be applied to large basins without introducing biassed estimates of soil erosion losses when compared with smaller grid sizes. For larger grid sizes, they defined a correction factor which is essentially a function of the grid size area for the calculation of erosion losses from large basins. The following two limitations deserve further consideration: (a) since the analysis was carried out on a single basin in Canada, are the results applicable under different climatic conditions? and (b) because only two parameters, namely slope *S* and vegetation *C* were considered, should the spatial variability of the other parameters *R*, *K* and *L* be considered in further investigations?

This study has been undertaken in an effort to answer those two questions. The objective is to provide additional insight into the effects of spatial variability of the governing soil erosion parameters for the calculation of annual soil erosion losses under mediterranean climatic conditions. The effects of the spatial variability of the factors of the USLE on the calculation of annual soil erosion losses are critically reviewed through applications of the USLE in the Conca de Tremp area in Spain. A grid size analysis is also presented to either validate or modify the grid size factor proposed by Julien & Frenette (1987).

DESCRIPTION OF THE STUDY AREA

The Conca de Tremp area shown in Fig. 1 is located in the Lerida province, in the northeast of Spain. The total area, covering 43.1 km^2 is subdivided into four sub-basins corresponding to the Arroyo de la Columera (14.2 km^2), the Arroyo del Chuli (2.3 km^2), the Barranco de Francoli (19.6 km^2), and the Barrancos de las Moreras y del Molino (6 km^2). These sub-basins are tributaries of the Conques River flowing westerly into the Noguera Pallaresa River, in the pre-Pyrennean area of the Ebro basin.

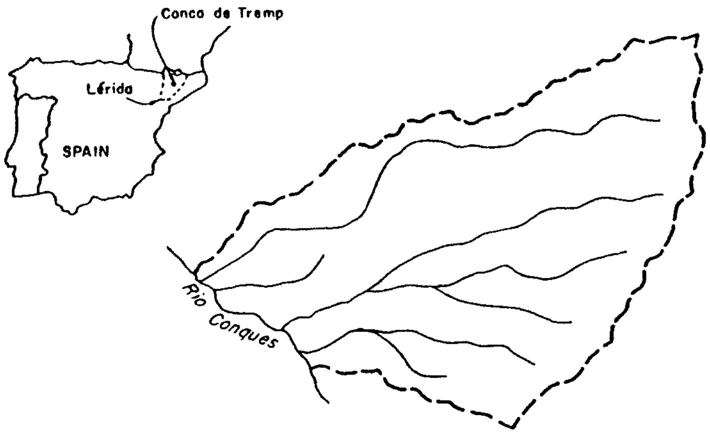

Fig. 1 Location of the Conca de Tremp basin study area.

The highest elevations in this rugged area reach 1460 m a.m.s.l. while the lowest elevations of the sub-basins vary from 530 to 550 m a.m.s.l. with a maximum total relief of 937 m. Detailed information for this study area is available in Redondo (1988). Typical mediterranean climatic conditions prevail in the area, with intense storms at the end of spring and beginning of autumn and dry spells in January–February and early summer. The mean annual precipitation is 690 mm and the mean annual temperature is 12.5°C.

The geology is rather complex, being affected by the orogenic and sedimentation processes in the pre-Pyrennean area. Previous studies (Steering Committee AUW, 1988) recognized four functional soil types corresponding to: piedmonts and conglomerates; colluvial sediments; sandstone and limestone areas; and alluvial sediments. Those soil types are closely related to the vegetation found in the area. The region has been intensively farmed for centuries and only the steepest areas remain forested. Cereals, such as wheat and barley, and almond trees are most common, alternating with vegetables and olive trees in the productive and warmer locations. Natural vegetation constitutes part of the typical mediterranean forest, with several species of oaks (*Quercus faginea, Q. ilex* and *Q. coccifera*) and patches of small mediterranean bushes around and between pine forests (*Pinus sylvestris, P. nigra*).

