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CONTRIBUTION TO RUNOFF EROSION OF EARTHEN CHANNELS

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Abstract. The purpose of the experimental study is to investigate the effect of earthen channel geometry on erosion by runoff. After the construction of an experimental setup, four geometric shapes were tested; the circle, the triangle, the sinus and the trapeze. These four forms were dug in agricultural sandy-loam soil. For all experiments, and for each geometric shape, discharge, slope inclination, time, and slope length were varied. Experimental results have shown that the geometry of earthen channels plays an important role in sedimentary dynamics. In addition, it was noted that for slopes less than 20%, the sinusoidal geometric shape allowed to have the minimum of sediment exported. For upper slopes, the minimum amount of soil exported, was obtained with the triangle. The analysis of the experimental results allowed us to see that the variation of the mass of soil exported as a function of the discharge, the slope inclination, the time and the slope length, followed power functions with respective exponents of 2.49, 0.88, -1.27, and -1.53.

Keywords: earthen channel, runoff, erosion, experimentation

1. INTRODUCTION

Due to a medium technical requirement and especially an affordable economic cost, earthen channels are widely used in the world as a drainage, irrigation and water transport system. In addition, in many countries, the human habit

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may become a factor favoring the choice of this type of channels. Despite all these advantages, earthen channels are quickly abandoned because they become degraded and ineffective due to runoff erosion, most often severe. In the field of irrigation, to preserve the water resource, specialists have invented increasingly water-saving systems, such as sprinklers and drip irrigation. In the field of water transport, the earthen channel was lined by erosion-resistant materials (Gupta *et al*. 2016). It is true that we won in water saving, but the investment costs are very large and require several years for them to be depreciated.

The new systems, apart from their exorbitant price, all require quite high levels of technicality. We believe that for many countries these conditions are not met. On this basis, it is thought that it is more important to try to optimize the existing systems. This optimization will focus on finding parameters that will increase the efficiency of the old system. As an example, we say that agricultural irrigation is outdated but Australia has achieved efficiencies exceeding 92% with this old system, after an optimization work (Saleh 2017).

Hydraulics shows that the erosion of the earthen channels is a direct function of the shear stress distribution on the wetted perimeter, which varies with the geometric shape (Depeweg *et al*. 2015, Dey 2014, Khodashenas *et al.* 2008).

The current experimental study aimed to increase our understanding of the effect of the geometric shape of earthen channels on the sediment stability of the wetted perimeter, subject to runoff erosion, with different values of slope inclination, discharge, slope length and time.

2. MATERIALS AND METHODS

All tests have been performed on an experimental setup manufactured completely in steel plate of thickness 1.5 mm. The flume is a rectangular box of 35 cm width, 25 cm depth and a slope length (L) varying between 150 and 500 cm (Fig. 1). The upstream part is equipped with a manual hydraulic jack to lift it. To collect the exported volumes of the mixture (runoff plus eroded soil), plastic containers were placed downstream of the experimental setup.

To get the desired moisture, we added water to the soil inside a concrete mixer. It should be noted that the soil used was initially ventilated, air-dried and cleared of large stones, after passing through a sieve of 3 mm × 3 mm. This is the first phase of homogenization. After mixing and before the filling of the experimental setup, the sandy-loam soil (Jahn *et al.* 2006) has undergone a second pass through the previous sieve. This is the second phase of homogenization.

Table 1. General characteristics of the soil (Haddad and Bouhadef 2012)

C (%)	S (%)	D_{50} (mm)	PI (%)	K_S (mm/h)	Po	D_r (t/m^3)
19	65	0.092	22.5	27	0.47	2.69

Note: C – clay; S – sand; D_{50} – median diameter; PI – plasticity index; K_S – saturated hydraulic conductivity; Po – porosity; D_r – bulk density

