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Prediction of sediment yield for mountainous basins in Colombia, South America

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ABSTRACT The Universal Soil Loss Equation (USLE) is tested for prediction of the sediment yield of the Río Cauca. Computed basin soil loss is shown to be sensitive to the method of handling spatially distributed data on basin characteristics. USLE procedures are found inadequate for extreme topographic and vegetational conditions, while it is probable that vegetation types are more dense than USA equivalents. Possibly due to this, computed soil loss greatly overestimates sediment yield calculated from limited transport data. Additional information about soil loss determination and measured transport is required for deciding whether soil loss is a good estimate for sediment yield in the area or that sedimentation on the flood plains of tributaries produces unacceptable delivery ratios. Prediction of sedimentation rates in mountainous reservoirs does not suffer this problem. Good station independent correlation between annual erosivity and a monthly precipitation index is found. A procedure for determination of the effect of extreme slope gradients is proposed.

INTRODUCTION

The main objective of the present study is to develop a procedure for estimation of sediment yield on the basis of basin characteristics rather than by measuring sediment transport in streams. In particular this should provide the boundary condition for a mathematical morphological model of the Río Cauca with respect to the amount of sediment delivered to the river by its tributaries. The procedure should permit sufficient spatial differentiation in order to allow prediction of the effect of future changes in land use and other factors affecting sediment yield.

If soil loss due to sheet and rill erosion was the major source of sediment to the Río Cauca, sediment yield could still be only a fraction of this, due to the influence of sedimentation zones. The first problem is to eliminate other sources of sediment yield, e.g. scouring of the bed of streams, the second is to eliminate potential sources of deposition which could result in unacceptably low sediment delivery ratios.

THE CAUCA BASIN

The basin (23 000 km^2 within the study area in Fig.1) is one of the major mountainous basins in Colombia and is confined between the Western and Central Cordilleras of the Andes Mountains.

Río Cauca The course of the river is divided into two parts, as illustrated by the profile in Fig.1: (1) the upper steeply sloping part with typical mountainous character down to Timba and (2) the lower alluvial reach down to La Virginia in which the meandering river receives a number of steeply sloping mountainous tributaries.

Topography The basin is composed of three topographically quite different geomorphological elements: (1) the geographical valley (4500 km^2) of lowland character, (2) the mountainous part (13 000 km^2) with slope steepness ranging from 30 to 300% with an average of 50-80%, and (3) the intermediate zone (5500 km^2) consisting of a pediment of alluvial and colluvial fans, confined between the 1000 and 1500 m contours in the south and the 900 and 1200 m contours in the north. Slopes in this area show a characteristic 10% steepness. The transition between the last two zones is generally as abrupt as the cross section in Fig. 1 suggests.

Streams Tributaries have bed slopes of 10-30% in their mountainous reaches, decreasing rather abruptly to 5-10% at the upper end of the pediment zone and more gradually decreasing to 0.2-0.5% close to the Río Cauca, where they generally adapt within short distance to the slope of the river of 0.03%.

Water balance From the average discharge and the drainage area at La Virginia (Fig.1) an average runoff of 747 mm $year^{-1}$ may be estimated for the basin. This is about one third of the annual precipitation. Characteristic is the difference between the mountainous part (1146 mm $year^{-1}$) down to Timba and the (warmer) valley (663 mm $year^{-1}$) with practically the same annual rainfall.

Rainfall regime The average annual rainfall of 2300 mm varies considerably within the basin and exhibits a strong correlation with altitude, which emphasizes its orographic character. With values of 1000-1500 mm at an altitude of 1000 m rainfall depths reach a maximum of 2000-4000 mm between 1200 and 2000 m and decrease to less than 1000 mm in the highest parts. Locally great deviations in this trend occur. Most of the rainfall is concentrated in short duration high intensity storms with 80-90% of the total storm depth occurring in the first 3 h of the storm.