As a consequence of climate, vegetation and soil conditions, the area shows good examples of all types of erosion, including sheet and rill erosion, frequent landslides and numerous gullies. Detailed information on the Conca de Tremp is available in Redondo (1988) and in Gonzalez del Tanago & Redondo (1989). This mediterranean basin is strikingly different from the Chaudière basin documented by Julien (1979) and Frenette & Julien (1986). The Chaudière basin covering 5830 km^2 in Canada is under a continental humid climate with severe winters, precambrian geology and relatively sparse and recent agriculture. Approximately two-thirds of the basin is covered with dense coniferous and deciduous forests.

EVALUATION OF THE PARAMETERS

The Conca de Tremp basin has been discretized using a square grid of 250 m side oriented NS–EW. Each square element (pixel) covers 6.25 ha resulting in 701 elements for the entire area. Soil erosion losses from each pixel are calculated from the well-known universal soil loss equation, $A = R\ K\ L\ S\ C\ P$.

The rainfall erosivity factor R of the USLE is evaluated using the regression equation developed for the mediterranean area by the Spanish Forest Service (ICONA, 1981) as follows:

$$R = 2.37\ P_{d2} + 0.51\ P_{\max} - 57.4 \tag{1}$$

where R is the erosivity index of the USLE; P_{d2} is the maximum daily precipitation in mm with a period of return of two years; and $P_{\max}$ is the average maximum monthly precipitation in mm. Taking into consideration the elevation differences within the study area, the hypsometric method is applied to obtain spatially varied values of the rainfall erosivity factor R which depend on altitude and precipitation, as recommended for small and medium size basins by Shaw (1983).

The soil erodibility factor K of the USLE is evaluated according to soil texture classification using the values from Stewart *et al.* (1975) considering that the organic matter content is less than 4%.

The topographic factors L and S are difficult to evaluate on large areas. They are commonly analysed together and referred to as the joint factor LS. The detailed results of applying the method of Williams & Berndt (1976) and comparisons with field data have been presented by Gonzalez del Tanago & Redondo (1989). Two methods of evaluating the joint factor LS are considered here: (a) average values for each sub-basin; and (b) values calculated for each grid cell. The first method is based on the contour-extreme-point technique to evaluate the average basin runoff length while the contour-line method estimates the average basin relief. In the second method, the runoff lengths are evaluated from the drainage density method proposed by Horton (1945) and the grid slope gradients are calculated from the grid slope method.

The cropping management factor C is also somewhat cumbersome to evaluate on large areas. Vegetation and land use maps are used to define five different cover types: agriculture, coniferous trees, deciduous trees, range lands and unproductive (urban areas and rock outcrops). Taking into account the values presented by Wischmeier & Smith (1978) for range and idle lands, C values of 0.7 for agriculture and 0.15 for open forest and range land are considered as representative of the study area.

No particular soil conservation practices are observed at the present time, and the conservation practice factor P equals unity. Some decades ago, many "bancales" and terraces were constructed, but field mechanization forced the farmers to remove them in order to improve motor tillage on small and mostly steep field properties.

SPATIAL VARIABILITY OF THE PARAMETERS

A rainfall erosivity map for the Conca de Tremp basin is presented in Fig. 2. The values of R reported in Fig. 2 correspond to average conditions for mediterranean countries as reported by Masson (1971) and ICONA (1981). The spatial variability of the factor R is not significant and average values for

