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Rate of erosion processes on experimental areas in the Marchiazza basin (northwestern Italy)*

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ABSTRACT This paper deals with the results of a 3 year study on slope erosion. Systematic surveys were performed on seven experimental plots and two small basins. Freeze-thaw cycles appear to be a preliminary factor inducing soil erosion. The displacement of grains occurs due to the impact of raindrops. The eroded material moves downward to the rills and thalwegs, whence periodically it is removed by "debris flow" phenomena. Comparing the material carried away and rainfall, it was observed that the amount of erosion is related, in the first place, to maximum rainfall intensity and, in the second place, to duration of "erosive rainfalls" as well as total rainfall depths. In late spring and summer when heavy rainstorms often occur, slope erosion is very intense and 60-80% of the annual erosion occurs. The rate of erosion on bare soil was 6 mm year^{-1}, on grass it was 0.2 mm year^{-1}; no erosion was observed in wooded areas.

<u>Vitesse de l'érosion sur parcelles expérimentales dans le bassin versant du Marchiazza (Italie nord-occidentale)</u>
RESUME Sur la base d'observations périodiques qui se sont déroulées pendant 3 ans on a pu examiner en détail les phénomènes d'érosion qui affectent les débris en place provenants d'une roche mère (rhyolites ignimbritiques permiennes) à fissuration élévée et par endroits soumise à des processus d'altération marqués. On disposait de neuf parcelles, à surface plane ou en entonnoir, différentes les unes des autres par leurs dimensions, le pendage, l'exposition et le couvert végétal. L'action répétée du gel et du dégel favorise la désagrégation du sol, et ensuite c'est surtout l'impact de la pluie qui produit le déplacement élémentaire des particules. Les matériaux érodés vont s'accumuler dans les dépressions du terrain, d'où ils sont entraînés de temps en temps par des phénomènes de "debris flow". Par comparaison entre les précipitations et les quantités des matériaux emportés on a pu vérifier en termes quantitatifs que celles-ci sont à relier étroitement à l'intensité maximale de la pluie, et, en second lieu, avec la durée

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des "pluies érosives" et la hauteur totale de la pluie. Lors des orages de la fin du printemps et de l'été, l'érosion est plus active et représente 60-80% du total annuel. D'aprés les contrôles effectués, la vitesse de l'érosion atteint 6 mm an^{-1} dans les zones dénudées, tandis que dans celles protégées par un couvert de gazon elle ne dépasse pas 0.2 mm an^{-1}; en forêt elle est pratiquement inexistante.

INTRODUCTION

In various areas located in the Marchiazza basin (east of Biella, Piedmont) experimental research directed to quantify erosion processes on slopes has been carried out for 4 years. The present paper discusses the results of systematic studies performed from October 1976 to October 1979 on seven plots and two small basins with different slope, exposure and vegetation.

The area under consideration is composed of Permian rhyolitic ignimbrite, locally intensely fractured and liable to deep weathering processes. In the Marchiazza basin (surface area 5.3 km^2, average slope 17°), areas covered by broad-leaved trees and conifers prevail, 30% of the surface is covered by grass and shrubs, while areas with no plant cover account for about 7%. Here, outcropping rock is usually overlain by a thin layer (1-10 cm) of coarse-grained regolith (D_{50}>2 mm). On this soil marked degradational processes caused by meteorological factors can take place, depending on the slope characteristics.

MEASURING EQUIPMENT

At 380 m a.s.l., in the centre of the basin, seven experimental plots were successively arranged, the details of which are given in Table 1. Plots 1, 2, 3, 4, 5 are on bare soil, while plot 6 is entirely covered by purple moor-grass (*Molinia caerulea*) and plot 7 is under chestnuts and oaks, with undergrowth dominated by ferns.

All the plots except plot 4 are fenced on three sides by iron sheets; the lower side is connected to a storage box used to collect the erosion products from each rainfall event; a screen prevents rain from falling directly into the box, while total runoff is collected in a series of cascade-connected drums. In plots 1 and 2 a tilting bucket device provides a continuous record of runoff.

At about 460 m a.s.l., below a crest line, two small basins were established (Table 1). A number of ordinary nails painted in stripes were driven in on each of these basins in order to check the rate of erosion visually; the nails were arranged along parallel lines for ease of recognition. A sheet barrage at the outlet of each basin allowed progressive storage of removed materials; the volume of the accumulated material was checked by periodical surveys.