Vegetation The natural vegetation follows a mountainous tropical selva sequence: (1) a sparse "paramo" vegetation above 3000 m, (2) dense humid cloud forest between 2000 and 3000 m, and (3) warmer but similar forest at lower altitude. Large scale deforestation since the seventeenth century, particularly in the zone between 1000 and 2500 m, has resulted in an abundance of clean tilled crops and pastures replacing the forest.

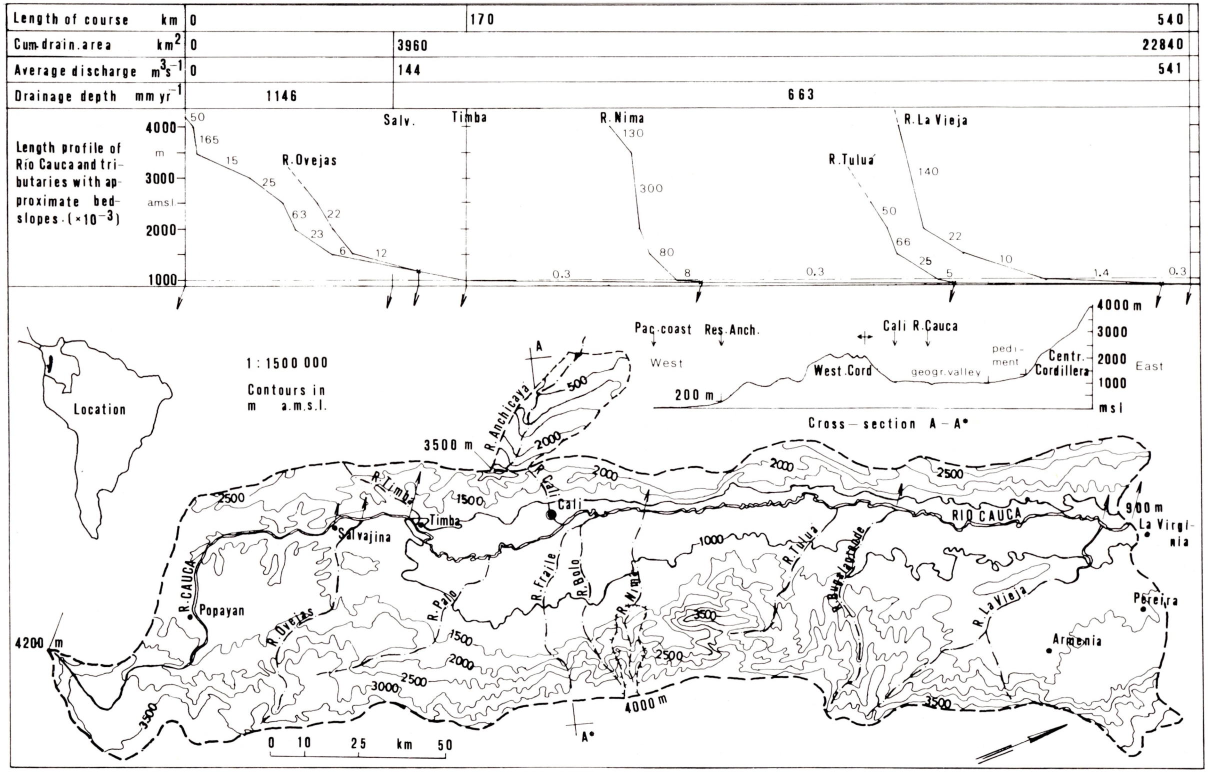

FIG.1 The Cauca basin.

Soils The soils in the region are mainly of the red or yellow lateritic type with locally a high content volcanic ash and generally a considerable fraction of silt, which classifies them as rather erodible silt loams.

Erosion Erosion problems are primarily related to firstly widespread sheet and rill erosion in the lower mountainous parts and secondly the rapid development and extension of gullies, mostly initiated by road construction.

