Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation
(Proceedings of the Vienna Symposium, August 1991) IAHS Publ. no. 203, 1991.

SEDIMENT PRODUCTION FROM UNMETALLED ROAD SURFACES

W. FROEHLICH
Institute of Geography Polish Academy of Sciences,
Department of Geomorphology and Hydrology, Research Station,
Frycowa 113, 33-335 Nawojowa, Poland

ABSTRACT Unmetalled roads greatly accelerate runoff and erosion processes and provide the main source of suspended sediment transported by Carpathian rivers. In the instrumented drainage basin of the Homerka stream (19.6 km) systematic measurements of runoff, suspended sediment and erosion of unmetalled roads were carried out both on an experimental slope under cultivation and in the forested area. The average contribution of sediment from the unmetalled roads amounts to about 70-80% of the suspended sediment load of the Homerka drainage basin.

INTRODUCTION

Unmetalled roads are a characteristic feature of the Carpathian landscape and date back to the original clearing and cultivation of the land. The network of these field roads is related to the field pattern. Major roads tend to be located along both watercourses and divides and to be linked by a dense network of secondary roads which run downslope or at an inclination to the slope. In narrow valley bottoms unmetalled roads often run along stream channels which in forest areas often serve for log transport. Logging accelerates sediment production because a high proportion of the eroded sediment is introduced directly to streams (Reid & Dunne, 1984).

Roads were usually built on the dry, convex or straight parts of slopes where the bedrock is not too deep. These secondary roads are mostly 2-5 m wide and occur in materials ranging from loam to bedrock. They characteristically have longitudinal profiles marked by a sudden change of inclination often exceeding 20°. During several centuries of agriculture the unmetalled roads have evolved into ravines several meters deep.

Drainage density is a critical factor in determining sediment yield (Campbell, 1983; Walling, 1983). Unmetalled roads increase the natural drainage density by creating a network of seasonal drainage lines, and greatly accelerate runoff and erosion processes and provide the main source of suspended sediment transported by Carpathian rivers (Froehlich & Slupik, 1986).

STUDY AREA AND METHODS OF INVESTIGATIONS

In the instrumented Homerka drainage basin systematic measurements of runoff, suspended sediment transport and erosion of field roads were carried out both on an experimental slope and in forested drainage basins (Fig. 1). The drainage basin of the Homerka stream (19.6 km) is representative of the largely deforested Carpathian basins at an altitude of 375-1060 m a.s.l. Forests, which occupy 52% of the drainage basin, are presently under inten-