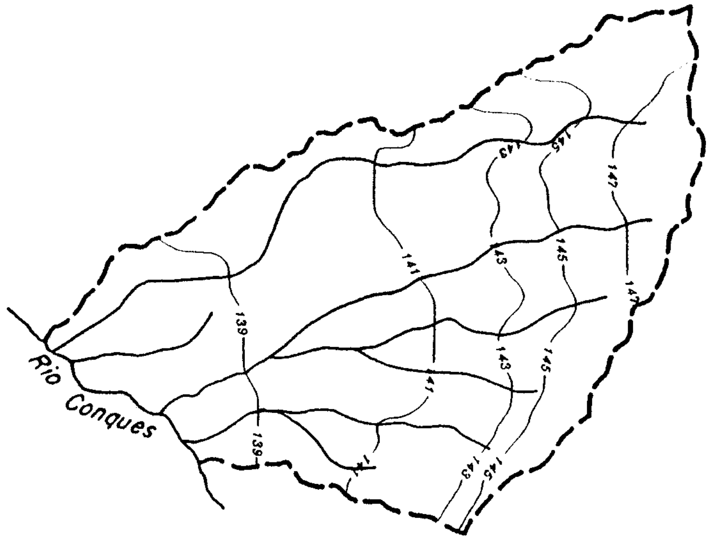

Fig. 2 Map of the factor R for the Conca de Tremp basin.

the entire basin can be assumed. Similar results for the soil erodibility factor K are shown in Fig. 3, where the spatial distribution of this factor is once again relatively uniform. Both the rainfall erosivity and the soil erodibility factors are relatively constant at a regional scale because similar climatic and geological conditions prevail over many large areas. For instance, it is well known from the iso-erodent map (Wischmeier & Smith, 1978) that the factor R varies very gradually over the United States east of the Rocky Mountains. Similarly, soil erodibility is closely related to the texture and soil formation processes (Romkens, 1985), which in turn depend on geological and climatic conditions. The methodologies to evaluate the R and K factors proposed by Wischmeier & Smith (1978) and later revised by Romkens (1985) and Weltz *et al.* (1987) are relatively easy to apply and sufficiently accurate provided enough raingauges and soil samples are available for the study area.

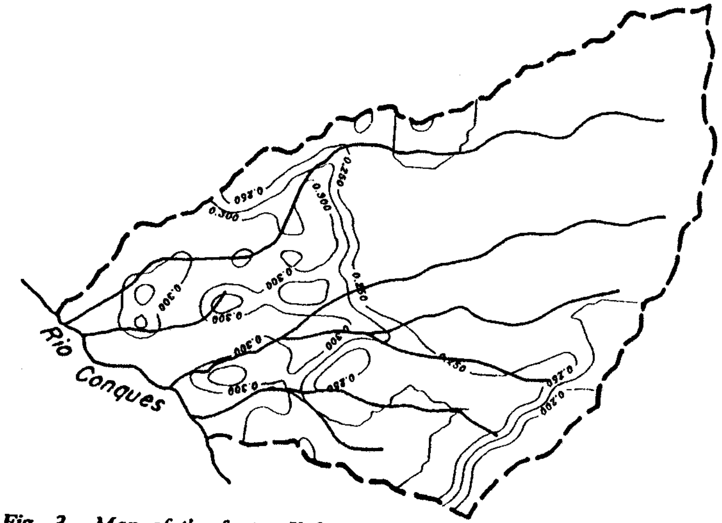

Fig. 3 Map of the factor K for the Conca de Tremp basin.

On the contrary, irregular relief and slope gradient cause significant spatial variability in the topographic factors L and S. The topographic factors are among the most difficult to evaluate outside plot size fields. Williams & Berndt (1976) proposed methods to estimate average values of the slope gradient and slope length of a basin. The slope steepness factor S of the USLE has been recently revised by McCool *et al.* (1987), who proposed a linear relationship between soil losses and slope gradient. Average values of slope gradient and runoff length for sub-basins and grid cells are required and accurate evaluations deserve further investigations. The use of geographic information systems may warrant further advances in this field, and telescopic grid size investigations similar to Julien & Frenette (1987) may also provide unbiassed soil erosion estimates at various grid sizes.

Accurate evaluations of average runoff lengths used for the runoff length factor L of the USLE remain very difficult and time-consuming, representing one of the most subjective factors of the USLE (Simanton *et al.*, 1980). Although the influence of the runoff length on rill formation and soil losses from rill-susceptible lands has been clearly recognized (Meyer *et al.*, 1975; Foster *et al.*, 1977), the methodologies for its quantitative evaluation have not been significantly improved.