THE RELATION OF SOIL LOSS TO SEDIMENT YIELD

Considering sheet and rill erosion as the process of erosion by non-concentrated water, where particles are loosened from the soil by splashing raindrops and transport takes place by sheet flow, the only other important source of sediment yield would be gully erosion from the bed of streams, e.g. scouring by concentrated flow.

Sheet and rill erosion From the grain size distributions presented in Fig.2 for all sediment observed in the Río Cauca, it

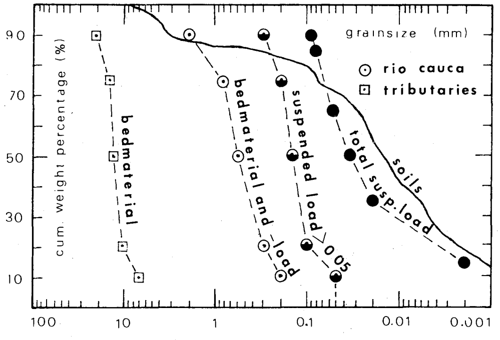

FIG.2 Typical grain size distributions in the Cauca basin. Note that all curves are approximate, except for soils.

follows that the bulk of material involved in sediment yield comprises particles smaller than 2 mm (D_{90}). Considering the gullies mentioned in the former paragraph as the uppermost branches of tributaries and the increasingly coarse bed material as one proceeds upstream from the point where the distribution curve for bed material of tributaries in Fig.2 was observed, it follows that gully erosion by bed scouring would involve particles over 7 mm in size (D_{10}). From this it is concluded that sheet and rill erosion is the main source of sediment yield. It must be noted that gullies can still contribute to sediment yield by increased sheet and rill erosion on their slopes.

Sediment delivery ratio Apparently no deposition of fine material in stream beds occurs. This would leave the sediment delivery ratio in the range 90-100% assuming that the potential sedimentation on flood plains of tributaries is of minor importance, which is yet to be proven.

Coarse fractions The distribution curve for soils in Fig.2 shows only a small fraction of particles greater than 2 mm. This supports the foregoing, but this small fraction is still responsible for the building of alluvial fans, and also contributes to sedimentation in reservoirs in mountainous streams.

UNIVERSAL SOIL LOSS EQUATION (USLE)

A simple procedure for estimation of soil loss due to sheet and rill erosion is provided by the USLE, in the form presented by Wischmeier (1972a), i.e. A = RKLSCP. The fact that R, in the present study computed from Wischmeier's EI_{30} index, can be determined for individual rainstorms as well as for any period by linear accumulation, provides the possibility of modelling soil loss and sediment yield on both a short and a long term basis. Verification with measured transport data is likewise possible.

EVALUATING SOIL LOSS IN LARGE BASINS IN THE TROPICS

A general problem in any large scale complex basin concerns the aggregation of many individual landslope elements, where calculation of soil loss for each separate element following the basic USLE concept is laborious and inefficient. It is more convenient to work with basin average characteristics (e.g. average slope - gradient, -length, etc.) or some kind of grid evaluation procedure. There are, however, a number of features that will result in systematic over- and underestimation of total basin soil loss when care is not taken. Other problems include:

Extreme slopes The slope-gradient in the study area greatly exceeds the range for which Wischmeier (1972a) provided the slope effect relation (0-50%). Since this relation gives unrealistic values for such slopes an extrapolation procedure has been developed. Slope length also exceeds the normal ranges, particularly in combination with steep slopes. According to Wischmeier (1972a) L accounts for the increase in erosive potential of runoff-induced erosion, relative to rainfall-induced erosion which S accounts for. Considering the degree of saturation of the transport capacity at the bottom of the slope as crucial for both effects, there should be a limit to L for extremely long slopes. As the original relation for L is used in this study due to the lack of an alternative, a systematic overestimation of soil loss might result.