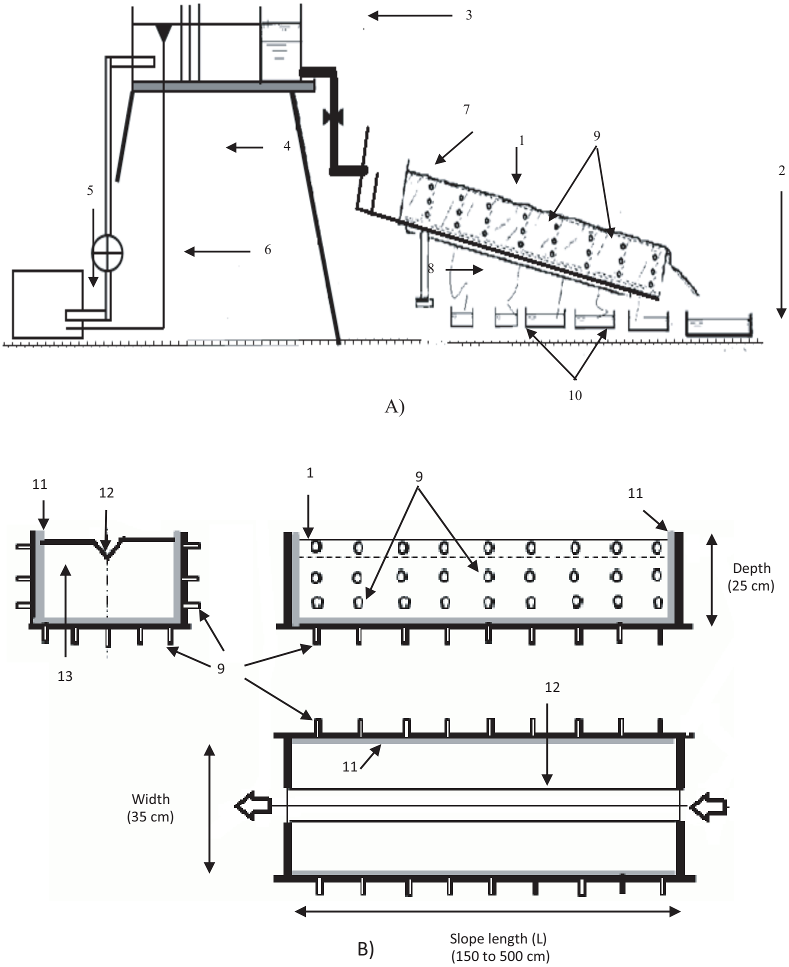


Fig. 1. Experimental setup (Haddad and Bouhadef 2012)

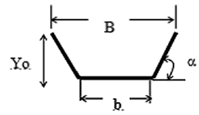
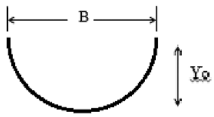
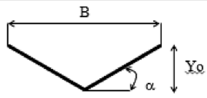
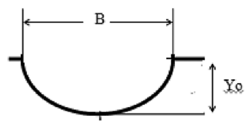
A) General form; B) Details of experimental flume

Note: 1) experimental fume; 2) basin for collecting soil exported; 3) supply tank; 4) overfull; 5) suction tank; 6) pump; 7) thin wall weir; 8) hydraulic jack; 9) holes for drainage; 10) basins for infiltration collecting; 11) sponge; 12) geometrical shape (triangle, sine, trapezoid, circle)

The flume was designed to be everywhere permeable. The latter will be ensured by the realization of a hole network, of diameter 1 cm and spaced of 10 cm × 5 cm, on the two side walls and the bottom. In order to avoid migration of the solid particles, a filter, made of sponge sheet of 5 mm thick, is placed between the soil and the inside of the soil box. The soil is placed on the inside by successive 5 cm horizontal layers and is then subjected to a vertical settlement, by the free fall of a steel ball of 9 cm diameter, from a height of 30 cm, on a flat surface in steel plate of thickness 4 mm, length 30 cm and a width of 33 cm, placed above the soil (Römkens *et al*. 2001). The same procedure is repeated for each 5 cm layer to obtain a total soil depth, inside of the soil box, equal to 25 cm. Before beginning the shaping of the first geometric form of the earthen channel, the soil was left standing for ten minutes.

For each shaping of a given geometrical form, a special metal tool will be used which will have the same shape as the earthen channel. The four small metal tools represent the reduced forms of manual hoes used by farmers (Fig. 2) or those that can be placed as a furrow opener at the back of the tractors. Once the channel has been excavated, the experimental setup is lifted, using a hydraulic jack, to obtain the first slope inclination and clear water supply can be started. At the end of each test, the portion of the earthen channel that was eroded and then transported by the runoff was collected in plastic containers. After 6 hours of decantation, the solid phase was recovered and dried for 24 hours at 105° C in an oven. The geometric dimensions of the earthen channels (Table 2) have been obtained by application of movable-bed hydraulic models theory (Dey 2014, Chanson 2004, Julien 2002).