Gonzalez del Tanago & Redondo (1989) applied three methods to calculate the runoff length and three other methods to calculate the slope gradient on the Conca de Tremp area. They found that none of the three runoff length methods gives significant correlation when compared with field measurements. Similarly, the three slope gradient methods provide calculated slope values generally smaller than the field measurements, particularly in steep areas. They concluded that the estimation of the L and S factors on basins with irregular topography remains tedious and imprecise. The uncertainties in evaluating the combined LS factor of the USLE are well illustrated at a sub-basin scale in Fig. 4 compared to the grid scale in Fig. 5. It is concluded that grid size evaluation of the topographic parameters is essential to describe the spatial variability of surface erosion.

Finally, the evaluation of the factor C shown in Fig. 6 also remains very subjective for non-agricultural fields. Dissmeyer & Foster (1984) proposed a method to evaluate the C factor for forested lands and, more recently, Weltz *et al.* (1987) revised previous procedures, considering conditions of vegetation canopy, root biomass and soil roughness. Those methods tend to become overwhelming when applied to large basins.

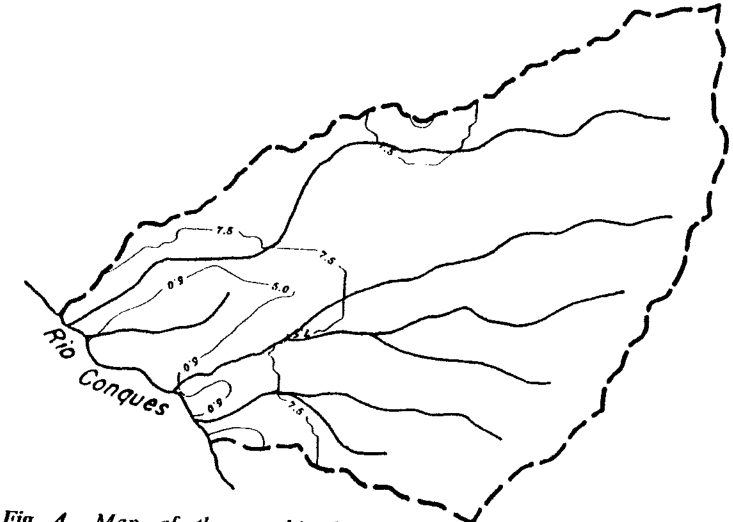

Fig. 4 Map of the combined factor LS per sub-basin for the Conca de Tremp basin.

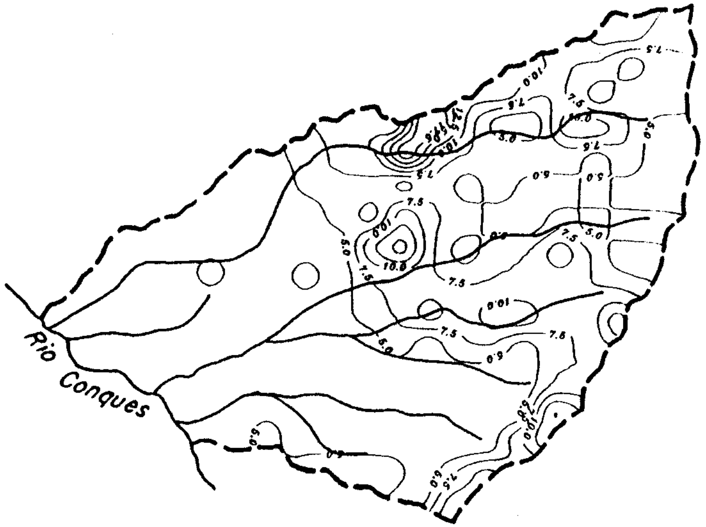

Fig. 5 *Map of the combined factor LS per grid for the Conca de Tremp basin.*

Average annual soil erosion losses are calculated from the topographic factors plotted in Fig. 5 and the final soil erosion map is presented in Fig. 7. It is found that the topographic factors L and S and the vegetation and land use factor C determine most of the spatial variability in soil erosion losses from large basins. Comparatively, the rainfall erodibility and the soil erosivity parameters remain relatively uniform at the basin scale. These findings corroborate those of Julien (1979) on the Chaudière basin in Canada under different climatic conditions. The spatial variability of the factors S and C requires particular attention in investigations of soil erosion mapping.