Vegetation Vegetation types in the study area are not covered by existing procedures for determination of C. Where possible, values have been adopted from USA equivalent types, although it might be expected that tropical types are systematically more dense due to humid conditions. As C is the most sensitive parameter in the study area (0.45 for bare soil, 0.001 for the most dense USA forest), it is expected that soil loss is consequently greatly overestimated. A calibration of C for tropical rainforest is presented.

Soils The influence of volcanic ash is not included in the erodibility nomograph presented by Wischmeier *et al.* (1971), and used in his study although he reports that this substantially increases erodibility. On the other hand a stone cover on the soil surface, which frequently occurs in the study area, should have the opposite effect. As no field data are present both effects are assumed to compensate.

PROPOSED SLOPE EFFECT RELATION FOR EXTREME GRADIENTS

Wischmeier (1972a) provided the following relationships between slope gradient, s(%) and the slope gradient effect S:

$$S = (0.43 + 0.30s + 0.043s^2)/6.613 \qquad s < 20\% \text{ (tested)} \qquad (1)$$

$$S = (s/9)^{1.4} \qquad s < 50\% \text{ (untested)} \qquad (2)$$

A theoretical examination of the relationship between slope angle θ (arctan(s/100%)) and the slope gradient effect S has been carried out by considering the flow of water and sediment at the bottom of a uniform slope. The parameters involved are defined in Fig.3. The effective precipitation q (m^2s^{-1}), which is the incoming source of

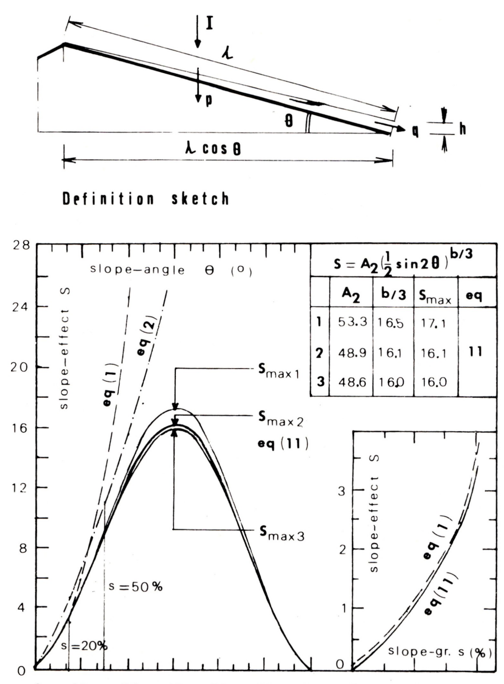

FIG.3 Proposed S(θ) relation and the relations provided by Wischmeier (1972a).

overland flow, is derived through equation (3) from the intensity of rainfall I (m s^{-1}) on the vertical projection of the overland slope length λ (m) and the fraction p that infiltrates. Assuming stationary and gradually increasing flow, the discharge at the bottom of the slope is equal to q and can be written as equation (4), where h (m) is the depth of flow at that site, and $\bar{u}$ (m s^{-1}) the average flow velocity. Assuming turbulent flow and only a slight degree of gullying, $\bar{u}$ follows from equation (5), where C_c ($m^{\frac{1}{2}}s^{-1}$) represents the Chézy roughness value. Finally the sediment transport capacity T_c (m^2s^{-1}) is assumed to be related to $\bar{u}$ by means of equation (6), where a and b are constants depending on flow and sediment properties. The equations describing the flow of water and sediment at the bottom of the slope to the drainage channel per unit width are:

$$q = I\ (1 - p)\ \lambda \cos\theta \quad \text{(source)} \quad (m^2s^{-1}) \tag{3}$$

$$q = h\ \bar{u} \quad \text{(continuity)} \quad (m^2s^{-1}) \tag{4}$$

$$\bar{u} = C_c\sqrt{(h \sin\theta)} \quad \text{(Chézy flow)} \quad (m\ s^{-1}) \tag{5}$$

$$T_c = a\ (\bar{u})^b \quad \text{(general transport law)} \quad (m^2s^{-1}) \tag{6}$$

