LABORATORY INVESTIGATION OF SHEET EROSION

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Experimental determination of the loss of soils due to the surface sheet erosion in a hydraulic laboratory involves significant possibilities:

1. to develop the physical background of the familiar empirical methods (e.g. those by *Wischmeier—Smith*, *Holly*, *Horton*);

2. to economically modify the parameters of erosional processes (soil grade, state and slope of the soil surface, rainfall intensity, the test length).

All these experiments may contribute to the development and improvement of soil preservation works. As a matter of course, laboratory experiments are known to have also inconvenients, stressing the complementary field investigations.

Since 1972, the Institute of Water Management and Hydraulic Engineering has been concerned with laboratory studies on surface erosion processes on commission of the *Research Institute for Water Resources Development*. The earlier findings will be recapitulated or referred to, while recent results will be reported in detail.

1. Testing equipment and methodology

The most significant achievements of the first years were the construction of the testing equipment and the development of the test method [1, 2], relying on the valuable instructions of *Z. Szigyártó* and *B. Kazó*.

The model was a basin $L = 8$ m long, 30×30 cm in cross-sectional area and variable slope, with four filling and outlet orifices in the bottom. The basin bottom was covered by a gravel layer 5 cm thick under a fine-mesh copper sieve (Fig. 1).

A sprinkler apparatus at 4.0 m height above the soil trough emitted rainfall at a changeable intensity. The sprinkler device was a lath containing 247 nozzles and moving along a hypocycloid path, assuring thereby a rainfall of uniform intensity throughout the surface.

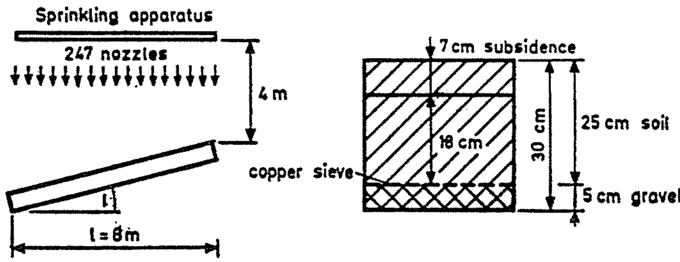

Fig. 1. Experimental setup

The soil was placed in the model without ramming, at uniform density and water content, produced by alternating capillary and gravity water filling cycles. The tests were made on brown calci-encrusted wood soil from the *Péli* valley.

In the tests the following values were kept constant:

average size of sprinkle drops $d_h = 5$ mm,

average area of sprinkled surface $A_h = 2.4$ m^2.

The following parameters were varied:

slope	$I = 0$ to 25%
sprinkling intensity	$i = 0$ to 120 mm/h
slope length	$L = 8$ to 96 m.

Further, it should be noted that the test setup was a true-to-size piece of reality. Because of their complexity, the processes have not been scaled down, there being no *small-scale model*, the experiment can be considered as a full-scale test.

The sprinkling intensity was maintained by means of a rotameter. The model soil runoff discharge was measured by cubing until a steady-state value set in. The sediment concentration in the water collected was determined by cubing after deposition and desiccation.

2. Experiments in the 8 m testing equipment

The quantity of the soil washed down or its concentration in the runoff started from zero, first rapidly increasing then tending to decrease (Fig. 2), corresponding to that in the sewerage of towns. The results are expressed by a third-order function [3]:

$$q_E = \frac{t}{At^2 + Bt + D}$$

and

$$C = \frac{t}{at^2 + bt + d}$$

Fig. 2. Soil loss in the 8 m long model

where:

q_E — specific quantity of eroded soil (g/s.m²);
C — sediment concentration in runoff (g/litre);
t — runoff time (s);
A, B, D, a, b, d — parameters depending on soil quality, gradient I and intensity i:

$$A, B, D, a, b, d = f(e^I, i);$$

thus:

$$q_E = f(t, e^I, i),$$
$$C = f(t, e^I, i), \text{ and}$$
$$E = q_E \cdot t.$$

Parameters determined in experiments on the calci-encrusted brown wood soil were:

$$A = 5.75\, e^{-0.127}\, I_i^{-1.19}$$
$$B = 8580 e^{-0.055}\, I_i^{-2.30}$$
$$D = 37 \cdot 10^6 e^{-0.206}\, I_i^{-3.99}$$
$$a = 0.00124\, I^{-0.490}$$
$$b = 8.59 e^{0.080}\, I_i^{-1.37}$$
$$d = 0.0525 e^{-0.076}\, I.$$