Table 2. Geometrical characteristics of the earthen channels (Haddad and Bouhadef 2012)

Trapeze (TPZ)	Circle (CIR)	Triangle (TRG)	Sine (SIN)
			
Yo = 3.2 cm B = 7.3 cm b = 2.6 cm	Yo = 3.2 cm B = 6.4 cm	Yo = 3.2 cm B = 9.5 cm	Yo = 3.2 cm B = 10 cm

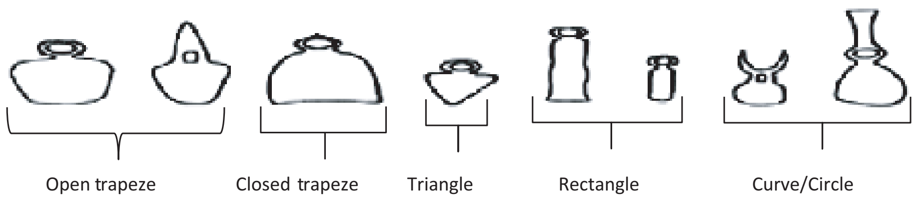


Fig. 2. Some hoes used in agriculture (Haddad and Bouhadef 2012)

3. RESULTS AND DISCUSSION

The results of the tests relating to the influence of the geometry shape, slope inclination (P), discharge (Q), time (T) and slope length (L) on the sedimentary stability of earthen channels are summarized in Figs. 3–6.

It is useful to point out that the measurements of masses, discharges, volumes, angles, times and lengths have been made with moderately accurate means of measurement. The relative measurement error was taken equal to 5%. For this reason, on all the experimental points, we have drawn the error bars, horizontal and vertical, of 5% value (USDI 2001).

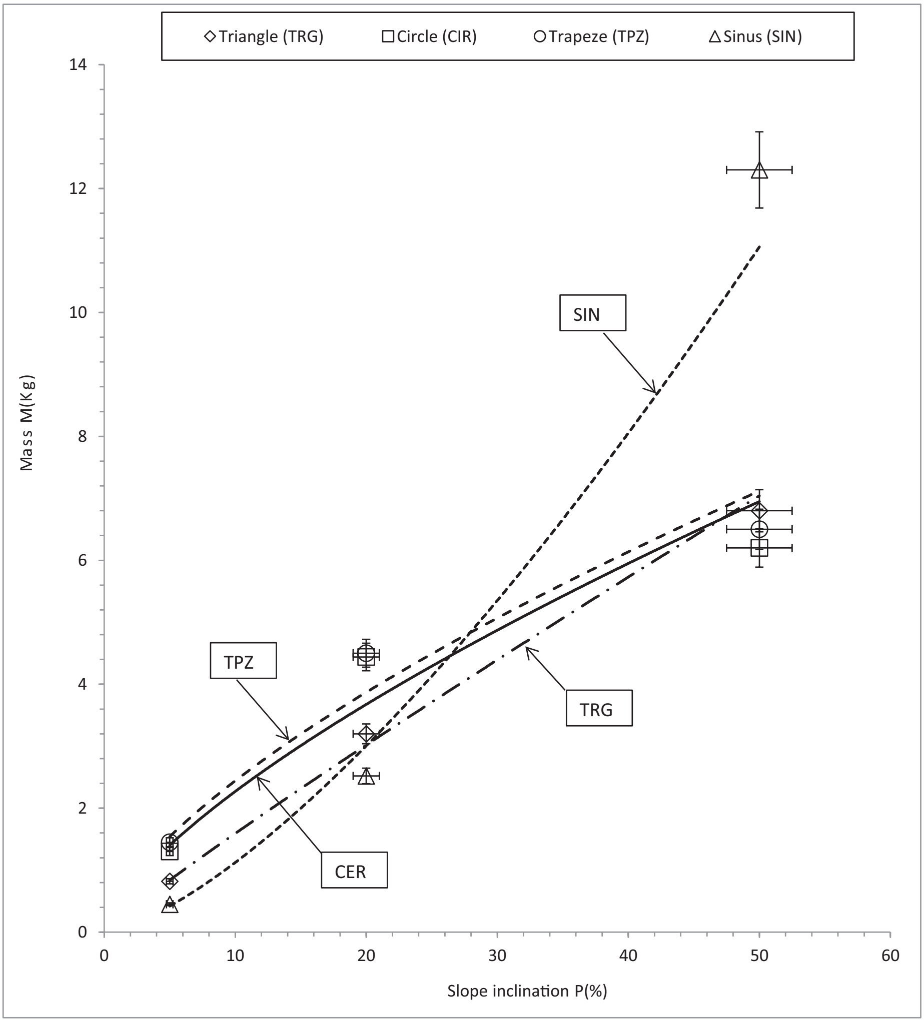


Fig. 3. Evolution of the mass exported (M) as a function of the slope inclination (P) (Q = 6 l/min, T = 2 min, and L = 1.5 m)

