EVALUATION OF UNCERTAINTY IN EROSION CALCULATIONS USING RUSLE

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ABSTRACT

Results from a research project undertaken by INMAC with the general objective of improving erosion evaluations using RUSLE, for protection works design purposes, are presented. Measurements are carried out using as experimentation field the ‘Macueta’ pipeline track, in the North of Argentina, which opening and closure was the responsibility of INMAC. The specific objective of the research program is to formulate and validate measurement methodologies, in order to reduce the uncertainty in erosion loss evaluations using RUSLE.

Three different measurement methodologies are undertaken: soil loss volume at a sediment trap on a pilot slope, soil loss volume for a particular slope along the track from sediment trapped in retaining works, and soil loss for different pilot lots along the track using a net of sticks. Soil loss calculations are performed using two different software tools, *TALUD* and *RUSLE2*.

It is shown that using sediment traps is the most efficient strategy from the point of view of accuracy. The results show that soil loss estimations using RUSLE for specific events is usually large, above 50%. Recommendations to reduce the calculation uncertainties are presented. However, it is concluded that reduction of uncertainty below 30% seems unlikely.

The application of *RUSLE2* to erosion estimation for particular events does not seem to be a way to improve accuracy.

Key words: RUSLE; soil loss measurements; uncertainty; error estimation

1. INTRODUCTION

RUSLE is the most popular calculation tool used for erosion evaluations from slopes. It was initially formulated for mean annual soil loss calculations, i.e., the average annual loss expected over a relatively long series of years (let say, 10 years). This means that the actual value for a particular year, within the series, can vary significantly from that average. In other words, the use of RUSLE as a prognosis tool, for a particular year, carries a relatively large uncertainty.

The application of RUSLE was later extended to calculate mean monthly soil losses. Being based on a much narrower data set, it should be expected that the uncertainty associated to the monthly value is higher than the one attached to the annual value.

Presently, some attempts to apply RUSLE for particular events are also reported. Of course, this pushes farther the uncertainty issue. Moreover, from laboratory experiments it has been shown that the value of the cover factor, *C*, for event applications, could be effectively much higher than the values reported for long term evaluations (Kelsey 2002).

In order to improve erosion evaluations using RUSLE, for protection works design purposes, a research project was implemented by INMAC, taking as experimentation field the 'Macueta' pipeline track, in the North of Argentina, which opening and closure was the responsibility of INMAC. This 60 km long track, for a gas transportation pipeline belonging to Pan American Energy, develops between altitudes 522 and 1142 meters above mean sea level. The specific objective of the research project was to formulate and validate measurement methodologies, in order to assess the uncertainty attached to erosion loss evaluations using RUSLE, and discuss strategies to minimize it.

The research project involved the following tasks: (i) installation and operation of rain gages, in order to obtain site and time specific rainfall-runoff erosivity factors, *R*; (ii) design, installation, and operation of a sediment trap on a pilot slopes, in order to measure soil loss volume; (iii) evaluation of soil loss volume for a particular slope along the track, from sediment trapped in retaining works; (iv) measurements of soil loss for different pilot lots along the track, using a net of stikcs; (v) soil loss calculations for the three field cases using two different software tools, *TALUD* and *RUSLE2*, in order to compare among them and with the measured sediment volumes.

In the present paper, the methodologies are explained and the results are discussed. Conclusions are obtained regarding uncertainty of soil loss evaluations using RUSLE.

2. RUSLE

RUSLE (Revised Universal Soil Loss Equation, Wischmeier & Smith 1965,1978) is an empirical model developed to predict long-term annual soil loss from slopes, under specific tillage systems and management practices, due to stormwater action. It is based on the following equation for the spatial and temporal average soil loss per unit area, *A*:

$$A = R * K * LS * C * P \qquad (1)$$

where *R* is the rainfall-runoff erosivity factor (which represents the forcing), *K* the soil erodibility factor (the soil resistance), *LS* the topographic factor (the geometric effects of the slope), *C* the cover-management factor (the protection effects produced by soil coverage or irregularities), and *P* the support practice factor (the control effect produced by physical interventions).