3. Virtual extension of the slope length (Fig. 3)

The limited laboratory area available for the experiments did not allow models longer than 8 m, therefore the effect of the slope length has been studied by virtually lengthening the slope [4]. In studying the effect of the slope length, both the gradient and the rainfall intensity were kept constant:

$$I = 9.2\%; \quad i = 20.0 \text{ mm/h}.$$

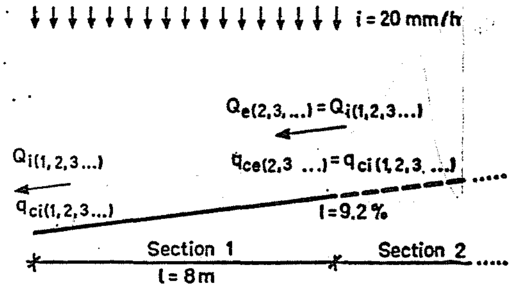

Fig. 3. Virtual lengthening of the model

The virtual extension of the slope length consisted in that the discharge at the lower end of the 8 m long model obtained with the starting parameters Q_i, q_i, and the sediment concentration C or sediment runoff q_c were used as input at the upper end of the model ($Q_e = Q_i$ and $C_e = C_i$) in the next experiment. Thereby the slope length was extended from 8 m to $8 + 8 = 16$ m. By successive repetitions the virtual slope length was extended to 96 m.

The inflow at the upper end of the model comprised:

— supply of concentrated slurry,

— supply of pure water.

The sedimentation of the concentrated slurry was prevented by intensive stirring. The slurry was supplied to the top of the slope by means of a chemical feeding pump. The needed sediment discharge (g/h) was obtained by adjusting the slurry concentration and the pump discharge. The missing discharge was supplied from an overhead reservoir through a rotameter.

Here it is to be noted that a certain amount of the water fallen on the upper part of the slope infiltrated into the soil all along the slope, it sprang up at the slope end. Surface and subsurface water could not be separated.

To maintain the uniformity of upper inflow, the upper 0.5 m length of the soil mass was covered with a *nylon sheet.*

The starting time of the upper inflow was determined so as not to cause inflection on the discharge hydrograph. The inflow started 4 to 15 minutes after the beginning of the outflow, usually in two steps. In the first step usually lasting 2 to 6 minutes, the concentration was the same as in, and the discharge the half of that of, the full inflow.

From the beginning of the outflow until the steady state of discharge, and then, from stopping the rainfall, i.e., the inflow, until the change slowed down, samples were taken each two minutes. Sampling took 10 to 60 seconds, depending on the discharge. In the case of abrupt changes, samples were taken each minute. In the case of steady-state discharges, samples were taken each five minutes. Upper inflow and sprinkling were continued until the discharge became steady for at least 20 to 30 minutes. Hereafter, first the sprinkling, and then, after 3 to 12 minutes, the inflow were stopped. After sprinkling stopped, the concentration in, and after shutting down the inflow, discharge of, the outflow rapidly decreased. The discharge was metered for 12 to 30 minutes after stopping the inflow.

The measurements were accompanied by taking photos of the development of channel erosion.

4. Experiments on extended slope lengths

4.1. *Water discharges and concentrations*

In Figs 4 and 5, the values measured on slope lengths $L = 32$ m and $L = 96$ m have been plotted, indicating also the parameters of sprinkling and of the upper inflow, as well as the time elapsed from the beginning of the sprinkling to the beginning of the outflow.