GRID SIZE EFFECTS

The influence of the grid size on the computation of soil erosion rates in the Conca de Tremp basin is considered. The total drainage area has been discretized into 701 square elements each covering a surface area A_0 = 0.0625 km^2. The USLE is applied to successive square matrices formed by 1 × 1 element, (0.0625 km^2), 2 × 2 elements (0.25 km^2), 3 × 3 elements (0.56 km^2), up to 39 × 39 elements. This procedure proposed by Julien & Frenette (1987) leads to the definition of a relative grid size factor Q_e^* calculated for each matrix from the following expression:

$$Q_e^* = n\ S\left[\Sigma_{i=1}^n \frac{R_i}{n}\ \Sigma_{i=1}^n \frac{K_i}{n}\ \Sigma_{i=1}^n \frac{L_i}{n}\ \Sigma_{i=1}^n \frac{C_i}{n}\ \Sigma_{i=1}^n \frac{P_i}{n}\right] / \Sigma_{i=1}^n R_i K_i L_i S_i C_i P_i \qquad (2)$$

where n is the number of elements within each matrix of area $A = n\,A_0$, and R_i, K_i, L_i, S_i, C_i and P_i are the values of the USLE factors for each element i.

Similarities between the results of the Conca de Tremp basin and those

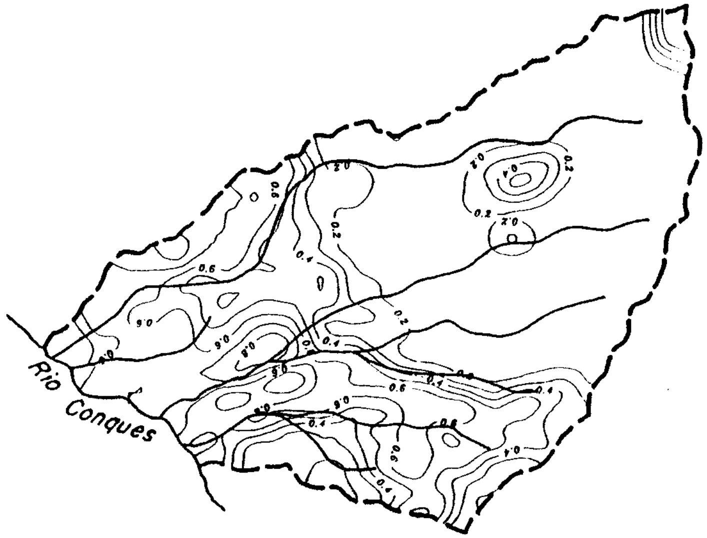

Fig. 6 *Map of the factor C for the Conca de Tremp basin.*

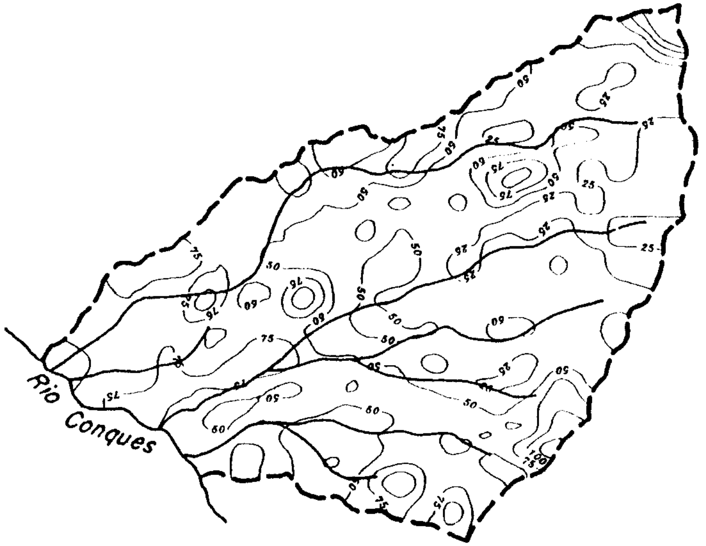

Fig. 7 *Annual soil erosion losses E in tons per hectare for the Conca de Tremp basin.*

from the Chaudière basin are shown in Fig. 8 where the data from both basins are superposed. The relative grid size factor Q_e^* defined in equation (2) is corrected for the bias induced at infinitesimal grids according to the procedure detailed in Julien & Frenette (1987). Accordingly, the grid size factor Q_e is calculated from the relative grid size factor Q_e^* as follows: $Q_e = 1.13 Q_e^*$. At a given grid size area, the analysis of the fluctuating values of Q_e shows that the average value $\overline{Q}_e$ is essentially constant for grid sizes smaller than 0.4 km². This means that slight differences exist between