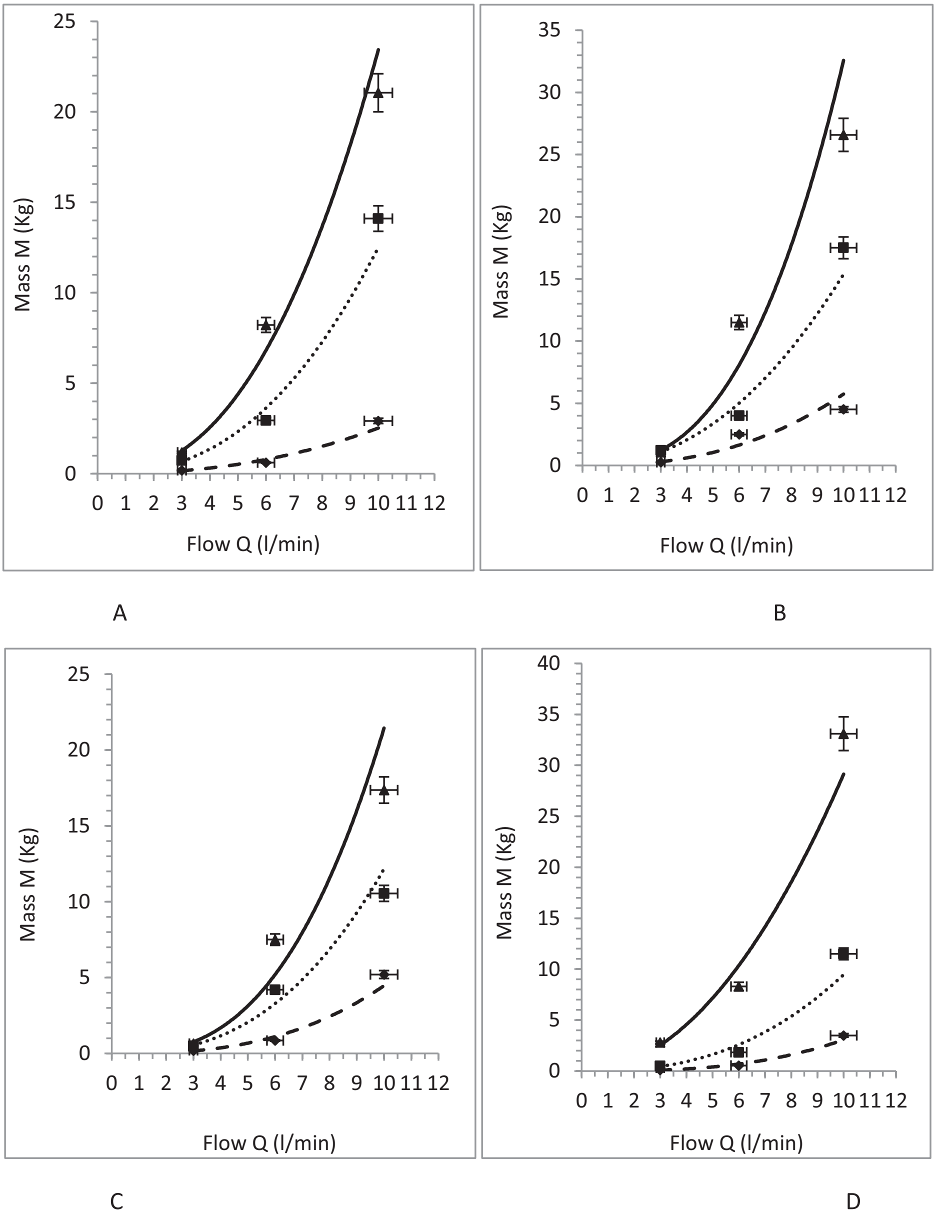


Fig. 4. Evolution of the mass exported (M) as a function of flow rate (Q)