The rainfall-runoff erosivity factor for a single storm is given by

$$R = E * I_{30}\ ;\ E = \int_{t_o}^{t_o+T} e\ i\ dt\ ;\ e = 0.29\left[1 - 0.72 * \exp(-0.05 i)\right]; \qquad (2)$$

$$I_{30} = \max_{t_o \le t \le t_o + T - \tau} \left[\frac{1}{\tau} \int_t^{t+\tau} i \, dt \right]$$

where E is the total energy of the storm, e the instantaneous storm energy, i the instantaneous intensity, I_{30} the maximum 30-minute intensity, t the temporal coordinate, t_o the initial instant of the storm, T the storm duration, and τ = 30 minutes. When using RUSLE to estimate average annual soil loss, R is calculated from the values associated to each storm: if M storms occur during N years, then

$$R = \frac{1}{N} \sum_{k=1}^{M} R_k \quad (3)$$

If seasonal variations in soil loss are needed, R must be obtained from (3) by using only data for the specific season months.

The soil erodibility factor is calculated from (Wischmeier & Smith 1978):

$$K = \left[2,1x10^{-4} M^{1,14} \left(12 - OM\right) + 3,25\left(s-2\right) + 2,5\left(p-3\right) \right] / 759 \quad (4)$$

where M is the product of the primary size fractions of particles (modified silt and silt+sand), OM the percentage of organic matter, s a class index which characterizes soil structure, and p a class index which characterizes soil permeability.

The topographic factor, *LS*, is calculated from the slope length and steepness; corrections are suggested in case that rill erosion clearly predominates on interrill erosion, and vice versa.

The cover-management factor, C, is obtained from data on previous land use, canopy cover, superficial cover (mulching), superficial roughness and soil moisture.

Some procedures are available to obtain the support practice factor, P, for specific control measures.

The classical RUSLE calculation is implemented in software *TALUD* (Menéndez et al. 2005). A more elaborated methodology is presently available in software *RUSLE2* (USDA 1998).

3. MACUETA PIPELINE TRACK

The pipeline (Figure 1) starts at Piquirenda Plant (altitude 522 m) and ends at Macueta mountains (1142 m), crossing mountains and valleys along its 60 km length. About 50.5 km (86% of the total lenght) has longitudinal slopes between 0 and 15%; 7.4 km (12.6%) between 15 and 30%; 760 m (1.3%) between 30 and 45%, and 60 m (0.1%) between 45 y 60%. The mean slope is 7.5%.

The pipeline develops across 25.5 km of forest, and 6.9 km of prairie; the remaining length runs along 16.5 km of roads, and 9.8 km of an existing pipeline track. It crosses several water courses.

No unstable slopes were observed along the whole track.

4. SEDIMENT TRAP ON PILOT SLOPE

4.1 Design and measurement

Erosion measurements were undertaken at a pilot slope along the pipeline track, using a sediment trap. Figure 2 shows the selected slope, quite uniform, well confined and easily accessible. It is 7.9 m long; the upper width is 12.9 m, which reduces nearly linearly to 10.2 m at the toe.