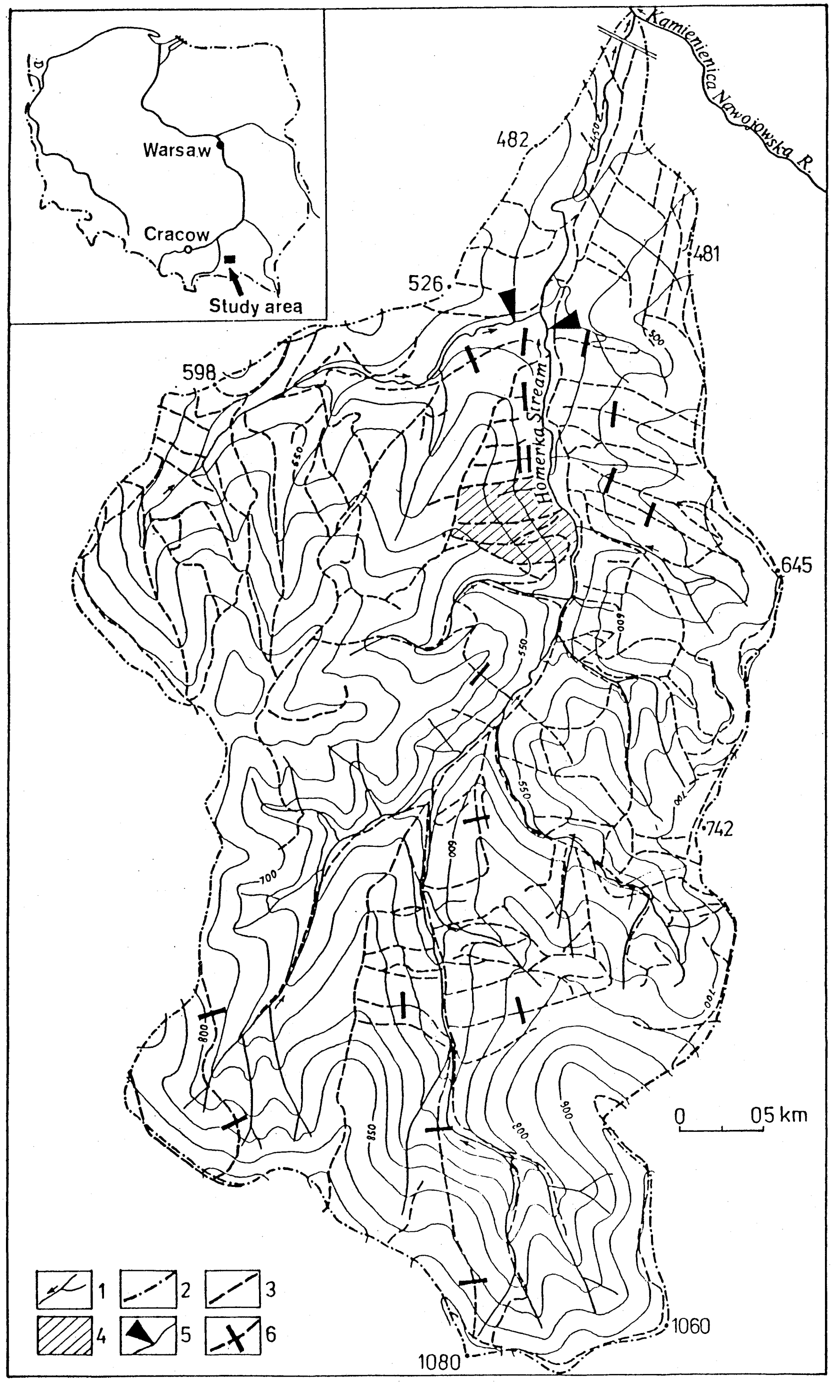

FIG. 1 The Homerka drainage basin: 1 - stream network; 2 - drainage divides; 3 - unmetalled road network; 4 - the experimental slope; 5 - stream sampling stations; 6 - sites for measuring unmetalled road surface changes.

sive exploitation.

The 500-700 m long convex-concave experimental slope is located on an area of 26.5 ha (Fig. 2) at the boundary of the forest and agricultural areas at an altitude of 458-608 m a.s.l. The length of the unmetalled roads on the experimental slope is 3.3 km, i.e. 11.9 km km^{-2} whereas the density for the whole drainage basin is 5.3 km km^{-2}. The experimental slope is composed of several sub-basins representing the main Carpathian areas contributing streamflow and sediment. Characteristics of these basins are: 1 — Holocene gully; 2 - unmetalled roads; 3 - interchannel areas. Each of the drainage basins was instrumented (Fig. 2).

The rate of road incision was measured at 30 transverse profiles on the experimental slope and at 25 other points in the drainage basin with respect to steel bench marks. Measurements along a profile were undertaken every 10 cm with an accuracy of ±2 mm. The small, 2 m, distance between individual cross sections also enables the rate of deepening along the longitudinal profile of the unmetalled roads to be determined. The cross sections were measured in spring and autumn, and in summer after each heavy rainfall event. Measured profiles were established on different kinds of roads, depending upon the depth of incision, regolith material, slope inclination, length of the eroded segment and frequency of traffic.

TRANSPORT OF SUSPENDED SEDIMENT

The greatest concentrations of suspended sediment were observed on the unmetalled roads (Fig. 3). Even after insignificant precipitation of only a few mm, an increase in water turbidity was noticed. Simultaneous measurements of the concentration of suspended sediment during different types of high water stage indicate that concentrations are always much lower in water draining from the Holocene gully than in water flowing down the roads. They also were different for particular roads. The lowest suspended sediment concentrations (<117 mg l^{-1}) were measured in overland flow in the interchannel area.

The concentration of suspended sediment in the runoff from the unmetalled roads closely related to the intensity of soil splash due to raindrop impact. Research on soil splash on experimental plots imitating a ploughed field and an unmetalled road suggest that splash intensity may be 30 times greater on an unmetalled road than on a field (Froehlich & Slupik, 1980).