A) Triangle B) Circle C) Trapezoid D) Sine

(T = 2 min and L = 1.5 m); - - - - 5% ········ 20% —— 50%

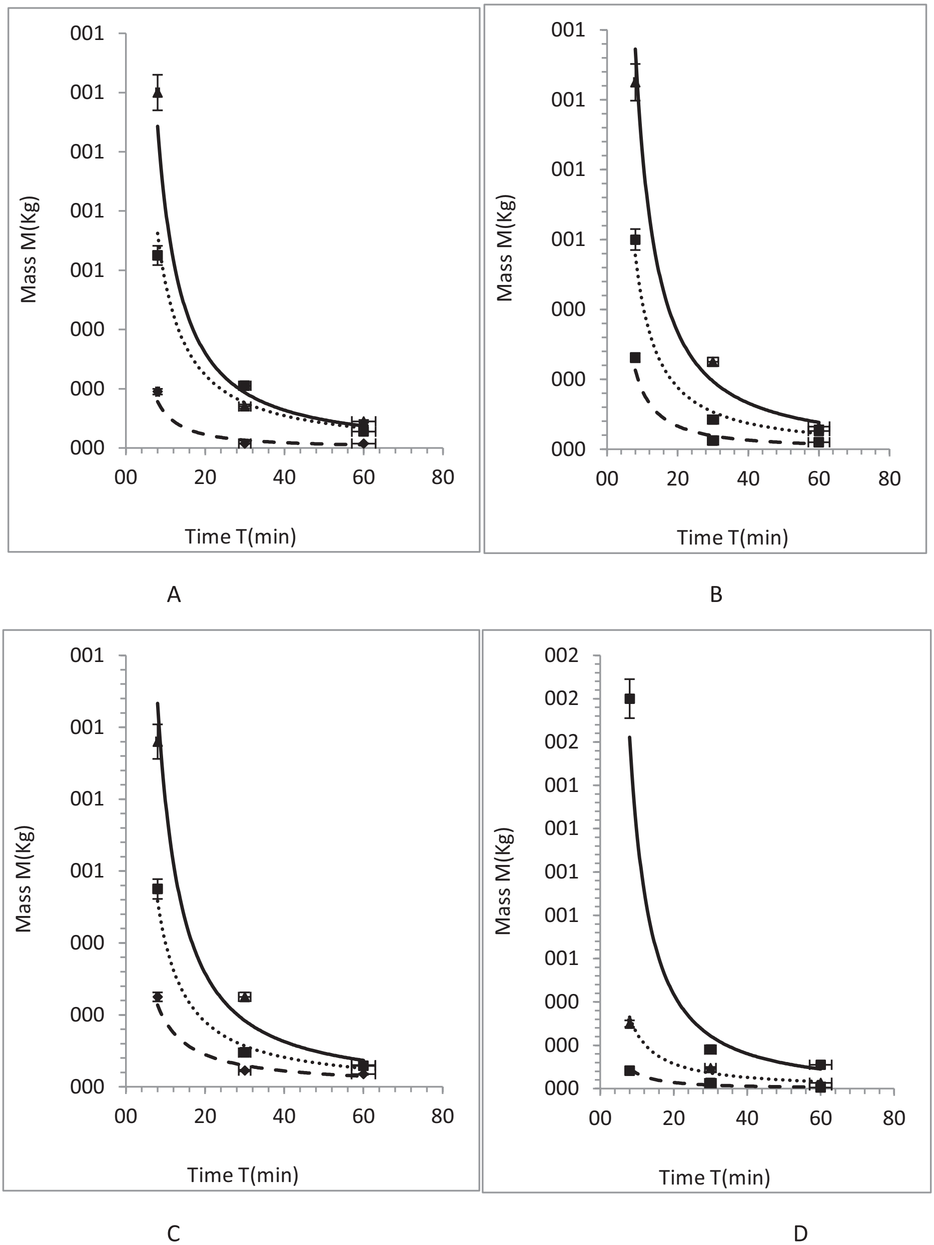


Fig. 5. Evolution of the mass exported (M) as a function of time (T)