calculations at grid sizes of 1 × 1 (0.0625 km²), 2 × 2 (0.25 km²) or 3 × 3 (0.56 km²). At larger grid sizes, the average value of the grid size factor gradually decreases and the results are almost identical to those of the Chaudière basin. The dispersion around the mean also varies with the grid size as shown in Fig. 8. Maximum dispersion is identified for grid sizes between 0.2 and 10 km². Overall, the data points of the Conca de Tremp basin are mostly confined within the confidence intervals at 95% defined from the Chaudière data set.

It is concluded from these observations that the grid size factor proposed by Julien & Frenette (1987) is equally applicable to both the Chaudière and Conca de Tremp basins under different climatic, geological and land use conditions. The soil loss equation can be applied to areas up to 0.125 km² without introducing bias. The grid size factor from Fig. 8 should be considered when applying soil loss equations to larger grid sizes or drainage areas.

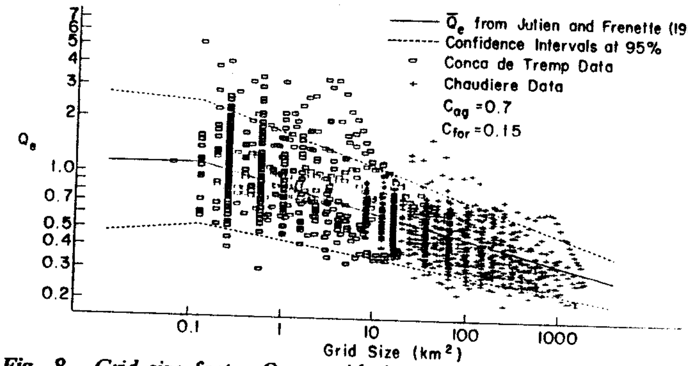

Fig. 8 Grid size factor Q_e vs grid size or drainage area.

PARTIAL CORRECTION FACTORS

The following investigation was carried out in order to determine which of the different factors of the USLE primarily affects the relative grid size factor Q_e^*. Partial correction factors are defined with reference to the spatially varied factors of the USLE. For instance, the partial correction factor Q_{RKL}^* describes the effect of the spatial variability of the factors R, K and L. The partial correction factor Q_{RKL}^* describes the ratio between the product of spatially-averaged values of the individual factors R, K and L, divided by the sum of products of R_i, K_i and L_i for each element of the grid:

$$Q_{RKL}^* = n \left[\Sigma_{i=1}^n \frac{R_i}{n} \, \Sigma_{i=1}^n \frac{K_i}{n} \, \Sigma_{i=1}^n \frac{L_i}{n} \right] \Big/ \Sigma_{i=1}^n R_i K_i L_i \qquad (3)$$