Precipitation was measured by two rainfall recorders placed near the plots and the basins, respectively. A meteorological

Table 1 Characteristics of the experimental areas

Plot	Size (m)	Average slope (°)	Exposure	Distinctive features
1	2 × 1	14	S	Bare soil
2	2 × 1	24	NE	Bare soil
3	6 × 1	18	SW	Very poorly vegetated with tufted grass
4	2 (in length)	14	SE	Bare soil; open on both sides
5	2 × 1	14	SE	Bare soil, dug soft
6	2 × 1	11	SW	Densely vegetated, with a grass cover
7	2 × 1	18	SW	Under wood, on a bed of dead leaves
Basin	**Area (m^2)**			
1	236	35	N	Bare soil
2	177	33	E	Partly vegetated, with heath bush and birches

station, including anemograph, barograph, thermohygrograph and directional pluviometer was also set up near the plots. The purpose of the pluviometer is to evaluate the average angle of raindrops, and, consequently, the actual water inflow in each plot.

Field surveys made every week identified 81 rainfall events, 48 of which appeared particularly significant from the appreciable quantities of materials collected.

PROCESSING OF DATA

Pluviometric data recorded during each event were analysed and plotted in the form of histograms showing constant rainfall intensities and duration. By comparing these graphs and the relevant masses of sediment collected at the end of each rainfall, a range of low intensities for which there was negligible or no sediment transport was identified for all the plots. The upper limit of this range varied from a minimum value of 4 mm h^{-1} (plot 5) to a maximum of 10 mm h^{-1} (plots 1, 4 and 6), according to the different characteristics of the plots.

The mass of materials removed during each event was related, by the multiple regression method, to maximum rainfall intensity; the average value of intensities $\geq$ 10 mm h^{-1} and their total duration; total rainfall depth; total duration of the rainfalls considered; and total runoff.

A correction factor for inflows to each plot, calculated from the data from the directional pluviometer, was introduced; however, no appreciable changes in the results were observed; thus, the pluviometric values mentioned hereafter are those directly obtained from records. However slope erosion is indeed affected by the angle of incidence of raindrops, because this results in different inflow rates and therefore, different erosion effects. The results here are due mainly to the kind of instrument employed, which can provide only total rain depths and therefore estimate only the average angle of incidence of the raindrops during the whole event; it cannot provide information on the variations that occurred during the event.

The rainfall energy was evaluated according to Wischmeier's formula but the effort involved in applying this formula did not seem worthwhile, compared with the results attained with the multiple regression method. More significant results would probably be achieved by employing a formula for energy suitable for local climatic conditions. No such formula, however, is yet available.

In applying the multiple regression method, the most significant parameter proved to be the maximum rainfall intensity in minimum time intervals of 5 min. The mass of eroded material seems to be less dependent on the duration of erosive rainfalls and on the total amount of precipitation. Here, an "erosive rainfall" is defined as a rainfall having an intensity $\geq$ 10 mm h^{-1}

On the whole, the three 2 m^2 plots on bare soil (plots 1, 2 and 5) behaved very similarly, the values of the exponents in the regression formulas being quite close to each other. Plot 4, open on both sides, and plot 3, 6 m long, are not included in this group: for the latter the total duration of the event replaces the duration of erosive rainfalls and includes total rainfall depth.

Total runoff may replace total rainfall depth without the regression being sizeably affected; in some cases this leads to a slight improvement in the regression coefficient. The runoff coefficient varies from event to event, ranging from an average value of about 0.2 in the plots on bare soil, to 0.03 in the plots with vegetation (Table 2). It will be observed that the

Table 2 Runoff coefficients. Mean values and coefficients of variation

Plot	1	2	3	5	6	7
<RC>	0.20	0.21	0.17	0.25	0.03	0.03
CV	1.02	0.80	0.52	0.81	0.71	1.14

larger area in plot 3 results in a less variable runoff coefficient. In the plots on bare soil the changes in this parameter appear mainly dependent on the rainfall characteristics of an event, while, in the plots with vegetation, the seasonal influence is stronger.

The average ratio between the maximum instantaneous runoff recorded on plots 1 and 2, and the corresponding rainfall intensity, is 0.58 and 0.44, respectively, reaching peaks of up to 0.88.