The maximum recorded suspended sediment concentration from the unmetalled roads was about 1.5×10^5 mg l^{-1}. During rising stages the suspended sediment concentration was always greater on the unmetalled roads than in the Homerka stream channel (Fig. 3). The maximum suspended sediment concentration precedes the peak flow.

After extended drought periods even small amounts of precipitation, produced high suspended sediment concentrations on the unmetalled roads. This is because during the high water stage, loose particles on the surface are swept off the unmetalled road surface. The more compact ground is then uncovered and undergoes compaction by rain drop impact. Additionally, the road surface is protected by a pavement composed of the coarser fraction of weathered material. The amount of loose particles on the unmetalled road surface depends, therefore, on the length of time between high water stages. This changes from one rainfall event to another. Succeeding flood events separated by short intervals and covering similar contributing areas, therefore, display decreasing suspended sediment concentrations. Each high water stage is marked by a distinct loop in the relation between water

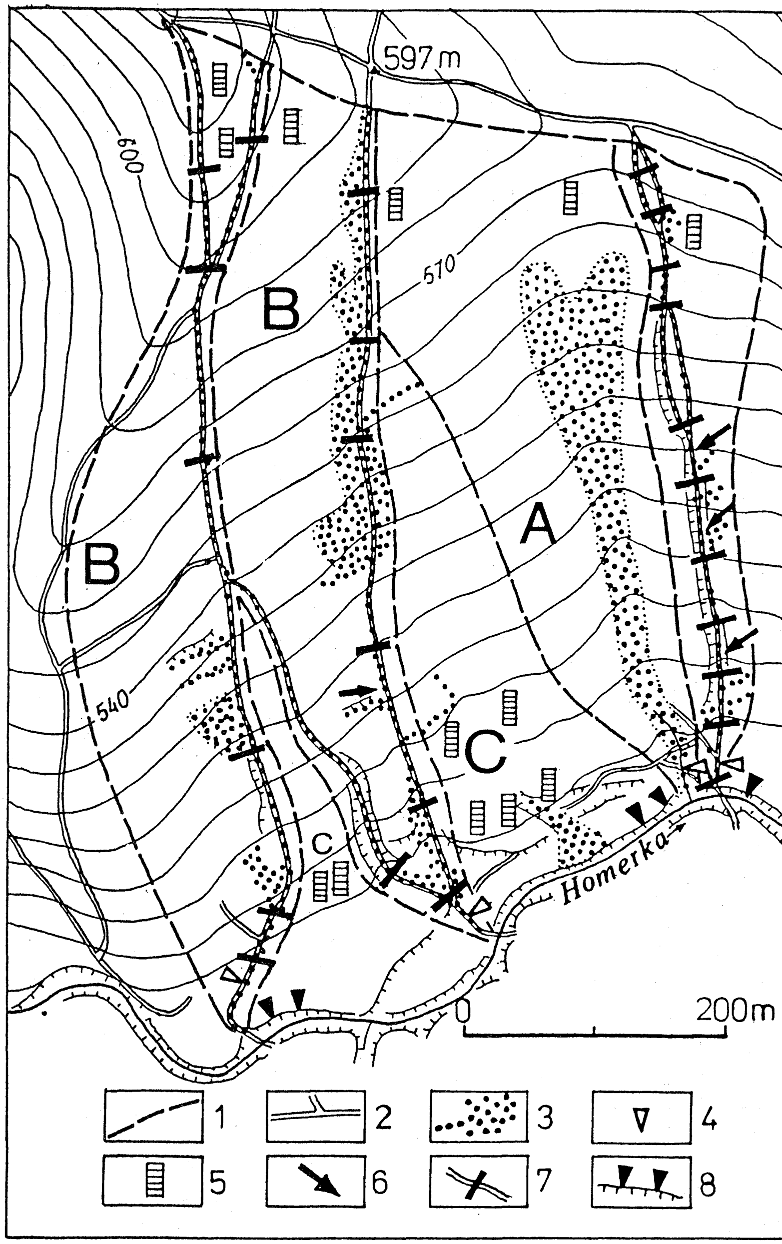

FIG. 2 The experimental slope in the Homerka drainage basin: 1 - drainage divides; A - drainage basin of the Holocene gully; B - drainage basins of the unmetalled roads; C - drainage basins of the interchannel areas; 2 -unmetalled roads; 3 - contributing areas; 4 - points for measuring concentrated flow and taking water samples; 5 - containers for measuring sheet flow and taking water samples; 6 - outflow of furrows; 7 - sites for measuring unmetalled road surface changes;8 - sites for measuring channel erosion rates.