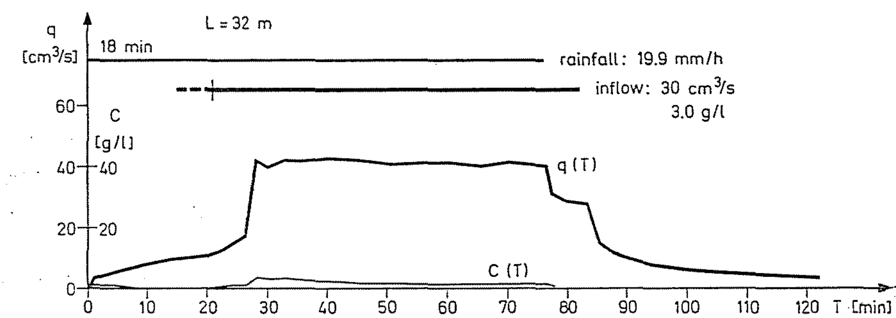

Fig. 4. Discharge and concentration for $L = 32$ m

Fig. 4 shows that for $L = 32$ m, seven minutes after the inflow got constant, also the discharge of the outflow did. Rainfall and inflow stoppage is immediately and sharply manifest in the outflow discharge. The longer the slope, the faster the variations (Fig. 5).

The experiments invariably showed the concentration to rapidly decrease with stopping the rainfall in spite of high upper inflow discharge and concentration. This fact supports the statement found also in publications that *sheet erosion is mainly due to splash erosion*, the water runoff along the surface mainly transports the soil grains broken up.

From the above statement it also follows that the runoff concentration but slightly depends on the inflow water concentration. Part of the inflow sediment is deposited on the model and rainfall erodes mostly the original soil. To support this statement, in the case of lengths $L = 56$ to 80 m, slurry

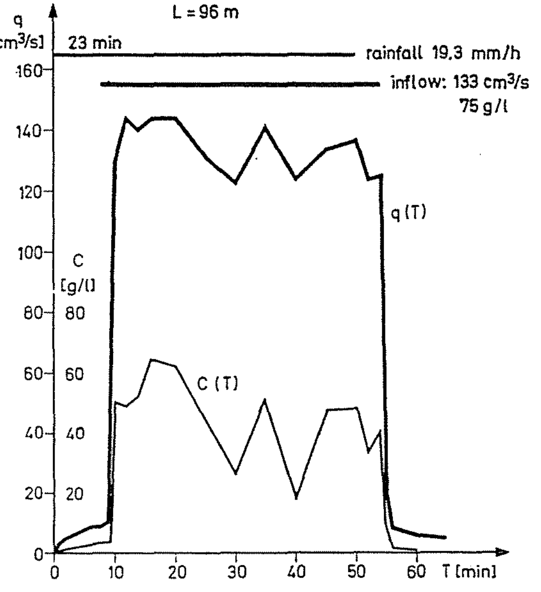

Fig. 5. Discharge and concentration for $L = 96$ m

was made with loess of light colour, strongly different from the soil placed in the model, so that the part deposited in the upper third of the model length was perspicuous. For an abundant upper inflow, the loess got sooner washed down.

Fig. 5 shows the runoff concentration to be rather variable, due to the *channel erosion*, first observed on the 48 m length, of an intermittent development in time, responsible for the strongly variable concentration.

4.2. *Water discharges and sediment volumes*

Inflow and outflow discharges and sediment were investigated. As an example, Fig. 6 shows test results on the slope length $L = 48$ m, and the water quantity sprinkled before the beginning of the runoff (19.2 litres).

According to the figure, the sum curve of the outflow is parallel to that of the inflow at a time lag of about 7 minutes. The total amounts of outflow and inflow are equal, after, however, stopping the inflow, the outflow but slowly accumulates. Since few of the tests lasted long enough, in most cases only apparent differences of a few percent were obtained. The deviations may also be attributed to primary soil states somewhat scattering around the average.

