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A New Laboratory Equipment for Assessing Soil Erosion by Water

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Abstract: *The design, construction and testing of a laboratory research facility to quantify wash erosion by overland flow is described. The design allowed slope length, slope gradient, and flow rates of water to be controlled. The apparatus was used to test the wash erosion from two Trinidadian soils (sandy loam, and clay), with four levels of peat content (0, 4%, 8%, and 12% by mass) exposed to two lengths of slope (1.54 m and 2.62 m), and two slope gradients (9% and 30%). Wash erosion was greater in soils with the higher slope gradient of 30% and slope length of 2.62 m than in the ones with the lower slope parameters. Increasing levels of peat was found to decrease wash erosion at all combinations of parameters. Wash erosion was higher in the sandy loam than the clay soil at the higher slope gradient. The opposite trend occurred at the lower slope (9%), where soil loss was greater in the clay. A multiple linear regression equation was developed for predicting wash erosion from the experimental factors. The major advantages of the constructed research facility are that unlike most previously devised equipment, it allows for small incremental changes to be made in the slope length as well as the slope gradient; it allows for the efficient separation of the eroded sediment from the runoff water during testing and it allows for the efficient removal of infiltrated water during testing.*

Keywords: *Soil, wash erosion, slope gradient, slope length, laboratory equipment*

1. Introduction

Soil erosion, and its associated impacts, is one of the most important (yet probably the least well-known) of today's environmental problems. The resulting cost of this phenomenon is huge, in the United States about US$44 billion annually (Pimental et al., 1995), the United Kingdom £90 million (Environment Agency, 2002) and in Indonesia US$400 million in Java alone (Magrath and Arens, 1989). These costs originate from both on-site and off-site effects of erosion (Morgan, 2005). On-site effects are particularly important on agricultural lands. Off-site problems generally result from downstream or downwind sedimentation. Soil erosion and its associated impacts are the most striking features on most landscapes in the steep sloping and mountainous topography of the Caribbean (Ahmad and Breckner, 1974). In the larger Caribbean Islands, soil erosion levels and land degradation generally have reached very high levels (Mahabir and Al-Tahir, 2008; Wuddivira et al., 2010) mainly as a result of deforestation over the years. The outcome includes loss of soil, breakdown in soil structure, a reduction of nutrients and of organic content. This decline in fertility leads to increased costly fertiliser use, affects food production and food security and a substantial decline in land values.

Thus it is vital that new methods and practices to monitor, reduce or control erosion are developed and existing ones improved. All strategies for soil conservation must be based on at least one of the following: providing a barrier against raindrop impact, increasing soil aggregate stability, increasing infiltration capacity of the soil to reduce runoff and/or increasing surface roughness to reduce velocity of runoff and wind (Morgan, 2005).

There are different types of erosion by water with fluvial or wash erosion being the most predominant (Morgan, 2005) hence the reason why this type of erosion was chosen for investigation. Fluvial erosion can occur either through the process of rain splash or overland flow (Quansah, 1981). In order to study the overland flow method, water of a known flow rate is allowed to flow over the soil plot. By measuring the volume or weight of eroded sediment and comparing it with original soil values from the soil plot, the resulting level of erosion can be determined. In addition, by relating the quantity of eroded sediment to the length of the rainfall simulation time, the rate of erosion can be determined. From literature, different methods have been used to measure soil erosion, some of which are reviewed in the following section.

2. Existing Designs and Methods of Measuring Soil Erosion

2.1 Hudson (1965) Collecting Apparatus

The standard field plot was 22m long and 1.8m wide. The edges were made of sheet metal, wood or any stable material that did not leak or was prone to rusting. The edges extended 15-20cm above the soil surface and were properly embedded into the soil. At the down slope end a collecting trough was positioned, and was covered to prevent direct entry of rainfall. The collecting trough sediments and runoff were sent to the collection tanks. In order to determine the level of soil erosion, the sediment was separated from the runoff and sediment mixture collected by adding a flocculating agent. Although this plot may give the most reliable readings for soil loss per unit area, problems that could affect the outcome of the data include overflowing of the collecting tanks, silting of collecting troughs and pipes leading to tanks, and runoff entering the top of plots.