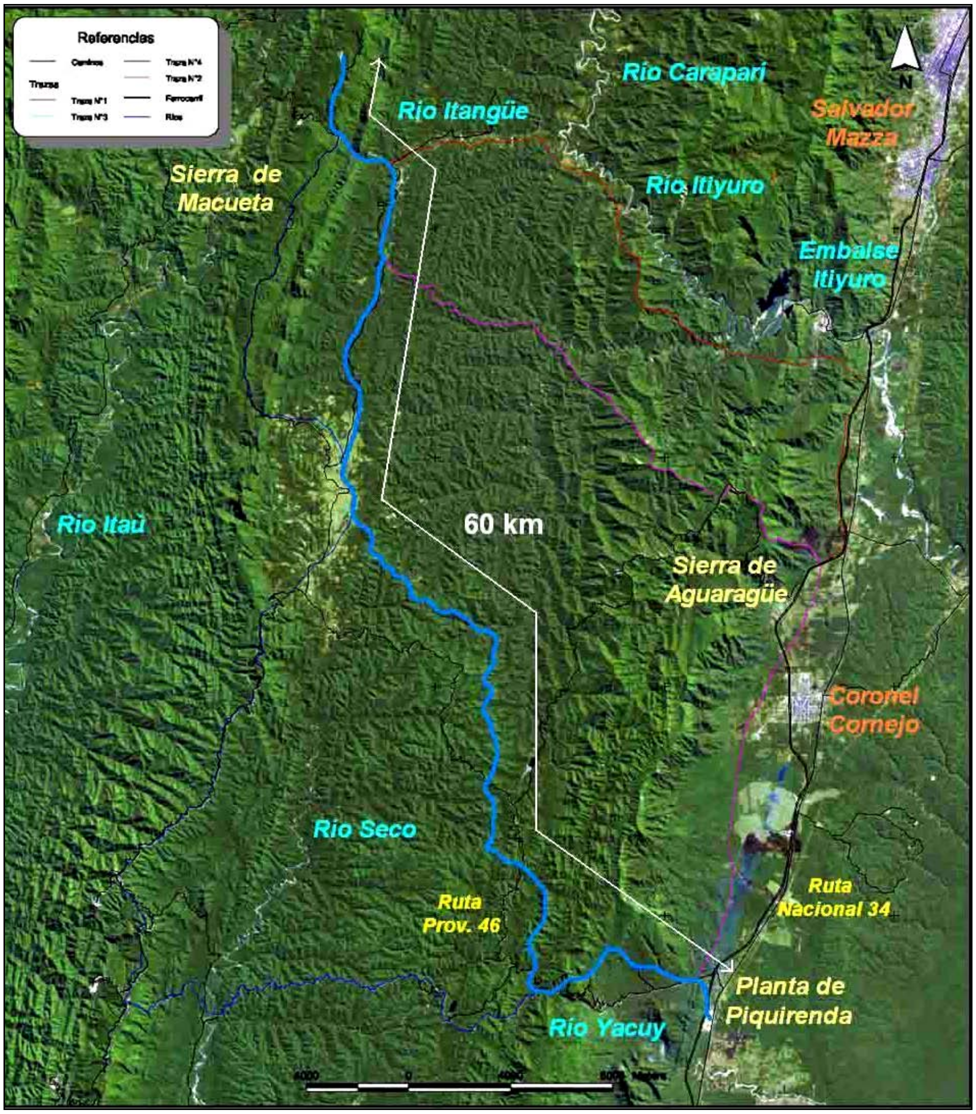

Figure 1. Macueta pipeline track

In order to give proper dimensions to the trap, calculations were performed using RUSLE. From field measurements, the slope steepness was estimated as 20%, and the slope length as 8 m. Based on soil maps from the National Institute of Agricultural Technology (INTA), the soil was characterized as sandy loam, with 40% silt, 80% modified silt, 45% sand, no organic matter, soil class by structure 'Very fine grain' (< 1 mm), and soil class by permeability 'Mildly fast' (1-2 mm/h). No limitation on soil moisture was considered. Being an artificial slope, where all vegetative cover was removed, no biomass was present. A rain gage was installed close to the pilot slope ('Valle de Acambuco' rain gage), starting its operation on 12 January, 2006. Figure 3 shows the hyetograph for the highest intensity recorded storm, which occurred on 16 January. The associated *R* factor was 570 MJ mm/ha/h. However, at a second rain gage installed at about 30 km from the test site ('km 12' rain gage), a much more intense storm was recorded, with an *R* factor of 2083 MJ mm/ha/h, which was used as the design forcing. There was no canopy cover. No tillage, no mulching and no support practice were assumed. Rill erosion was considered as dominant, due to the relatively high steepness. The superficial roughness was characterized by a random roughness height of 3.9 cm, which corresponds to a condition after work with chisel, considered to be similar to the one performed by the machinery traversing the site.