In examining the quantities of soil material flowing in and out of the model, the quantity of material swept down was seen to be multiple of that

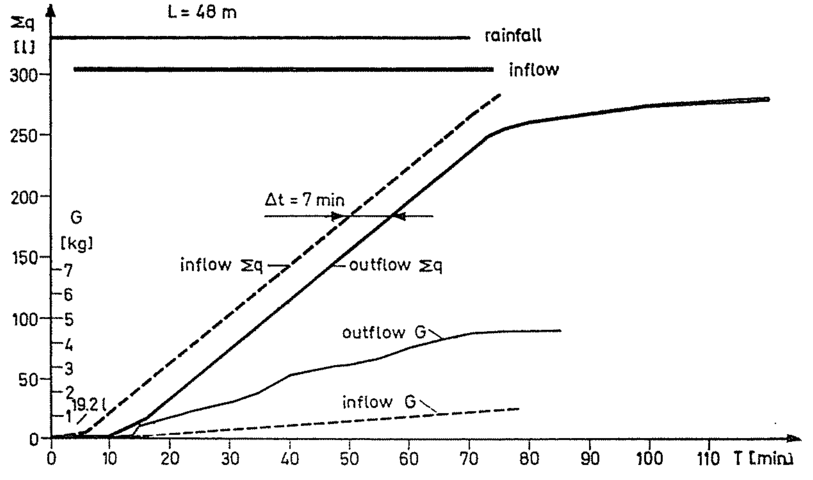

Fig. 6. Quantities of inflow, outflow and sediment for $L = 48$ m

supplied. The curve of the total mass of sediment discharge began its steep ascent together with that of the total mass curve of the water discharge. Thus, at about ten minutes, the sediment supply exceeded that leaving the model.

Fig. 6 clearly shows the sediment discharge to hardly increase after the sprinkling has stopped although soil flowing in is still increasing for several minutes.

4.3. *Velocities*

For three test arrangements, the surface velocity of the water flowing downslope was measured at different sections of the 8 m long slope by adding a colour. The measurements were made when the outflow discharge became constant and also the depth and velocity of the surface sheet became steady. The measurement results were as follows:

$L = 8$ m	$v = 4.4$ cm/s
$L = 24$ m	$v = 5.2$ cm/s
$L = 40$ m	$v = 7.4$ cm/s,

i.e., with the extension of the slope length, the velocity of the surface sheet of water increased.

For the length $L = 40$ m, the measurement results are detailed in Fig. 7. The maximum velocities have been obtained in measuring the peak of the wave of the colouring material. The measurement results show a mild parabolic change along the length of the model.

The average velocities have been determined by making use of the downflow curve.

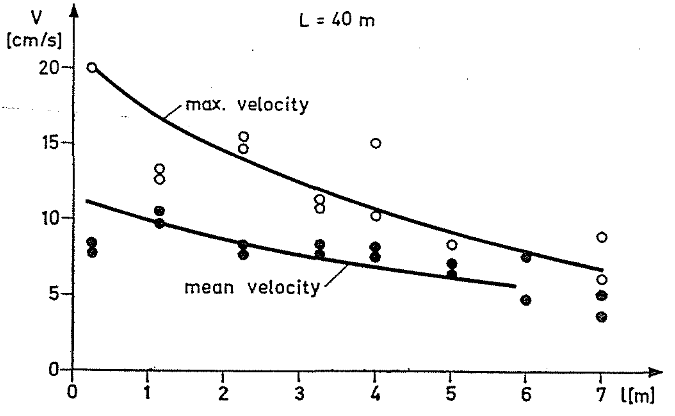

Fig. 7. Surface sheet velocity

5. Effect of the length of slope on the sheet erosion

In Chapter 4 the development in time of the erosion parameters were described for different slope lengths. Now let us investigate the variation of the parameters according to the variation of the slope length.

5.1. *Water discharge and concentration*

In Fig. 8, the stabilized outflow discharge q and the stabilized average concentration of the sediment in the outflow water C vs. slope length have been plotted.