Similarly, the modified correction factor Q_{RKLC}^* describes spatial variability in the factors R, K, L and C, and finally the factor Q_s^* describes only the variability in the slope factor S:

$$Q_{RKLC}^* = n \left[\Sigma_{i=1}^n \frac{R_i}{n} \, \Sigma_{i=1}^n \frac{K_i}{n} \, \Sigma_{i=1}^n \frac{L_i}{n} \, \Sigma_{i=1}^n \frac{C_i}{n} \right] \Big/ \Sigma_{i=1}^n R_i K_i L_i C_i \qquad (4)$$

$$Q_s^* = \frac{n\,S}{\Sigma_{i=1}^n S_i} \qquad (5)$$

The partial correction factors Q_{RKL}^* and Q_{RKLC}^* in Figs 9 and 10 show very similar results in which both factors are nearly equal to unity regardless of the drainage area. It is interesting to note that, although R and K are relatively uniformly distributed, the parameters L and C are largely varied on the basin. The influence of the spatial variability of these four factors does not significantly contribute to the decrease in Q_e^* with drainage area. On the other hand, the analysis of the slope factor yields different results as shown in Fig. 11. A gradual decrease in the correction factor Q_s^* is found as the drainage area increases. The effect of the slope overshadows the influence of all other factors, resulting in the general trend for Q_e previously discussed.

This analysis demonstrates that the random variability in the factors R,

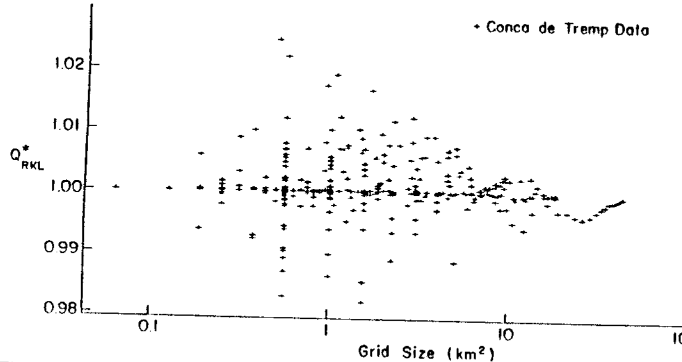

Fig. 9 Partial correction factor Q_{RKL}^* vs grid size or drainage area, Conca de Tremp basin.

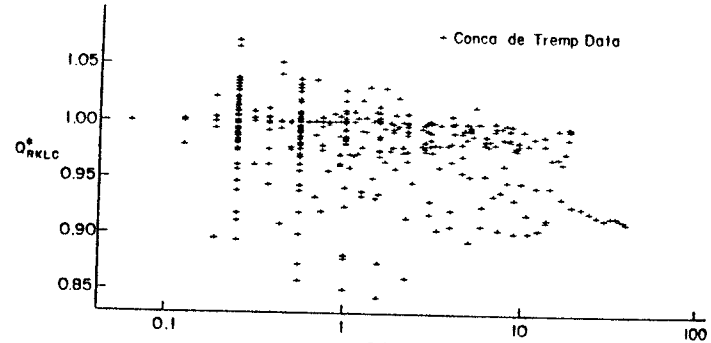

Fig. 10 Partial correction factor Q^*_{RKLC} vs grid size or drainage area, Conca de Tremp basin.

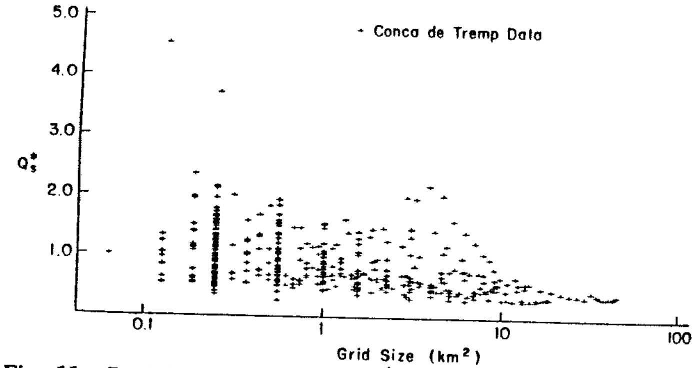

Fig. 11 Partial correction factor Q^*_s vs grid size or drainage area, Conca de Tremp basin.