Figure 2. Pilot slope

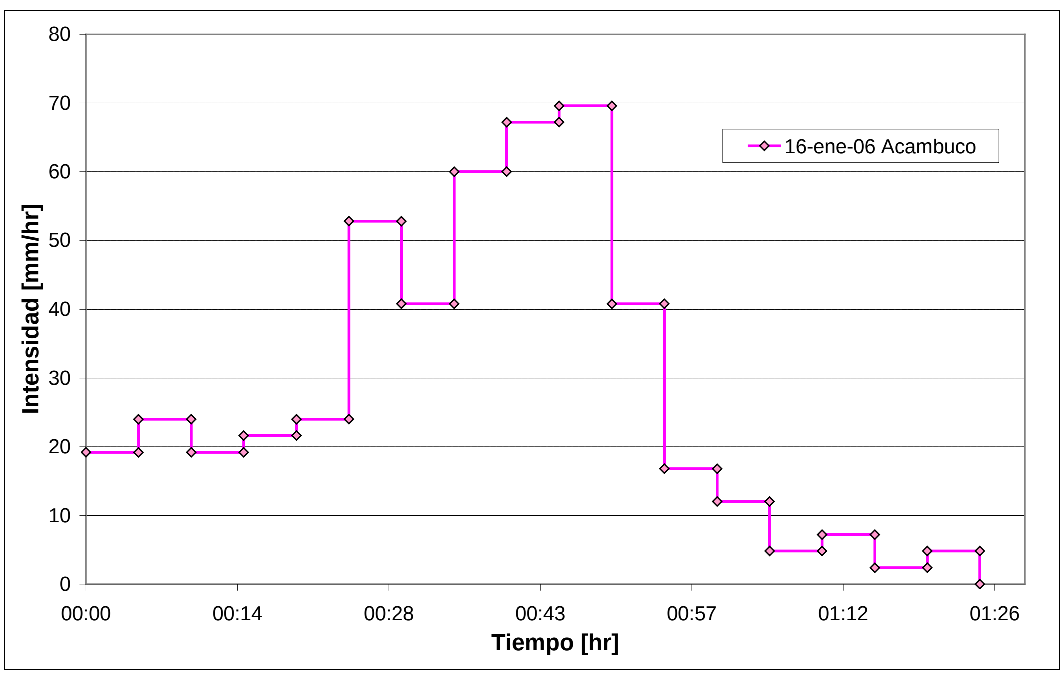

Figure 3. Hyetograph of maximum storm at Acambuco rain gage

Applying *TALUD*, the erosion rate was determined as 40 ton/ha, which means about 2.5 mm assuming a porosity of 40%. The corresponding soil volume per unit width is 22 dm^3/m.

The trap length along the slope had to be long enough to allow the sediment transported in suspension by runoff to fall into the trap. The sheet flow depth and velocity, for the design storm, were estimated using software *ESCURRE* (Menéndez et al 2004), which transforms rainfall into runoff, considering that the basin is the pilot slope. Manning roughness coefficient was estimated as 0.022 $m^{-1/3}s$, resulting a maximum sheet flow depth of 1 mm and an associated flow velocity of 0.42 m/s. On the other hand, the sediment fall velocity was determined using software DOER Tools[1]. A mean particle diameter of 83 μm was used as input, giving a fall velocity of 0.72 cm/s. Combining both velocities, it results that a horizontal length of 6 cm is necessary for a sediment particle initially at the sheet water surface to reach the sheet bottom and, hence, to be trapped. That constitutes, then, the minimum trap length.

The trap location along the slope had to be above the maximum water level at the slope toe during the design storm, in order to avoid the trap to be inundated. The basin corresponding to the water course running at the slope toe was determined from the available digital terrain model. The hydrograph was calculated using software *ESCURRE*. The water level corresponding to the peak discharge (4.2 m^3/s) was determined using software *PERFILES* (Menéndez et al. 2002), resulting a depth of 0.4 m above the water course bottom.

Based on these calculations, the trap was designed as an elongated wooden box 6.63 m long, lying across the slope at 0.5 m above the water course bottom. The box cross section was 20 cm width, with height 15 cm downstream and 23 cm upstream. It was covered with a filter fabric (Figure 4).

The sediment trap worked from 22 to 25 March, 2006. The trapped sediment was 32 dm^3. The estimated measurement error was 3 dm^3, i.e., about 10%

Figure 4. Sediment trap

[1] http://el.erdc.usace.army.mil/dots/doer/subtools/dtb010.html

4.2. Calculation

Calculations were undertaken using *TALUD*. The erosivity factor *R* for that period of time was calculated using the rain record from the Valle de Acambuco rain gage. The main uncertainty in the *R* value arises from the sampling time interval. Using 5 and 10 minutes sampling and taking the difference between them as a measure of the uncertainty, we obtained $R = 230 \pm 10$ MJ mm/ha/hr, i.e., a ±4% uncertainty.

For the erodibility factor, *K*, the major source of uncertainty comes from the mass distribution by class. Hence, calculations were performed varying the fraction contents: 30 to 45% for silt, 60 to 80% for modified silt, 30 to 45% for sand, and 1 to 5% for organic matter. We took the average value as an estimation of *K*, and the maximum variation for a single parameter change as a measure of the uncertainty, obtaining $K = 0.05 \pm 0.01$ ton h/MJ/mm, i.e., a ±20% uncertainty.

In the case of the topographic factor, *LS*, measurement errors are present in the slope length and the topographic level difference between its extreme points. They were estimated as 0.1 m, obtaining $LS = 0.84 \pm 0.05$, i.e., a ±6% uncertainty.