2.2 Morgan (2005) Gerlach Trough

This trough which was developed by Gerlach (Morgan, 2005) measured sediment loss and runoff by utilising simple metal gutters. Standard size was 0.5m long by 0.1m wide. Its sides were closed and a moveable lid was attached to it. A pipe was connected to the base of the trough that led to the collection bottle. Typically about 2 or 3 troughs were grouped together across the slope side to side and groups were installed at different lengths along the slope. Advantages of using this method include that it was simple and cheap so making it ideal for sample measurements over large areas. This apparatus provided a reasonable assumption of erosion along both straight and curve slopes. Also edge effects were avoided as no plot boundaries were used.

2.3 Hudson (1993) Erosion Pins

This method consists of driving a pin into the soil so that the top of the pin gave a datum from which changes in the soil surface level could be measured. By being observed weekly or monthly, the amount of erosion taking place at a specific point could be determined by measuring the change in height of the pin. The advantage of this monitoring technique is that it is economical and easy to use. Also it provides a clear way of knowing how much erosion is taking place, and analysing which months of the year that erosion occurs the most. These pins may cause erosion of the slopes themselves. Also it is not possible to tell when exactly the erosion occurred as the pins just indicate how much sediment has been removed.

2.4 Tilting Erosion Flume with Rainfall Simulator

This apparatus was designed to measure erosion on steep landscapes (Sheridan and So, 2001). It allowed for a variation of steepness from 5 to 30% and was investigated using a simulated rainfall. Experimental plots were 3m long, 0.8 m wide and 0.15m deep. Each plot was rained on for a predetermined time and rainfall intensity at different slope angles. Runoff and erosion rates were determined from timed runoff samples.

2.5 Use of Photogrammetry in Monitoring Soil Erosion

Yamamoto et al. (2002) developed a system that consists of two digital cameras, a rain simulator with a 12 m high tower, and connected to a computer. The inclusion of the cameras allowed for video recording and monitoring of the entire erosion process from start to finish. The system was tested by using soil boxes with a 10° slope under simulated rainfall, surface water flow, and a combination of both rainfall and surface flows and intermittent surface flow. The soil was packed to a 3 cm layer on top of a 7 cm sand layer, which was placed on the top of 3 cm of gravel. Drainage water was collected at the bottom of the box. A flume was connected to the lower end of the soil surface, and runoff water and soil were collected periodically. The sediment was oven dried and weighed to determine the erosion level.

2.6 Automated Erosion Wheel

Klik et al., (2004) designed an automated device for measuring runoff and soil loss. This equipment was used for continuous runoff measurement from plots up to 60 m^2. It is similar to a turning wheel with a horizontal axle. The automated erosion wheel (AEW) consists of four equal sections each one holding five litres of runoff resulting in a resolution for each tip of 0.08 mm for 60 m^2 plots. The automated erosion wheel is capable of measuring a maximum runoff rate of 75L min^{-1}. Each tip was monitored automatically in real time by a data acquisition system.

Most of these equipment and methods were developed for field measurements of soil erosion. Although field measurements of soil erosion are desirable particularly for measuring annual rates of erosion, laboratory measurements ensure a greater control of factors affecting soil erosion. A clear understanding of soil erosion processes and the development of soil erosion models requires precise and controlled measurements in the laboratory (Zhang et al. 2002). From a search of literature, few researches have actually developed standard equipment for measuring soil erosion in the laboratory. Researchers like Lyle and Smerdon (1965), Nearing et al. (1991) and Zhang et al. (2002) used flumes which represent a precise method for measuring soil erosion in the laboratory. The effects of the length of slope and the slope gradient which exist in the actual fields could be simulated in the laboratory experiments using flumes.

Lyle and Smerdon (1965) did not vary their slope gradients while measuring erosion, while Nearing et al. (1991) varied their slopes within a narrow range of 0.5%

to 2%. However, Zhang et al. (2002) used a flume in which the slope was varied from 3.5% to 46.6%. More recently, CRSRI (2008) developed a mobile soil erosion measuring laboratory which can be carried from place to place on a truck with a slope varying measuring equipment and rainfall simulator similar to the tilting erosion flume above described by Sheridan and So (2001). The major advantage of the equipment that was developed in the present study is that it provides a method for varying both the length of slope as well as the slope gradient while measuring soil erosion in the laboratory. It also allows for the efficient separation of the eroded sediment from the runoff water during testing and it allows for the efficient removal of infiltrated water during testing.