Eliminating h and q, the following expression for the transport capacity is derived from (3-6):

$$T_c(\theta) = A_1(\tfrac{1}{2} \sin 2\theta)^{b/3} \quad (m^2s^{-1}) \tag{7}$$

where the constant with respect to θ is written as:

$$A_1 = a(C_c^2\ I\ \lambda\ (1 - p))^{b/3} \quad (m^2s^{-1}) \tag{8}$$

in which all parameters are assumed independent of θ, or at least in combination. By the definition of S, according to Wischmeier (1972a), which is the ratio between the soil loss at specific slope-gradient and that of a 9% slope, its equivalent in terms of transport capacity follows from:

$$S_c(\theta) = (T_c(\theta)\ /T_c(9\%)) = A_2\ (\tfrac{1}{2} \sin 2\theta)^{b/3} \tag{9}$$

where the constant follows from:

$$A_2 = (\tfrac{1}{2} \sin\ (2 \arctan 0.09))^{-b/3} = (11.201)^{b/3} \tag{10}$$

Assuming that the saturation ratio between actual transport T (m^2s^{-1}) and T_c is independent of θ, equation (9) also holds for actual transport or soil loss. A_2 and b/3 are to be calibrated with actual data; in this case equations (1) and (2) are taken. This calibration in the range 0-50% gradient yields the following best fit:

$$S(\theta) = 48.9\ (\tfrac{1}{2} \sin 2\theta)^{1.61} \simeq 16(\sin 2\ (\arctan(s/100\%))^{1.6} \tag{11}$$

This result is represented in Fig.3 together with some slightly different alternatives yielding the same fit, and Wischmeier's relations. Some important conclusions are drawn from this result:

(a) The value b = 4.8 is reasonable for flow with mainly suspended load.

(b) A_2 is not sensitive to the choice of alternatives and corresponds closely with the theoretical value from equation (10).

(c) The maximum effect occurs between 0 and 90°, which Horton (1945) also reported.

(d) The fit of equation (11) to Wischmeier's relation in the range 0-20% is excellent, as can be noticed from the inset to Fig.3.

Evaluation The close agreement of the proposed relation with equations (1) and (2) is considered as a confirmation in the range 0-50% gradient. Outside this range no verification is yet possible. The angle at which the maximum occurs as well as its value are sensitive to possible inconsistencies in assumptions for this range, of which the most important are:

(a) Turbulent flow. This is necessary for both equations (5) and (6). It is expected, but needs to be verified, that the degree of gullying in rills, due to stones, vegetation, etc. guarantees this.

(b) Transport law. The significance of equation (6) for this type of flow, particularly at extreme slopes, needs to be investigated.

(c) Independent parameters. The necessary assumption is that the saturation rate T/T_c, p, C_c, a and b are independent of θ, or that their influence compensates for that of ignored parameters (e.g. soil moisture, etc.).

Equation (11) is used in this study as providing a better estimate than equations (1) and (2) for extreme slopes. A remark is made on the application. Since λ is kept constant, according to the definition of S, the latter concerns the soil loss per unit of upslope area. When working with horizontal units of area, S should be multiplied by $1/\cos\theta$. This becomes significant for slopes over 45% steepness and dominant for slopes near the vertical.

CALIBRATION OF THE VEGETATION EFFECT FOR HUMID TROPICAL FOREST

From data on the sedimentation rate in the reservoir of a hydro-electric plant in the Río Anchicayá, with a catchment area almost completely covered with equally dense forest as found in the Cauca basin, the C value has been calculated. The reservoir is situated in the mountainous reaches of the western slope of the Western Cordillera (Fig.1). On the basis of annual precipitation and topographic information, using other information from the Cauca basin, the following estimates for USLE parameters are obtained: R_{annual} = 4740 (metric units), K = 0.30 (t ha^{-1}(R-unit)$^{-1}$), LS = 50 and P = 1. The measured annual sedimentation amount in the reservoir is estimated at 0.5 10^6 $m^3 year^{-1}$, for 1955-1962. With a drainage area of 650 km^2 for the basin and assuming a specific weight of 2 t m^{-3} for deposited material, it follows that C = 0.000 22. This is about one fifth of the minimum value that Wischmeier (1972b) provided for USA forest. Because all data are approximate estimates this result is not very reliable, but provides a strong indication that vegetation in this region indeed has more protective power than

USA equivalents.