A) Triangle B) Trapeze C) Circle D) Sine

(Q = 6 l/min and L = 1.5 m); - - - - 5% ········· 20% —— 50%

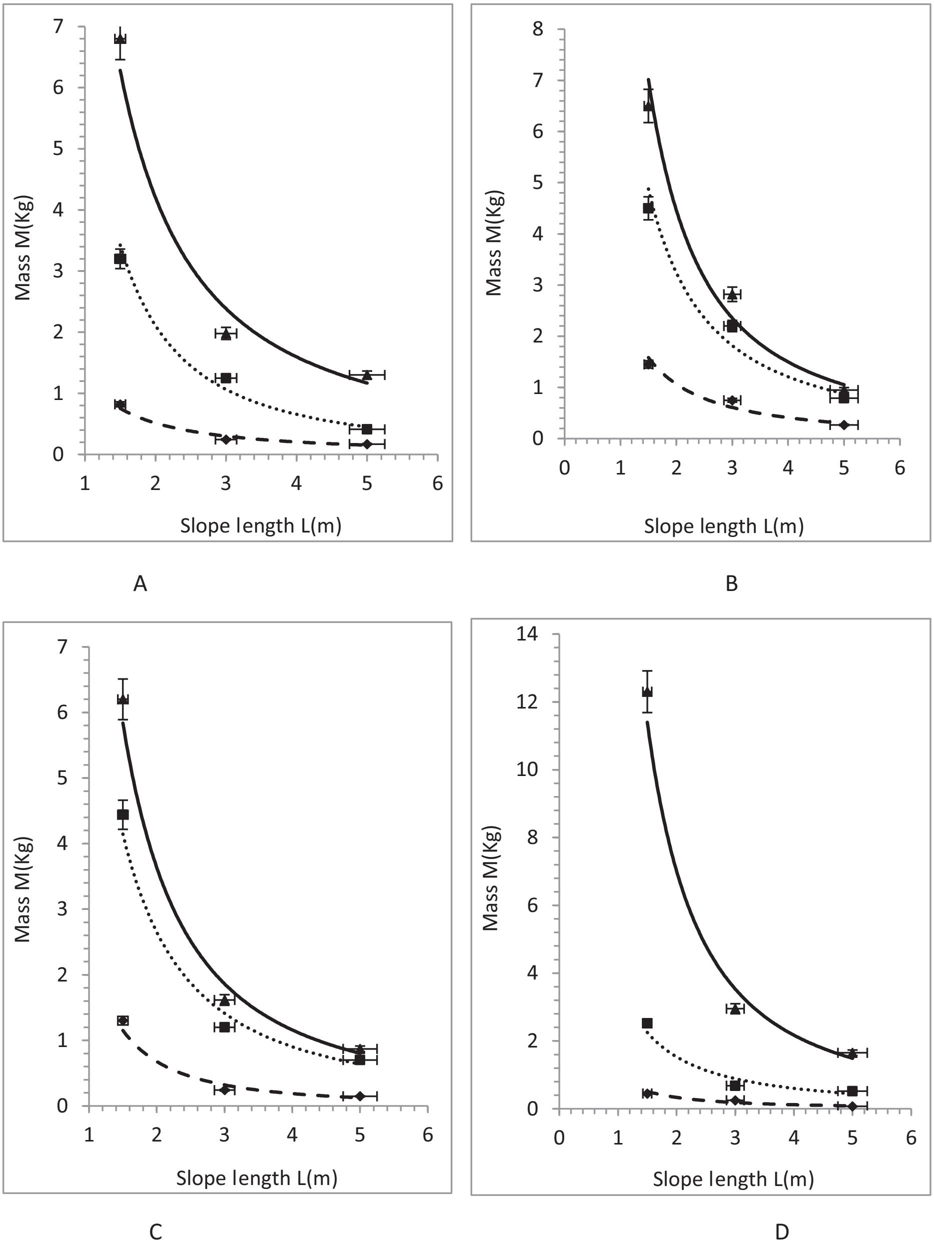


Fig. 6. Evolution of the mass exported (M) as a function of slope length (L)

A) Triangle B) Trapeze C) Circle D) Sine

(Q = 6 l/min and T = 2 min); - - - - 5% ········ 20% —— 50%

3.1. Evolution of the mass exported (M) as a function of geometric shape and slope inclination (P)

The curve in Figure 3 clearly shows that the geometric shape has a significant influence on soil erosion and that, for the same geometry, the slope plays a very important role.

Indeed, for the four geometric shapes, the same function of the exported soil mass $M = aP^b$ was obtained with the coefficients *a* and *b* which depend on the geometric shape and the slope inclination (P).