For the cover-management factor, *C*, the main uncertainties arise from the estimation of the random roughness of the ground surface (which contributes to the superficial roughness subfactor). Values ranging from 2 to 4 cm were considered. We then obtained $C = 0.63 \pm 0.17$, i.e., a ±25% uncertainty.

Combining the above results, the calculated erosion rate is 6.0 ± 3.3 ton/ha/year, i.e., a ±55% uncertainty. The total eroded volume was obtained as the erosion rate times the slope area above the trap times the dry density of sediments (using a porosity of 0.4), obtaining 20 ± 11 dm^3.

5. RETAINED SEDIMENT FROM SLOPE

5.1 Field estimation

A relatively steep slope was selected for a field estimation of eroded soil. At the slope toe silt fences were present. Figure 5 shows part of the fence after the first storms of the rainy season, indicating a partial failure. The retained sediment is also observed.

Based on the fence width, retained sediment layer height at the fence, and length of the deposited sediment, the sediment volume was estimated assuming it constitutes a wedge. An estimation of the loss volume through the fence breach was also performed from observations. It resulted a volume of 2.0 ± 0.9 m^3, i.e., a 44% uncertainty.

5.2 Calculation

As the first storms occurred during November, 2005, no rain gages were yet installed at the site. Hence, rain records from two relatively far away stations, 'San Telmo' and 'La Colmena', located at about 70 km from the slope site, were used. They provided quite different *R* values: 256 and 111 MJ mm/ha/hr, respectively. Hence, the erosivity factor for the measurement site was considered to lie within the interval between those two values, i.e., $R = 180 \pm 70$ MJ mm/ha/hr, which means a ±40% uncertainty.

For the erodibility factor, the same considerations as for the pilot slope apply. Hence, $K = 0.05 \pm 0.01$ ton h/MJ/mm, i.e., a ±20% uncertainty.

The slope geometry was obtained from a combination of the Digital Terrain Model, as obtained from the Shuttle Radar Topography Mission, and topography works performed by INMAC previous to pipeline construction (Figure 6). The error in the slope length was estimated as 5 m, while for the topographic level difference it was taken as 0.5 m, giving $LS = 2.8 \pm 0.6$, i.e., a 19% uncertainty.

Figure 5. Silt fence

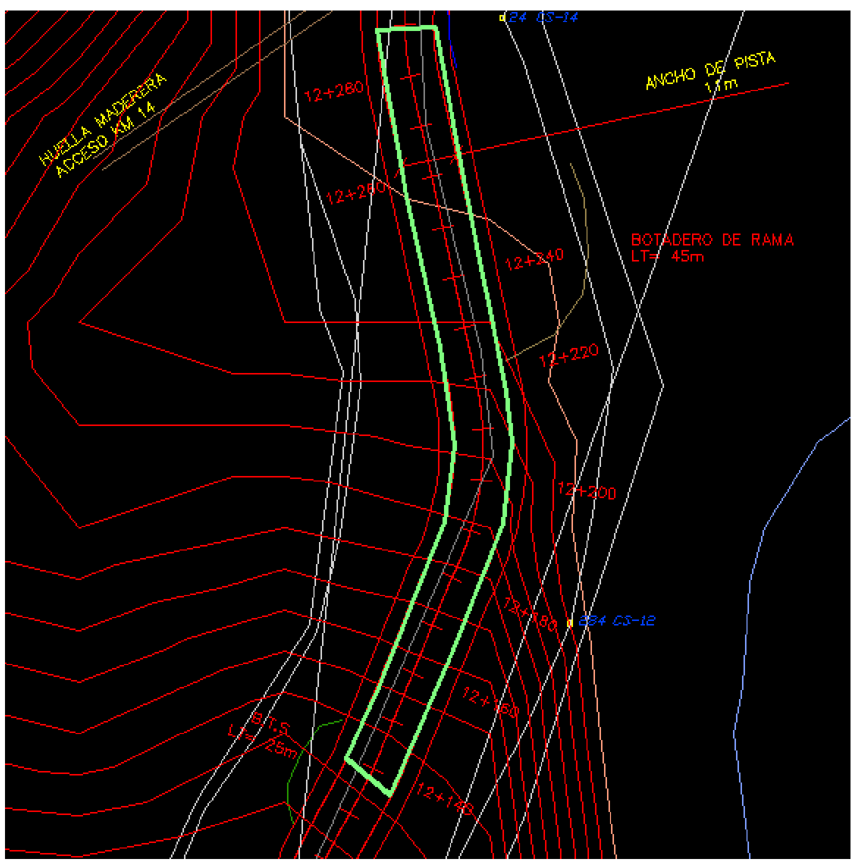

Figure 6. Slope topography

The main uncertainty source for the cover-management factor is, again, the random roughness of the ground surface. That parameter was now varied from 3 to 4 cm, as rougher surface was clearly observed. No mulching was present. We obtained $C = 0.55 \pm 0.07$, i.e., a 13% uncertainty.