SOIL LOSS RESULTS FOR THE RIO NIMA BASIN

Detailed computations have been carried out in a pilot watershed, the Río Nima basin (120 km^2), which can be considered as representative of the mountainous part of the Cauca basin. The area is indicated in Fig.1. For the soil loss evaluation a 500 m grid (470 grid points) has been applied. Some of the most important results are presented below.

Rain erosivity On the basis of an analysis of 134 rainstorms in the period 1970-1978, following the concept of Wischmeier (1959), for two stations in the lower and intermediate part of the basin, a good correlation between storm precipitation P_s (mm) and storm erosivity R_s (metric) with 7% error in the mean and no difference between stations has been found:

$$R_s = 0.004\ 89\ (P_s + 15)^{2.244} \qquad \text{(metric units)} \qquad (12)$$

Assuming that the rainfall amount on the 134 storm days also follows equation (12) with respect to erosivity, the relation between 24 h erosivity R_{24} and 24 h rainfall P_{24} is obtained:

$$R_{24} = 0.0841\ (P_{24} + 10)^{1.548} \qquad \text{(metric units)} \qquad (13)$$

With this equation, the annual erosivity R_{ann} has been calculated from daily precipitation records for 14 stations throughout the area, excluding days with less than 10 mm. Linear regression of R_{ann} on annual rainfall P_{ann}(mm) yields different lines with decreasing slope for stations higher in altitude, due to a corresponding shift in the distribution of P_{24} towards a smaller value of the mean. Regression of R_{ann} on the modified Fournier index (MFI), defined by Arnoldus (1977) as the accumulated sum of squared monthly precipitations over the year divided by P_{ann}, yields a station independent relation with 3% error in the mean (86 station years) of the form:

$$R_{ann} = 0.686(\text{MFI}) - 420 \qquad \text{(metric units)} \qquad (14)$$

which places it close to the regression line for the eastern USA reported by Bergsma (1978). The annual erosivity in the Río Nima basin ranges from 680 for stations at high altitude to 2000 for those at lower altitude, with an average of 1700 in the most susceptible lower part.

Soil erodibility On the basis of an analysis of 12 soil samples, which may be considered as representative of the Cauca basin, 90% of the area shows K values between 0.31 and 0.39, while lower values (0.06-0.12) occur in 10% of the area occupied by alluvial plains along streams.

Slope effect The combined LS distribution is determined using equation (11) and $L = (\lambda/22.1)^{0.6}$. This gives values of 20-60 in the lower zone, 80-140 in the higher part, declining again to 60-80 in the uppermost part, with an average of 80 for the basin. A random sample of streamline profiles shows systematic concavity, resulting in a correction factor of 0.90 to be applied to the above figures. It shows that L is almost as powerful as S, with average values of 6-7 due to relatively long slopes (500 m).

Vegetation effect The following values are selected: C = 0.45 for gullies (1% of the area), 0.15 for overgrazed artificial pasture (4%), 0.025 for permanent clean-tilled crops (15%), 0.003 for natural rangeland and paramo (50%) and 0.000 22 for mountainous cloud forest.

Soil loss A total annual soil loss of $2\ 10^6$ t year^{-1} for the period 1970-1978 has been computed for the basin, of which 65% originates from the lower part under 2200 m. The small area occupied by gullies produces one third of the total amount, which emphasizes the sensitivity of C. In the absence of substantial erosion control measures a value of P = 1 has been taken. The presence of spatial correlations between R, LS and C indices introduces considerable overestimation effects on soil loss when respective parameter-point values are averaged for sectors before soil loss is computed: +50% error for the lower zone and +25% for the total basin.