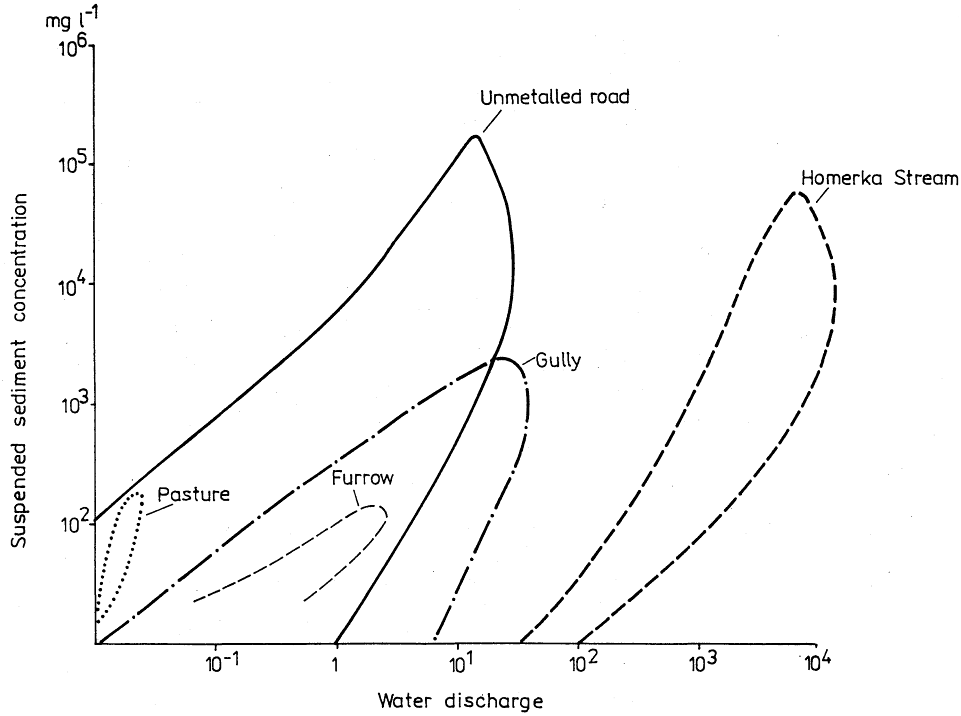

FIG. 3 The relationship between water discharge and suspended sediment concentration in the Homerka stream and various contributing areas on the experimental slope.

discharge and suspended sediment concentration.

The magnitude of the suspended sediment concentrations is related to particular features of the roads, namely to their depth of incision, the grain size composition of the regolith exposed in the road ravine, the moisture contents of the ravine regolith and frequency of traffic. In general, for old, deeply incised roads where the bottom is paved with residual gravel, suspended sediment concentration is less than for new roads incised into the loamy weathering products.

Most of the sediment supplied from unmetalled roads to the Homerka channel came from erosion of the road ravines and partly from erosion of field furrows. Alonso *et al.* (1988) show that soil losses depended greatly on the furrow gradient. Only during times of overland flow and wash was sediment supplied from field furrows, and this was always significantly less than that supplied from roads (Fig. 3). Moreover, the frequency of sheet wash on fields is less than that on unmetalled roads.

Similar parameters of suspended sediment transport were found to be important for the unmetalled roads in the forested part of the Homerka drainage basin. As is generally known, wash processes in forested areas of the lower subalpine region are quantitatively unimportant. It can be expected, therefore that the largest portion of suspended sediment comes immediately from unmetalled roads.