- For the triangle shape, $M(TRG) = 189.71P^{0.92}$
- For the circle shape, $M(CIR) = 457.83P^{0.69}$
- For the trapezoidal shape, $M(TPZ) = 528.04P^{0.67}$
- For the sine shape, $M(SIN) = 42.60P^{1.24}$

These expressions show that, for slopes less than 20%, the sinus form (SIN) exports the least sediment. Between 20% and 46%, it is the triangular geometrical shape (TRG) which is the most resistant with regard to erosion. In addition, it can be seen that if the slope were multiplied by 10, from 5 to 50%, the mass of soil exported would be multiplied by 8.3, 4.8, 4.5 and 27.3, respectively for triangular, circular, trapezoidal and sinusoidal shapes.

The hydraulicians have shown by the tests and demonstrated by the theory that to have a sediment transport, it is necessary that the velocity of water exceeds a certain critical velocity obtained experimentally. We can also speak of sediment transport based, not on the velocity but on the hydraulic shear stress. In the same way, to have a sediment transport, it is necessary that this shear stress must exceed a certain critical constraint, obtained experimentally. Mathematical expressions of velocity or shear stress always contain geometric parameters such as wetted area and hydraulic radius. This means that different geometrically-shaped earth channels cannot have the same response to erosion and sediment transport.

For the slope, Chezy's general equation shows that increasing the slope inclination will increase the kinetic energy of the runoff, hence the erosivity of the water.

In the United States, Zingg has shown that soil losses increase exponentially with slope inclination. The exponent was close to 1.4 (Roose 1996). In Central Africa, Hudson and Jackson obtained exponents ranging from 1.63 to 2.17 (Roose 1996). In Senegal, Roose observed that the erosion-runoff pair increases very rapidly from a slope of 0.5% (Roose 1996).

3.2. Evolution of the mass exported (M) as a function of the discharge (Q)

For the evolution of the mass (M) of the soil exported as a function of the geometrical shape of the earthen channels and discharge (Q), it can be represented by the relation M (Q) = vQ^s, where *v* and *s* are experimental parameters.

- For the triangular shape (TRG): $2.28 < s < 2.42$ and $13.17 < v < 90.19$
- For the circular shape (CIR): $2.56 < s < 2.77$ and $8.42 < v < 36.03$
- For the trapezoidal shape (TPZ): $2.18 < s < 2.73$ and $20.18 < v < 60.87$
- For the sine shape (SIN): $2.02 < s < 2.92$ and $3.66 < v < 275.93$

Table 3. Experimental parameters

	Enter parameters				Exit parameter
Geometric shape	Slope inclination P (%)	Discharge Q (l/min)	Time T (min)	Slope length L (m)	Exported mass M (kg)
Triangle (TRG) Circle (CIR) Trapezoid (TPZ) Sine (SIN)	5 to 50	3 to 10	8 to 60	1.5 to 5	To determine

It can be seen that whatever the geometrical shape of the earthen channel, the variation of the mass exported (M), based on the discharge (Q), is well estimated by: M (Q) = $vQ^{2.49}$.

As mentioned in the introduction, hydraulics show that erosion of earthen channels is a direct function of the distribution of shear stress (τ) on the wetted perimeter (P_W) which varies with the geometrical shape. In other words, if the geometric shape varies, the distribution of the shear stress on the wetted perimeter varies, so the erosion will vary from one geometrical shape to another.

We know that, $\tau = c\rho gPR$ (Depeweg *et al*. 2015) and $Q = R^{2/3}P^{1/2}A_w/n$ (Manning's or Chezy's equation).

The combination of the two expressions gives: $\tau = c\rho gn^{3/2}P^{1/4}Q^{3/2}$ with:

τ = Tensile force per unit wetted area (N/m^2) or shear stress

c = Correction factor that depends on the aspect ratio (B/H)

- $1 < B/H < 4$ (narrow channels), $c = 0.77e^{0.065\,(B/H)}$
- $B/H \geq 4$ (large channels), c = 1

ρ = Density of water (1,000 kg/m^3)

g = Acceleration due to gravity (9.81 m/s^2)

P = Bed slope or slope inclination (m/m)

R = Hydraulic radius (m) = wetted area A_w /wetted perimeter P_w

H = Water depth (m)

B = Bed width (m)

Q = Discharge (m^3/s)

A_w = Wetted area (m^2)

n = Manning's Roughness Coefficient ($s/m^{1/3}$)

From the above expression, an increase in the discharge (Q) increases the shear stress and, consequently, erosion increases. The same expression shows that increasing the slope inclination will increase the shear stress.