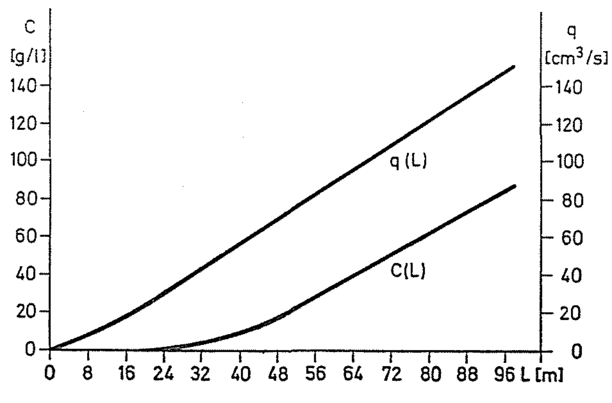

Fig. 8. Discharge and concentration *vs.* slope length

The points in the figure representing the discharges may be averaged by a straight line after the $L = 20$ m section. This line is parallel to that obtained by proportionally increasing the rainfall. The two lines are spaced apart at about 11 cm^3/s, to be considered as "*loss*" composed of

— evaporation,
— water leakage at sealing deficiencies,
— detention in the soil.

Gravity causes this latter to flow, after a long time, out of the soil. Its value has not been measured.

Concentration started increasing at the slope length $L = 24$ m, then abruptly grew up to $L = 48$ m, then followed a tangential line.

5.2. *Delay, storage and loss of soil*

Evaluation of the delays Δt interpreted according to Fig. 6 pointed out that the line of the delays declined linearly until $L = 32$ m, and then decreased ever less up to $L = 60$ m, with 7 to 8 minutes (Fig. 9).

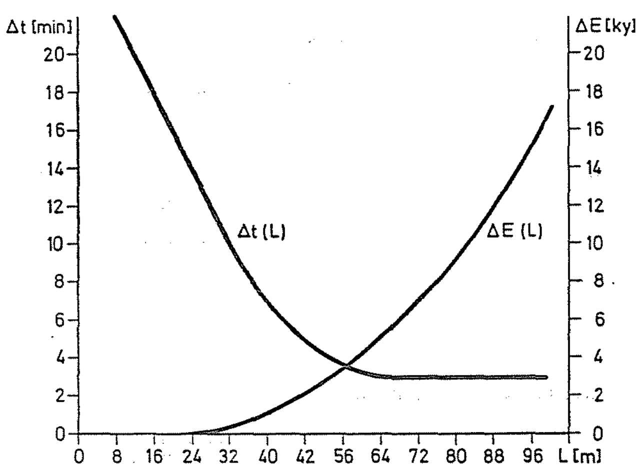

Fig. 9. Delay and sediment storage *vs.* model length

The difference between inflow and outflow is transitorily stored in the model, of volumes ranging from 6 to 30 litres, independent of the slope length, averaging 20 litres, but strongly depending on the initial state of the soil.

Also the difference ΔE between the inflow and outflow sediment masses is plotted in Fig. 9, calculated on the basis of 25 min. where the input and output of the model can be considered as constant. Up to the length $L = 32$ m, the loss of soil may only be expressed in grams, thereafter it rapidly increases.

5.3. *Mean velocity of flow*

In the model, the water moves not only on, but also under, the surface. The mean velocity of the water mass can be determined on the basis of flow curves (Fig. 10). The velocities have been determined from three starting points:

— from the beginning of the flow,
— from the beginning of the upper inflow,
— from the beginning of the whole inflow.

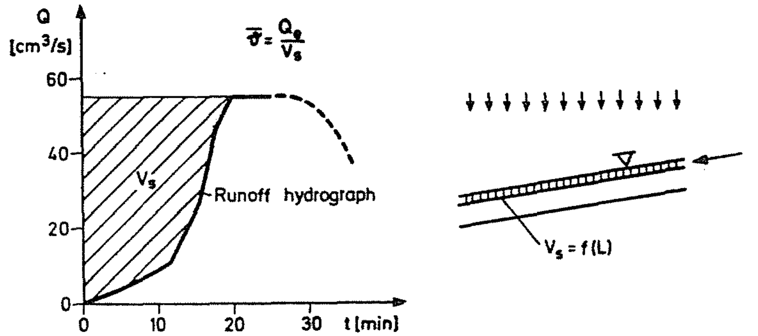

Fig. 10. Determination of the mean velocity

The calculated mean velocities along the slope length have been plotted in Fig. 11. The increase in velocities calculated according to the first two methods is faster than linear, those calculated according to the third method became constant after $L = 72$ m.