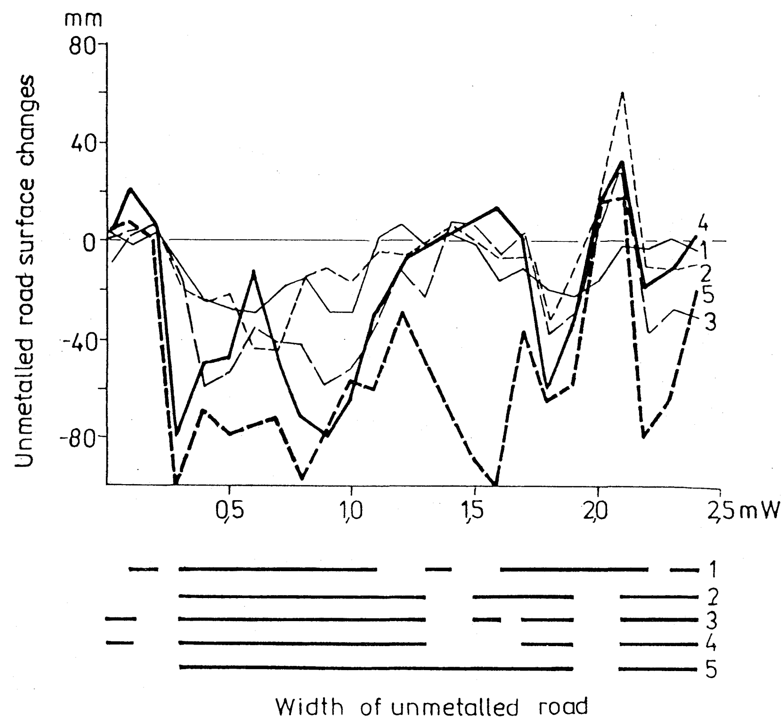

FIG. 4 Unmetalled road surface changes.

SEDIMENT DELIVERY

The direct supply of sediment to the channel varies, depending on rainfall duration and intensity. Circa 98% of all suspended sediment is supplied from unmetalled roads within the interchannel area, during precipitation events which are too low to trigger overland flow.

Sediment supplied from unmetalled roads and ploughed fields during the annual floods constitutes ca. 60-70% of the total load. The Holocene gullies supply 10-15%. Direct supply by overland flow from the interchannel areas does not exceed 1%.

During extreme floods, an increase in the suspended sediment supply from fields under cultivation to the unmetalled roads is difficult to ascertain. However, unmetalled roads deliver greater than 50% of the total sediment transported during extreme floods. Suspended sediment supply from the channels increases and is about 25-35%. The average contribution of suspended sediment from the unmetalled roads, therefore, is from 70 to 80% of the total suspended sediment load of the Homerka drainage basin (Froehlich, 1982).

THE RATE OF UNMETALLED ROAD INCISION

Analysis of the cross sections shows an intermittent deepening of the unmetalled roads, re-

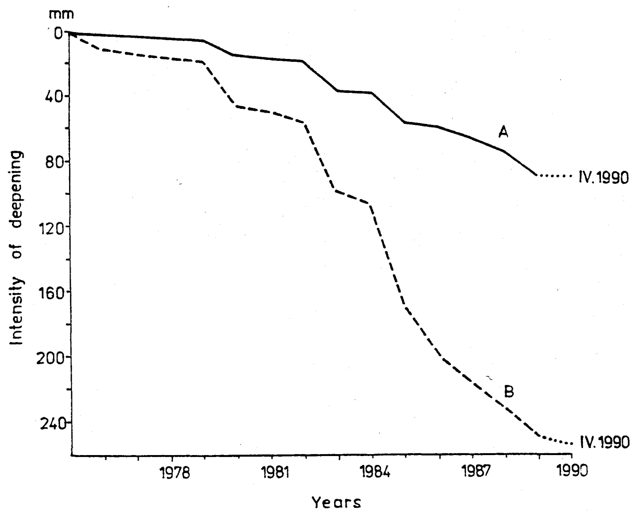

FIG. 5 Cumulative curves of unmetalled road incision: 1 - old road; 2 - new road.

lated to the seasons of the year and the frequency of extreme rainfall events (Fig. 4). For different unmetalled roads and cross sections, rates of deepening reflect the resistance of the substratum, slope inclination, the flow length and the traffic frequency (Fig. 5).

Deepening is more rapid during the summer months than in winter. This can be explained by fact that the main phase of suspended sediment supply from the unmetalled roads to the stream channel takes place during summer floods. Maximum unmetalled road incision rates were found after flash floods - in 1980 and 1985, when ravines become deepened by as much as 60 cm. Carts, lorries and agricultural machines cause furrows that facilitate the concentration of water, which leads to linear erosion.