3.3. Evolution of the mass exported (M) as a function of time (T)

We can see that if the flow duration (T) is greater than 30 minutes and the slope inclination (P) is less than 5%, all the geometric shapes of the earthen channels export masses of sediment (M) always less than 50 grams. It is for this reason that these experimental points do not appear on the curves of variation M = f (T).

It is important to note that with increasing runoff time (T), the exported mass (M) is always decreasing, regardless of the geometric shape of the earthen channels.

The function M = f (T) giving the variation of the mass exported (M) as a function of time (T) can take the form of M (T) = c / Td where *c* and *d* are experimental coefficients.

- For the triangular shape: $1.18 < d < 1.35$ and $2{,}578.3 < c < 17{,}273$
- For the circular shape: $1.02 < d < 1.33$ and $1{,}890.3 < c < 16{,}998$
- For the trapezoidal shape: $1.25 < d < 1.34$ and $3{,}692.1 < c < 18{,}646$
- For the sine shape: $1.15 < d < 1.43$ and $1{,}484.5 < c < 32{,}000$

According to the values of the coefficients *c* and *d*, the variation of the mass exported (M) as a function of time (T) takes the approximate form: $M (T) = c / T^{1.27}$.

This decreasing function of the soil mass exported can be explained by the fact that the flow inside an earthen channel is composed by two parts. The first part is the runoff. Inside the earthen channels, the flow is free, non-permanent and non-uniform. The second part, by seepage cause, is an underground flow through an unsaturated, heterogeneous and anisotropic porous medium.

With respect to the flow duration and the continual presence of seepage, throughout the wetted perimeter, runoff decreases in importance; therefore, erosive power, while advancing in the earthen channels.

3.4. Evolution of the mass exported (M) as a function of slope length (L)

The evolution of the exported mass (M) as a function of the slope length (L) can be represented by the relation $M (L) = f / L^k$, where *f* and *k* are experimental parameters. For the evolution of the exported mass (M) with the slope-length (L), it can be represented by the relationship $M(L) = f/L^k$, where *f* and *k* are experimental parameters that depend on the geometrical shape of the earthen channels.

- For the triangular shape (TRG): $1.33 < k < 1.68$ and $1{,}293 < f < 11{,}075$
- For the circular shape (CIR): $1.56 < k < 1.85$ and $2{,}433 < f < 11{,}393$

- For the trapezoidal shape (TPZ): $1.38 < k < 1.57$ and $2{,}770 < f < 13{,}285$
- For the sine shape (SIN): $1.34 < k < 1.69$ and $942.47 < f < 22{,}626$

Whatever the geometrical shape of the earthen channel, the evolution of the mass exported (M) as a function of the slope length (L) can be approximated by: $M (L) = f / L^{1.53}$.

It is practically the same reasoning as before. Reduction of erosion involves the reduction of shear stress that is the result of reduced runoff. The latter can be attributed to the increase in the volumes of water infiltrated by increasing the lengths of the channels.

4. CONCLUSIONS

In light of the results obtained, we can conclude that the geometric shape of the earthen channels plays a very important role in the sedimentary dynamics. In addition, we have shown that the functions related to the discharge, slope inclination, time and slope length all follow power functions. The exponent values of the power functions indicate that the discharge is the most influential parameter, followed by the slope length, the time, and the slope inclination. The sign of the four exponents indicates that there are two parameters favorable to erosion; the discharge and the slope inclination. The other two tend to minimize the amount of sediment exported; the slope length and the time.

Given the transversal dimensions of the geometric shapes, the soil masses exported seem relatively important. It is thought that, in addition to runoff erosion, mass movements of the soil, either by sliding or by rotation, are present and important, especially after rapid wetting of soils used which were always slightly moist.

To arrive at more general results, it would be interesting to consider longer slope lengths and flow durations. The theory of erosion, especially for cohesive soils (Elkholy *et al.* 2015, Partheniades 2009, Zhu *et al.* 2008), shows that the initial water content, soil and water pH, organic matter, compaction, age, soil temperature and water significantly influence sediment dynamics. To manage this large number of parameters, the use of the experimental design technique is strongly recommended.

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*The authors declare no conflicts of interests.

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