In terms of pluviometric parameters only, the equations (linear in logarithms) are as follows:

$$W_1 = 0.027\ I_m^{1.591}\ D_e^{0.505}\ H^{0.157} \qquad (R = 0.859; \quad N = 48)$$

$$W_2 = 0.047\ I_m^{1.413}\ D_e^{0.456}\ H^{0.316} \qquad (R = 0.911; \quad N = 48)$$

$$W_3 = 3.3\text{x}10^{-4}\ I_m^{2.441}\ D_t^{0.681} \qquad (R = 0.768; \quad N = 46)$$

$$W_4 = 0.949\ I_m^{1.365}\ D_e^{1.341}\ H^{-0.798} \qquad (R = 0.915; \quad N = 19)$$

$$W_5 = 0.074\ I_m^{1.633}\ D_e^{0.461}\ H^{0.075} \qquad (R = 0.891; \quad N = 25)$$

where $W_.$ is the weight of the materials collected at the outlet of plot · (g), I_m is the maximum rainfall intensity (mm h^{-1}), D_e is the duration of rainfall with intensity $\geq$ 10 mm h^{-1} (min), D_t is the total duration of the rainfall (min), H is the total rainfall (mm), R is the multiple correlation coefficient, N is the number of events considered.

The above equations enable an assessment to be made of slope erosion in other areas having physical and environmental features similar to those of the plots in the present survey.

The equations for plots 6 and 7 are not shown due to their low correlation coefficient. This is due to the nature of the plots themselves, where the incidence of casual factors appeared to be very important, because of the very small amount of material collected.

DISCUSSION

During the field surveys it was observed that the freeze-thaw cycles are an important factor inducing slope erosion processes. Due to this phenomenon a network of superficial cracks extends into the bedrock, while the repeated formation of ice needles perpendicular to the soil ("pipkrake") causes the mass of regolith material on top to become loose; on steeper slopes (over 20°) soil particles will then detach and roll down, even if no precipitation occurs.

The impact of raindrops disturbs individual soil particles from their former state of equilibrium, and subsequent impacts cause the soil particles to move, while overland flow will carry away finer particles.

In the basins, the movement of grains is increased by the steepness of the slopes; the materials tend to move towards rills and gullies, where mass movement, like a debris flow process, can take place whenever particularly intense rainfall occurs. It was observed that this phenomenon is started whenever the intensity of rainfall reached 20 mm h^{-1} for at least 20-30 min, this value being regarded as a critical threshold (Table 3).

Tables 4 and 5 show the total amounts of soil removed from the various experimental plots for subsequent discrete periods of approximately one year each. It should be noticed that in each control period the total rainfall was higher than the average annual rainfall (1400 mm); this value is the result of the processing of data supplied by Ministero dei Lavori Pubblici, Servizio Idrografico, and refers to the period 1924-1973.

Table 3 Maximum rainfall intensities and corresponding amounts of material carried away from the small experimental basins

Date	Rainfall depth (mm)	Time interval (min)	Volumes (dm^3)	
			No. 1	No. 2
17 June 1978	15	30	342	
7 Aug. 1978	5 12	5 15	367	
2 May 1979	9.4 8.2	15 20	113	
14 June 1979 16 June 1979	12 9.2	15 15	862	211
13 July 1979	7.4 18.2	25 20	510	253
7 Aug. 1979	12.4	20	67	
14 Oct. 1979	29	25	632	149

Table 4 Rate of erosion processes in the experimental plots

Plot	1	2	3	4	5	6	7
25 October 1976 - 10 October 1977							
Total rainfall: 2436 mm							
Amount of debris (kg)	2.903	4.384	5.077	4.516			
Debris-rainfall ratio (g mm^{-1})	1.19	1.80	2.08	1.85			
Thickness of soil eroded (mm)	1.06	1.80	0.73	1.65			
11 October 1977 - 18 October 1978							
Total rainfall: 1411 mm							
Amount of debris (kg)	0.675	1.478	3.060			0.054	0.018
Debris-rainfall ratio (g mm^{-1})	0.48	1.05	2.17			0.04	0.01
Thickness of soil eroded (mm)	0.25	0.61	0.44			0.03	$\simeq 0$
Runoff (mm)	104	190	201			58	38
19 October 1978 - 28 October 1979							
Total rainfall: 1484 mm							
Amount of debris (kg)	3.014	4.174	2.713		4.979	0.092	0.009
Debris-rainfall ratio (g mm^{-1})	2.03	2.81	1.83		3.35	0.06	$\simeq 0$
Thickness of soil eroded (mm)	1.10	1.71	0.39		1.91	0.04	$\simeq 0$
Runoff (mm)	430	310	261		311	51	36