In the spring, after the thaw, an increase in road surface level was observed sometimes. This can be explained by the effects of frost and by accumulation of weathered material slumping down the ravine walls or deflated from fields. This material often remains until summer because of the low intensity of both erosion and transport during the intra-winter and spring melts.

The average rate of deepening, calculated as the arithmetic average of all investigated sections, is 6.6 mm year^{-1}. Assuming an average width of 2 m and an average rate of deepening of 6.6 mm year^{-1}, one can see that for a road length of 76 m the yearly loss is 1 m^3. This gives only an indication of the rate of deepening and does not signify the absolute value.

A characteristic feature of unmetalled road deepening at the different cross sections, is the shifting of zones of erosion and accumulation (Fig. 4). Almost every rainfall event at most sites was accompanied by a change from deposition or net balance of material to erosion or vice versa. This suggests, amongst others things, intermittent transport of material along the roads. The incisions are very irregular features, in which narrow rills concentrate the flow and increase linear erosion. The deepening of the rills also leads to a lowering of the intervening surface, thus causing a general lowering of the road. This takes place most quickly at trough edges and is related to furrows left by the wheels of vehicles.

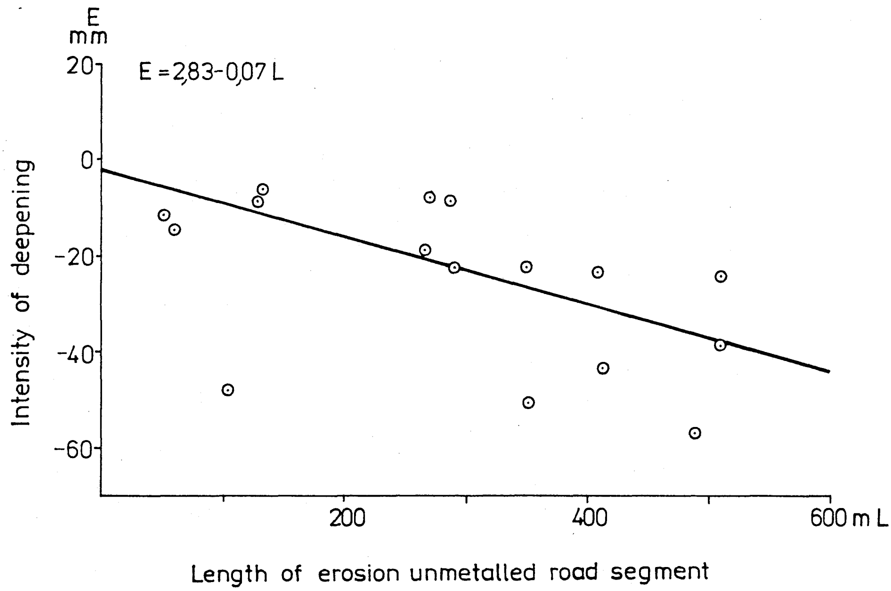

FIG. 6 The relation between length of eroding unmetalled road segment and intensity of deepening.