SOIL LOSS IN THE CAUCA BASIN

A generalization of the Río Nima results, taking into account additional data on annual rainfall, topography and vegetation for subcatchments representing 56% of the total mountainous area, results in a total soil loss of 110×10^6 t year^{-1}. Soil loss from areas other than the mountains have been neglected. The average soil loss (85 t ha^{-1} year^{-1}) is about half of that in the Río Nima area (166). Some results are presented in Table 1, with data on measured total sediment load in tributaries, which are rather unreliable except for the Río Cauca at Salvajina.

Although the uncertainties over soil loss computations outlined above do not permit conclusions based on absolute figures, some important relative observations concerning the distribution of soil loss are possible:

(a) Most of the soil loss occurs in both cordilleras, while the upper part of the Cauca basin above Salvajina contributes little sediment.

(b) The sediment delivery ratio decreases when average soil loss increases. This could be due either to the fact that overestimation effects are stronger at high soil loss (extreme conditions: L, S) or to sedimentation on flood plains of tributaries in the pediment zone.

(c) The fact that the western side lacks a substantial pediment (see Fig.1) makes it probable that the reported delivery ratios are at least partly due to errors in soil loss determination. As delivery ratios are relatively less for the eastern part, for almost the same average soil loss, the influence of sedimentation is more probable there. This is supported by the high delivery ratio at

TABLE 1   Soil loss for the mountainous part of the Cauca basin

Subcatchment	Drainage area (km^2)	Average soil loss ($t\ ha^{-1} year^{-1}$)	Total soil loss (solid) ($10^6 m^3 year^{-1}$)†	Measured sed. load (solid) ($10^6 m^3 year^{-1}$)†	Sediment delivery ratio (%)
Cauca-Salvajina	3 960 (30%)	15	2.2 (5%)	1.3	57
Río Timba	316	185	2.2	0.1-0.9	5-42
Río Jamundi	248	170	1.6	0.2-0.4	13-23
Rest	2 002	108*	8.2		
Total west	2 566 (20%)	124	12.0 (28%)		
Río Ovejas	653	74	1.8	0.1-0.4	3-21
Río Palo	1 180	157*	7.0	0.3-0.7	4-10
Río Guachal	600	199	4.5	0.2-0.6	4-14
Rest	4 005	118*	15.3		
Total east	6 438 (50%)	118	28.6 (67%)		
Caucas basin	12 964 (100%)	85	42.8 (100%)		

* Partly interpolated data.
† Density of solid material 2.65 $t\ m^{-3}$.

Salvajina, where no pediment influence is to be expected and soil loss is moderate, and where the transport data are the most reliable.

CONCLUSIONS

(a) The USLE concept is in principle adequate for estimation of soil loss in large complex mountainous basins on both a short and long term basis, while almost any desired degree of spatial differentiation in the results can be established. Whether soil loss computed in this way is also representative of the sediment yield of the Río Cauca in general cannot be decided yet since USLE parameters cannot be estimated accurately for the extreme conditions occurring in the basin. On the basis of grain size distributions, the only potential cause of discrepancy between soil loss and sediment yield is sedimentation on the flood plains of tributaries in the pediment zone. Hence it is expected that the concept is suitable for the sediment yields of rivers or reservoirs in mountainous reaches.

(b) USLE procedures for vegetation, slope length and slope gradient effect (C, L, S) need modification for extreme tropical mountainous conditions.

(c) A calibration of C for tropical rainforest yields a value as low as 0.000 22.

(d) Good station independent correlation has been found between annual erosivity and the modified Fournier index based on monthly precipitation.

(e) A proposed extrapolation formula for the slope gradient effect fits closely the data provided by Wischmeier (1972a) and indicates a maximum effect between 0 and 90° slope angle.

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