Table 5 Rate of erosion processes in the small experimental basins

Basin	1	2
9 Sept. 1977 - 4 Sept. 1978		
Total rainfall: 1025 mm		
Amount of debris (m^3)	0.709	$\simeq 0$
5 Sept. 1978 - 17 Oct. 1979		
Total rainfall: 1861 mm		
Amount of debris (m^3)	2.183	0.623
Rate of erosion (mm $year^{-1}$)	6.13	1.76

By comparing the periods 1976-1977 and 1977-1978 a decrease in the sediment yield can be observed in all the plots; except in plot 3 this decrease is not proportional to the decrease in total rainfall. This was probably due to the fact that, while in the 2 m^2 plots, a progressively smaller amount of material became available due to the "armouring" processes, in the plot 3 the downhill grain transport remained nearly the same.

On the contrary, in the period 1978-1979 (particularly in the first 6 months of 1979) a marked increase in sediment yield was observed in plots 1 and 2. In this connection, an analysis of the multiple regression results leads us to believe that the above mentioned changes in erosion processes might not depend on the pluviometric characteristics of the various events. In fact both the positive or negative differences between the observed and calculated values for each event, and the per cent difference of the sums of the former values, in each period, show differences to previously observed results.

The excessive sediment yield from the plots may be explained by the freeze-thaw processes. In the periods 1976-1977 and 1977-1978 the total duration of frost was 113 and 175 h respectively, with temperatures never below -7°C, but the 1978-1979 winter was considerably colder; in fact there were 86 peaks between 0 and -11°C, totalling about 580 h of frost. This resulted in an increase of the detrital layer by a thickness of some centimetres that persisted some weeks after milder temperatures had set in. Thus the conditions for soil erosion were re-established, because particles were disturbed from their previous state of equilibrium, following the armouring processes.

In the 3 year survey, erosive rainfalls occurred for a total of 56 h. On some occasions, however, a few events of short duration removed most of the materials: particularly, during the last year, when erosive rains fell for 17 h, but two events with a total duration of 1½ h caused the removal in each plot of about one half of the total annual mass of sediment (Table 6).

It was also observed in the plots, that more intense erosive processes occurred in late spring and summer, when 60-80% of the eroded material was carried away. This is apparent in Fig. 1; the high values in some winter months, particularly evident in plot 3, are considered anomalous with reference to rainfall only; they are in fact ascribed to freeze-thaw processes as formerly stated.

Other considerations resulting from the comparison between the

Table 6 Rainfall intensities and materials removed from plots during heavy rainstorms

Date	Rainfall depth (mm)	Time interval (min)	Amount of debris (g)			
			1	2	3	5
14 June 1979	32	60	851	920	562	1372
12-13 July 1979	15 16	15 15	869	946	439	1261

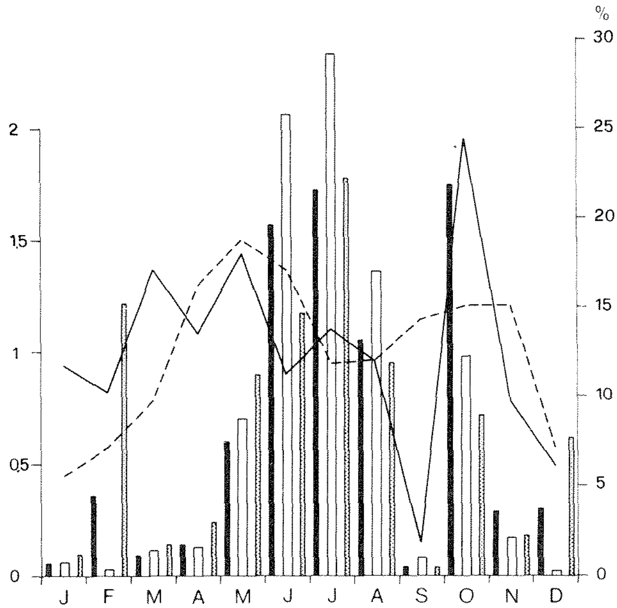

Fig. 1 Seasonal trend of erosion processes during the survey period in plots 1 (blank), 2 (black), and 3 (stippled) as a percentage of the total amount of material collected from each plot. In addition, graphs of the rainfall coefficients are shown for the periods 1976-1979 (solid line) and 1924-1973 (dotted line).

average monthly rainfall distribution, the rainfall distribution observed in the survey period and the histograms of eroded material are: summer rainstorms brought about widespread grain transport, whereas spring rains, though of greater depths, produced more moderate transport. It is remarkable that, during the 3 years of the survey, the month of September was characterized by very low rainfalls and, therefore, by poor sediment transport; in contrast, in October, a high rainfall depth was recorded together with a similarly high sediment yield; this was particularly high in plot 2 as shown in Fig. 1, where a mass transport process also occurred on an obviously reduced scale (14 October 1979).