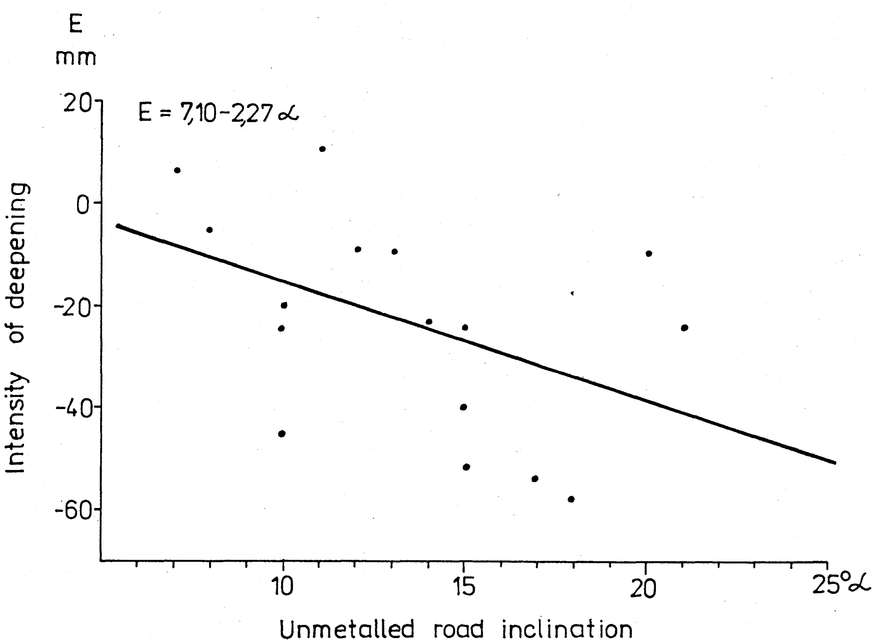

FIG. 7 The relationship between unmetalled road inclination and intensity of incision.

Anderson (1954) showed that sediment production is positively correlated with road length. The relation between road length and rate of incision is linear (Fig. 6). This tendency is not so clear for the oblique roads. The decline in the role of incision upslope is related to the decrease in the same direction of both the area of water supply and the road traffic. Deepening occurs intermittently, as seen by the occurrence of zones of intense erosion separated by those of temporary accumulation. These changes are mostly associated with the point where water leaves the unmetalled road.

There is a clear association between the rate of unmetalled road deepening and the slope of the road. The rate of incision is proportional to the road inclination and especially rapid where the inclination is over 15°. That relation is of a linear character (Fig. 7).

CONCLUSIONS

Unmetalled roads increase the natural drainage density by creating a network of seasonal drainage lines, which greatly accelerate runoff and erosion processes and provide the main source of suspended sediment transported by Carpathian rivers. This is the major cause of the rapid silting of dam reservoirs. The process is most important along unmetalled roads which are directly connected to stream channels. Old, deeply incised unmetalled roads provide relatively more runoff water because of their larger drainage areas. The newer unmetalled roads, as yet only slightly deepened, are being incised more rapidly into erodible surficial regolith. These supply very large amounts of sediment to the channels.

The increasing density of roads in the drainage basins of the Flysch Carpathians is a fundamental but underestimated cause of the increased frequency of floods, of the rapid silting of dam reservoirs, and of the deepening of channels, which causes a lowering of the groundwater table in the valleys and increase in amplitude of high water stages.

Road ravines are anthropogenic forms shaped by a complex of processes where the principle one is the linear erosion accelerated by the road traffic. Because of the importance of road traffic, the rate of road deepening is at variance with that of typical erosional Holocene gullies. When explaining, therefore, their origin and development we cannot apply classical models of gully-formation.

REFERENCES

Alonso, C. V., Meyer, L. D. & Harmon, W. C. (1988) Sediment losses from cropland furrows. In: *Sediment Budgets* (Proc. Porto Alegre Symp. December 1988) IAHS Publ. **174**:3-9.

Anderson, H. W. (1954) Suspended sediment discharge as related to stream flow, topography, soil, and land use. *EOS Trans. Am.Geophys. Union.* **35**:268-281.

Campbell, I. A. (1983) The partial area concept and its application to the problem of sediment source areas. In: *Soil Erosion and Conservation*, S. A. El-Swaify, W. C. Moldenhauer and Andrew Lo (eds.). Soil Cons. Soc. Am. 128-137.

Froehlich, W. (1982) Mechanizm transportu fluwialnego i dostawy zwietrzelin do koryta w gorskiej zlewni fliszowej (The mechanism of fluvial transport and waste supply into the stream channel in a mountainous flysch catchment). *Prace Geogr IG i PZ PAN.* **143**:1-144.

Froehlich, W. & Slupik, J. (1980) Importance of splash in erosion process within a small flysch catchment basin. *Studia Geomorph. Carpatho-Balcanica* **14**:77-112.

Froehlich, W. & Slupik, J. (1986) Rola drog w ksztaltowaniu splywui erozji w karpackich zlewniach fliszowych (The role of roads in the generation of flow and erosion in the Carpathian flysch drainage basins). *Przegl. Geogr.* **58**:67-87.

Reid, L. M. & Dunne, T. (1984) Sediment production from forest road surfaces. *Wat. Resour. Res.* 20(11):1753-1761.

Walling, D. E. (1983) The sediment delivery problem. *J. Hydrol.* **65**:209-237.