From the combination of the above results, *TALUD* provides an erosion rate of 14 ton/ha/year, with a ±92% uncertainty. Using the slope area, obtained from the digital terrain model (11m ± 1 m wide and 120m ± 5 m long), and a porosity of 0.40 ± 0.05 (±13%), this means 1.5 m^3, with an uncertainty of 113%.

For this case, calculations were also performed using *RUSLE2*. The *R* value was imposed as the one obtained with *TALUD*. The same soil composition as discussed above was taken. The topographic profile along the slope centreline, as obtained from the MDT, with a 10 m step was used as an input. For the soil cover, the category 'rough bear, freshly disturbed' was used. It came out a value of 20 ton/ha/year; this means an eroded volume of 2.1 m^3. The uncertainty estimation is not straight for *RUSLE2*. On the one hand, it can be assumed that it is a better model than *TALUD*, as it includes the whole topographic profile instead of only an average steepness. However, the error in the topographic profile itself is not low, as no detailed topographic survey was performed. Assuming that the uncertainty in the *LS* factor was halved (to ±10%), it arise an uncertainty of ±83% in the erosion rate and ±104% in the eroded volume.

6. SOIL LOSS ON PIPELINE TRACK

6.1 Setting and measurement

Soil loss on the pipeline track was measured on a set of square lots, 5 m side, distributed into two groups: one close to the km 12 rain gage (7 lots, K1 to K7), and the second one close to the Valle de Acambuco rain gage (3 lots, V1 to V3). For each lot, a net of metallic sticks (6 mm diameter and 0.4 m length), with a step of 1 m along each direction, was implemented (Figure 7). The sticks were initially levelled to the ground, and they protruded when erosion began. At regular intervals of time, measurements of the sticks heights above ground were performed, and the soil eroded volume calculated by integration throughout each lot. Table 1 presents the results of the measurements for the period February to April, 2006.

Figure 7. Lot on track

To estimate the uncertainty in the measurements, an analysis based on the dispersion of measured points were performed. Figure 8 shows lateral profiles of measured heights at each stick line (the lines are longitudinal to the slope) for lot K1. It is observed that variations along the lot (from profile to profile, for a given stick line) are more significant than across it (from stick line to stick line, for a given profile); hence, the *rms* value for each profile was determined as a measure of the measurement error for that profile, and the average *rms* among them considered as a measure of the uncertainty for the erosion rate. Table 1 includes the results.