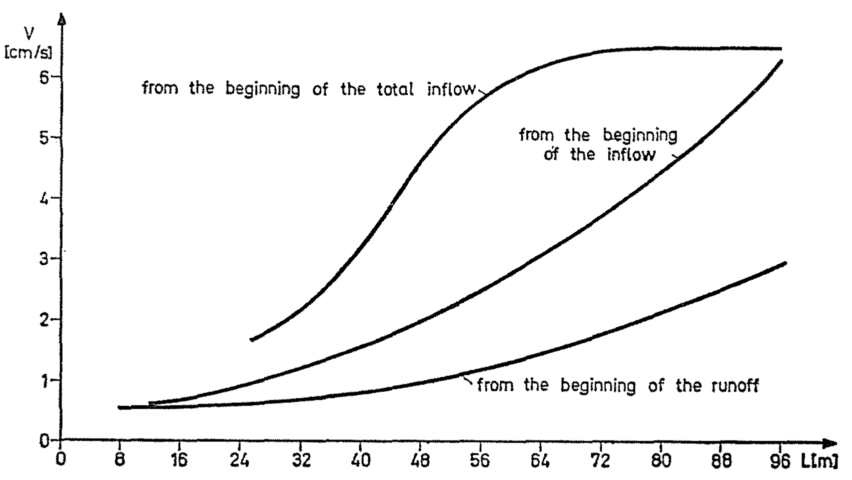

Fig. 11. Velocities *vs.* model length

6. Channel erosion

Up to $L = 48$ m, no channel or gully erosion could be observed. After this length channel erosion took place, always beginning at the edge of the lower third of the model length where the soil leaned against the steel wall of the model.

Starting times of channel erosion from the upper inflow are seen in Fig. 12.

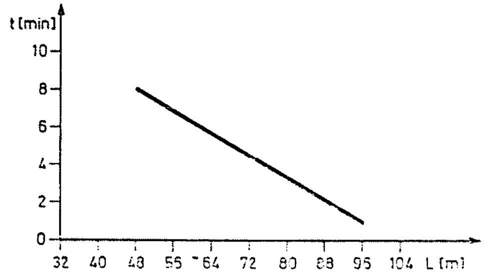

Fig. 12. Beginning of the channel erosion *vs.* model length

Between the rate of erosion and slope length no relationship has been found. The rate of channel erosion depends mainly on the initial soil state the uniformity of which could, however, only approximately be maintained even under laboratory conditions.

A particularly strong channel erosion has been observed along the slope length $L = 64$ m. After the tests, dimensions of three large channels have been determined:

Lower gully:	length		130 cm
	width		13 cm
	depth		11.5 cm
	capacity	about	7 litres
Intermediate gully:	length		170 cm
	width		6 cm
	depth		5 cm
	capacity	about	3 litres
Upper gully:	length		88 cm
	width		12 cm
	depth		4 cm
	capacity	about	3 litres.

The total channel capacity amounted to about 13 litres, 3.6 percent of the total soil volume.

In some cases longer slopes exhibited particularly marked gully erosions. Maximum channel dimensions (on different channels) were:

length	170 cm
width	13 cm
depth	11.5 cm
capacity	7 litres.

Summary

An erosion model and a sprinkling device have been built for studying the effects of the slope gradient, the rainfall intensity and the slope length on the erosion. By introducing sediment-charged water at the upper end of the 8 m long model, the slope length has been virtually extended to 96 m.

Experiments proved the sheet erosion to be due mainly to the splash erosion of rainfall, the runoff on the soil surface only transports the soil grains already broken up.

A relationship has been established between downslope discharge, concentration and slope length, some statements have been made on the delay, the detention, as well as on the surface and penetrating water velocities.

Under certain conditions of rainfall intensity and slope, the sediment concentration in the water flowing downslope and the amount of soil swept down were found to rapidly increase after a slope length 40 m, while the charge increases linearly. It is a hint to enforce hydraulic-hydrologic aspects in determining the check dimensions on inclined agricultural areas exposed to erosion.

Some observations have been made on channel erosion, leading to an approximate relationship between its beginning and the slope length.

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