Table 7 Grain-size distribution as a percentage of removed materials and undisturbed soil particles (values in brackets)

Plot	Gravel			Sand			Silt and clay
	coarse 20–60 mm	medium 6–20 mm	fine 2–6 mm	coarse 0.6–2 mm	medium 0.2–0.6 mm	fine 0.06–0.2 mm	<0.06 mm
1	0 (8)	15 (32)	35 (24)	26 (18)	15 (10)	5 (6)	4 (2)
2	0 (1)	10 (23)	27 (26)	27 (23)	17 (15)	8 (8)	11 (4)
3	0 (2)	25 (30)	35 (35)	20 (20)	12 (8)	4 (3)	4 (2)
4	0 (8)	12 (32)	28 (24)	31 (18)	20 (10)	8 (6)	1 (2)
5	0 (8)	24 (32)	34 (24)	24 (18)	12 (10)	4 (6)	2 (2)
6	0 (8)	6 (32)	14 (24)	25 (18)	25 (10)	13 (6)	17 (2)

Further observations can be made from the results of grain-size analyses carried out on a total of about 200 samples. Table 7 shows the grain-size distribution of the soil around the plots and the granulometry of all eroded products collected in the 3 years. Clearly, rainfall appears to have been selective on the size of removed particles; e.g. the amount of gravel ≥ 6 mm in size which forms an appreciable fraction of the soil, is considerably reduced in the collected materials. In particular, grains > 20 mm are never present. At the same time the percentage of materials < 2mm increases; this is in fact dominant in some plots.

It was observed that the grain sizes more likely to be transported are between 0.6 and 6 mm. In all the plots on bare soil, 54-61% of the materials removed were within this size range.

A strong difference may be seen between the grain-size distribution of sediments from the plots on bare soil and the grain-size distribution from plot 6, where about an 80% of the material is smaller than 2 mm, owing to reduced raindrop impact and the screening effect by the dense grass cover.

The artificial disturbance of the soil in plot 5 resulted in a great increase of the coarse fraction ranging from 2 to 20 mm, whose per cent values are comparable only with plot 3, where medium and fine gravels are present in high quantities in the original composition of the soil.

Experiments on the rate of movement of soil particles are currently being performed on a sample area with characteristics similar to plot 1. Grains, coloured depending on grading (from 2 to 12.5 mm), are employed as markers. In a period of 1 month, from 7 June to 9 July 1980, when a total rainfall depth of 366 mm fell, displacements of single grains were observed up to 1.70 m from the starting point. The bulk of coloured particles, however, hardly moved: only 3-21% (depending on grading) of the coloured particles moved distances ranging from 10 to 34 cm.

CONCLUSIONS

Referring to the data of Table 4, in 1 year out of the entire survey period, the rate of erosion ranged from a minimum of 0.25 to a maximum value of 1.91 mm in the plots on bare soil, depending on total annual rainfall depths as well as environmental conditions. In plot 6, with grass cover, the average annual erosion was contained within 0.037 mm while in plot 7, under wood, it was negligible.

In basin 1 (Table 5) rainfall depths similar to those on the plots, produced a stronger erosive effect (6.1 mm year^{-1}). As already observed in plots 6 and 7, in basin 2 the protective influence of vegetation, although not present over the entire area, contributed to reduced degradation (1.8 mm year^{-1}). On the whole, erosion in the basins appeared to be much faster than in the plots. This may be explained by differences in slope; however, from the data currently available, other things being equal, no relationship between this important parameter and the annual sediment yield can be established.

In addition, it should be pointed out that the measures taken up to now refer to slope erosion processes occurring in small elements of land: the data so obtained should not be readily employed for computations on larger areas. There is a need for further experimental research leading to the development of models for forecasting rates of erosion on a larger scale.

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