K, L and *C* exerts little influence on the calculated erosion rates at all scales. This is however not the case for the slope factor which decreases with drainage area (Leopold & Maddock, 1953). It is therefore concluded that the decrease in slope with increasing drainage area is reflected in soil erosion calculations using square grids via the correction factor shown in Fig. 8.

SUMMARY AND CONCLUSIONS

The universal soil loss equation is applied to the Conca de Tremp basin in Spain under mediterranean climatic conditions. The investigation of the spatial variability of the parameters of the USLE supports the following conclusions:

(a) the results show relatively uniform distribution of the rainfall erosivity *R* and soil erodibility *K* over the entire area. These two factors remain fairly constant at a regional scale and can be accurately evaluated from existing methods; and

(b) on the contrary, the spatial variability in topography, vegetation and land use conditions greatly contributes to the large spatial variability in soil erosion losses. The evaluation of the factors *L, S* and *C* remains imprecise and somewhat subjective, introducing potential sources of error when attempting to define the accurate soil erosion losses from each grid cell.

This grid size analysis of soil erosion from the Conca de Tremp basin in Spain demonstrates that previous results from the Chaudière basin in Canada can be applied under different climatic, geological, topographic, vegetative and land use conditions. This analysis corroborates the previous findings that the calculation of erosion losses does not depend on grid size at grid sizes smaller than about 0.125 km^2. At larger scales, the decrease in slope with increasing grid size or drainage area causes an underestimation of erosion rates at large grid sizes. Spatial variability in the other factors of the USLE such as rainfall erosivity, soil erodibility, runoff length, vegetation and land use does not significantly affect calculated erosion rates on large grid sizes. Therefore, the grid size factor proposed by Julien & Frenette (1987) can be used in calculating erosion losses on large basins from spatially-averaged values of each factor of the USLE.

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Hydrological response of a medium-sized mountainous catchment to climate changes

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Abstract The long term hydrological response of a medium-sized mountainous catchment to climate changes has been examined. The climate changes were represented by a set of hypothetical scenarios of temperature increases coupled with precipitation and potential evapotranspiration changes. Snow accumulation and ablation, plus runoff from the study catchment (the Mesochora catchment in central Greece) were simulated under present (historical) and altered climate conditions using the US National Weather Service snowmelt and soil moisture accounting models. The results of this research obtained through alternative scenarios suggest strongly that all the hypothetical climate change scenarios would cause major decreases in winter snow accumulation and hence increases in winter runoff, as well as decreases in spring and summer runoff. The simulated changes in annual runoff were minor compared with the changes in the monthly distribution of runoff. Attendant changes in the monthly distribution of soil moisture and actual evapotranspiration would also occur. Such hydrological results would have significant implications on future water resources design and management.

Réponse hydrologique d'un bassin montagneux de dimension moyenne aux changements climatiques

Résumé La réponse hydrologique d'un bassin montagneux de dimension moyenne aux changements climatiques est présentée dans cet article. Les changements climatiques ont été représentés par une série de scénarios hypothétiques de changements de température, ceux ci ont été combinés avec des changements de hauteurs de précipitations et d'evapotranspiration potentielle. L'accumulation de neige et l'ablation, ainsi que l'écoulement que peut présenter le bassin sous étude, en l'occurrence le bassin de la Mesochora en Grèce Centrale, ont été simulés à partir des conditions climatiques actuelles et hypothétiques, ceci par application des modèles établis par le Service National Metéorologique des Etats Unis pour la fonte de neige et les variations de l'humidité du sol. Les résultats de cette recherche, obtenus avec des scénarios alternatifs, suggèrent fortement que tous les

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