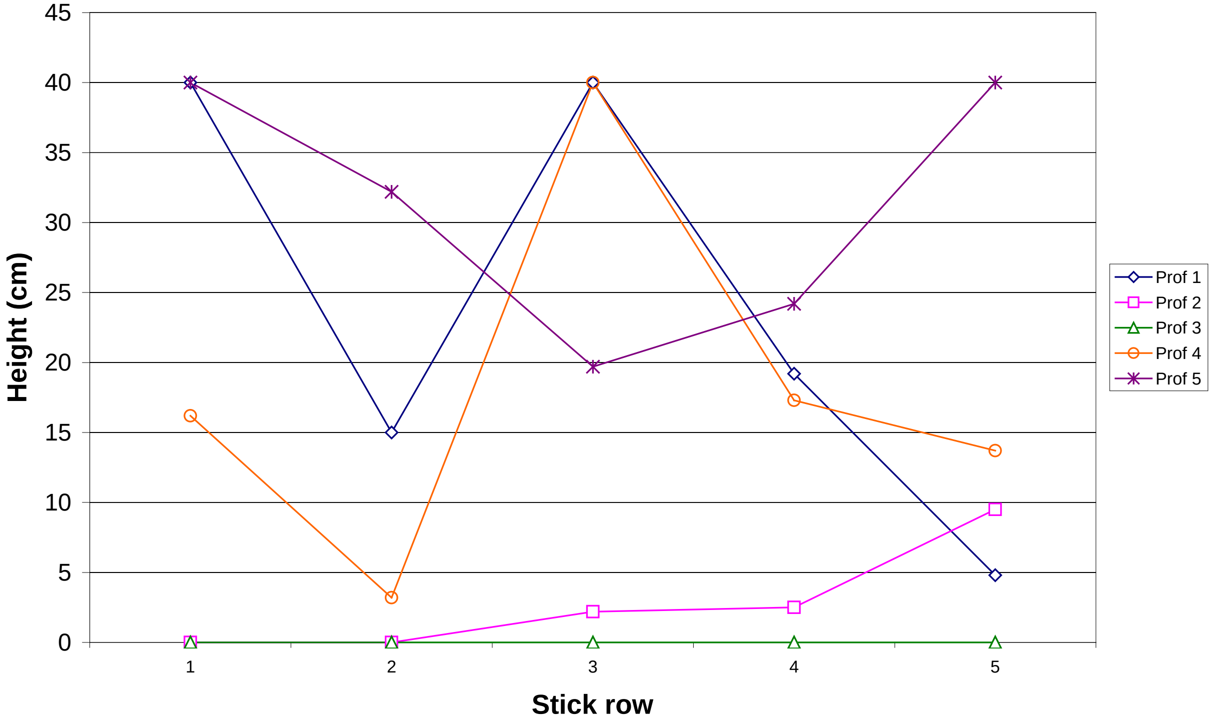

Figure 8. Lateral profiles of measured heights for lot K1

6.2 Calculation

The *R* values for the measurement period were *R* = 1510 ± 80 MJ mm/ha/hr (±5% uncertainty) for the *K*-group and *R* = 1050 ± 20 MJ mm/ha/hr (±2% uncertainty) for the *V*-group.

As for the previous cases we have *K* = 0.05 ± 0.01 ton h/MJ/mm (±20% uncertainty).

For the determination of the topographic factor, uncertainties of ±10 m in the slope length and ±5% in the slope steepness were considered. The results are shown in Table 1. It is observed that the uncertainty ranges from 16 to 47%.

In the case of the cover-management practice, the result from the pilot slope case were applied for the whole set, i.e., *C* = 0.63 ± 0.17 (±25% uncertainty).

From the combination of the above results, *TALUD* provides an erosion rate of 14 ton/ha/year, with a ±92% uncertainty. Using the slope area, obtained from the digital terrain model (11m ± 1 m wide and 120m ± 5 m long), and a porosity of 0.40 ± 0.05 (±13%), this means 1.5 m^3, with an uncertainty of 113%.

Table 1. Measured and calculated erosion rate (ton/ha) for lots

Lot	***Measured***	***R***	***K***	***LS***	***C***	***Calculated***
K1	**2000** (±110%)	1510 (±5%)	0.05 (±20%)	14 (±22%)	0.63 (±25%)	**650** (±75%)
K2	**1300** (±160%)	1510 (±5%)	0.05 (±20%)	14 (±22%)	0.63 (±25%)	**650** (±75%)
K3	**500** (±100%)	1510 (±5%)	0.05 (±20%)	16 (±16%)	0.63 (±25%)	**750** (±70%)
K4	**650** (±140%)	1510 (±5%)	0.05 (±20%)	16 (±16%)	0.63 (±25%)	**750** (±70%)
K5	**550** (±120%)	1510 (±5%)	0.05 (±20%)	6 (±17%)	0.63 (±25%)	**300** (±70%)
K6	**100** (±90%)	1510 (±5%)	0.05 (±20%)	0.2 (±47%)	0.63 (±25%)	**9** (±100%)
K7	**250** (±40%)	1510 (±5%)	0.05 (±20%)	0.6 (±39%)	0.63 (±25%)	**30** (±90%)
A1	**30** (±150%)	1050 (±2%)	0.05 (±20%)	0.6 (±41%)	0.63 (±25%)	**20** (±90%)
A2	**300** (±120%)	1050 (±2%)	0.05 (±20%)	14 (±21%)	0.63 (±25%)	**450** (±70%)
A3	**350** (±150%)	1050 (±2%)	0.05 (±20%)	14 (±21%)	0.63 (±25%)	**450** (±70%)

7. DISCUSSION

The comparisons between measurements and calculations for the three cases (named as A, B and C, respectively) are synthesized in Table 2. From them, the following observations can be made:

- The uncertainty in the measured value is much smaller for case A, showing that the sediment trap on a pilot slope is an adequate methodology.
- There is intersection between the intervals of the measurements and the calculations for all cases; i.e., the calculation model gives results that include the actual value. However, this is partly due to the high uncertainty intervals associated to both of them.
- If the mean values are compared, the calculation results lie within ±50% of the measurement for most of the 12 tests, except for three tests: K1, K6 and K7; the maximum difference is for the latter two tests, with around -90%.
- The contribution of the erosivity factor *R* to the uncertainty, between 2 and 5% for cases A and C, seems to be a lower limit which could be hardly improved. The high uncertainty in *R* associated to case B arises from the absence of a close-by rain gage.
- For the three cases, the contribution of the erodibility factor *K* to the uncertainty in the calculated values is significant: 20%. Soil testing could reduce the uncertainty in *K*, but a smart sampling should be undertaken in order to take into account the heterogeneity of soil at the local scale. It is speculated that, in any case, the uncertainty could not be reduced below 10%.
- The contribution of the topographic factor *LS* to the uncertainty in case A, 6%, also seems to be a lower limit which could hardly be improved. The relatively high uncertainties in *LS* associated to

cases B and C arise from the absence of more detailed field measurements.

- The other major contribution to the uncertainty in the calculated value comes from the cover-management factor *C*, which is 25% for most of the tests. A fast but relatively accurate way to estimate surface roughness would be necessary in order to reduce it., at least for the bear soil cases considered here. Again, it is speculated that reduction of uncertainty below 10% would be very unlikely.
- The inclusion of superficial cover would add another component to the uncertainty in *C*. In particular, the issue of variations in *C* when moving from a large time scale (yearly average) to a short time scale (event) should be investigated (Kelsey 2002).
- From the above considerations, it comes out that, even in the best scenario, it seems that uncertainty in erosion evaluation would not be below 30%.
- It is not clear that the application of *RUSLE2* to erosion estimation for particular events could mean any improvement in accuracy.

Table 2. Synthesis of measurements and calculations

Case	***Lot***	***Uncertainty***				***Measurement***	***Calculation***
		R	*K*	*LS*	*C*		
A. Sediment trap on pilot slope	-	±4%	±20%	±6%	±25%	32± 3 dm^3, ±10%	20 ± 11 dm^3, ±55%
B. Retained sediment from slope	-	±40%	±20%	±19%	±13%	1.3 m^3, ±100%	1.5 m^3, ±113% (2.1 m^3, ±104% from *RUSLE2*)
C. Soil loss on pipeline track	K1	±5%	±20%	±22%	±25%	2000 ton/ha, ±110%	650 ton/ha, ±75%
	K2	±5%	±20%	±22%	±25%	1300 ton/ha, ±160%	650 ton/ha, ±75%
	K3	±5%	±20%	±16%	±25%	500 ton/ha, ±100%	750 ton/ha, ±70%
	K4	±5%	±20%	±16%	±25%	650 ton/ha, ±140%	750 ton/ha, ±70%
	K5	±5%	±20%	±17%	±25%	550 ton/ha, ±120%	300 ton/ha, ±70%
	K6	±5%	±20%	±47%	±25%	100 ton/ha, ±90%	9 ton/ha, ±100%
	K7	±5%	±20%	±39%	±25%	250 ton/ha, ±40%	30 ton/ha, ±90%
	V1	±2%	±20%	±41%	±25%	30 ton/ha, ±150%	20 ton/ha, ±90%
	V2	±2%	±20%	±21%	±25%	300 ton/ha, ±120%	450 ton/ha, ±70%
	V3	±2%	±20%	±21%	±25%	350 ton/ha, ±150%	450 ton/ha, ±70%

8. CONCLUSIONS

The following are the main conclusions from the paper:

- Measuring soil erosion with sediment traps seems to be the most efficient strategy from the point of view of accuracy.
- The uncertainty in soil loss estimations using RUSLE for specific events (or a series of events) is usually large, above 50% and reaching 100% in some cases.
- To reduce the uncertainty, it is necessary to use close-by rain gages, undertake smart samplings of soil for test, make accurate measurements of the slope dimensions, and develop an efficient technique to measure surface roughness.
- In any case, it seems unlikely that uncertainty in erosion evaluation could be reduced below 30%.
- It is not clear that the application of *RUSLE2* to erosion estimation for particular events could mean any improvement in accuracy.

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