3. Description of the Constructed Research Facility

Figure 1 shows that the new soil erosion assessment facility measures wash erosion on soil surfaces with slope gradients (vertical/horizontal) varying from 0% to 30%. The overflow water trough, 0.4 m wide, 0.2 m deep, and 0.2 m length was supplied by an adjustable water supply. This trough has a gentle slope (15^o below the horizontal) and was provided with a smooth overflow onto the sliding or adjustable soil tray, where the soil to be tested was placed. The soil tray (0.4 m wide; 0.12 m deep and adjustable length) was made up of three sections such that they could slide into one another along the main support. Two detachable screw mechanisms were attached to the bottom sides of these trays. Variation in the length of these screws allowed for an overall variation in the length of slope. The overall length of the tray (slope length) could be varied from 1.54 m to 2.62 m, in increments of 3 mm.

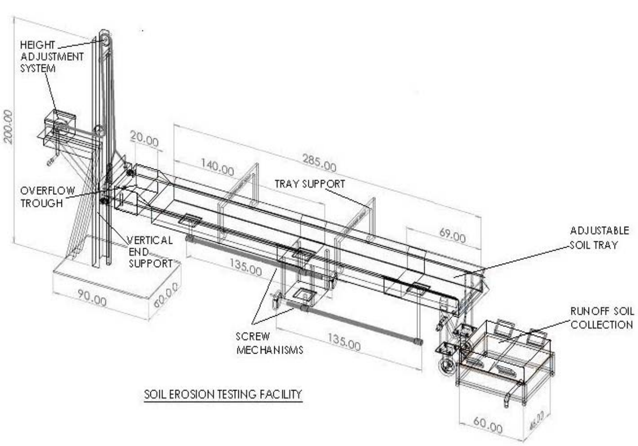

Figure 1. The Soil Erosion Measuring Apparatus

The soil tray rested on a vertical end support of fixed length of 1.98m. Variation of the slope angle was achieved by a height adjustment system adopting the use of a winch/pulley (see Figure 1). The winch had a self-locking mechanism, for variations in height to be made in increments of 2mm. The range of slope angles that could be achieved was 0% to 30%. A flexible drainage hose was added to the bottom end throughout the length of the soil tray. Before putting the soil to be tested in the tray, gravel was placed at the bottom to a depth of 80 mm, such that water that infiltrated through the soil first and then passed through the layer of gravel, which acted as a filter, and ensuring that clean water flowed down the drain.

The runoff soil collection tray (0.45 m wide and 0.15 m deep) consisted of two compartments, a larger main collection compartment (0.40 m length) and a smaller drainage compartment (0.20m length). A sloping barrier (at 60^o from the horizontal) that was inclined towards the smaller section and was lower than the surrounding sides separated these two compartments. During testing, the eroded soil and overflow water flowed into the first compartment where a majority of the soil settled under its own weight. The remaining soil/water suspension continued flowing over the sloping barrier. This gentle overflow caused further settling of eroded soil. A piece of nylon filter was attached to the entrance of this drainpipe which acted as a final filter for any remaining sediment that did not settle. Sediments collected from the tray following the tests could be oven dried to determine the mass of eroded soil.

4. Testing of the Constructed Research Facility

Two soils, Piarco sandy loam and Talparo clay (see Table 1) were used to test the new soil erosion facility. More elaborated testing of the facility has been subsequently carried out by Ekwue et al. (2009) and Ekwue and Harrilal (2010) and the aim is to test many soils from the Caribbean region in the future. Air-dried soil samples were ground to pass a 5mm sieve. A particle size analysis was carried out using the hydrometer method (Lambe, 1951). The organic matter content in the samples was measured using the method of Walkley and Black (1934). Organic matter content in the samples was increased by adding air-dried peat moss at rates of 4%, 8%, and 12% air-dry mass basis, respectively.

Table 1. Classification, organic matter, and the particle size distribution (%) of the soils

Soil Series	Classification*	Organic Matter Content (%)	Sand (0.06-0.002) mm	Silt (0.06-0.002) mm	Clay (<0.002) mm
Piarco	Aquoxic Tropudults**	1.7	64.9	17.0	18.1
Talparo	Aquentic Chromuderts	2.7	25.4	28.3	46.3

Remarks:

*Classification according to the Soil Taxonomy System (Soil Survey Staff, 1999).

** All values are means of three replicates.

For each test, soil was added to the soil tray to a depth of 20 mm (see Figure 2). This was then compacted by passing it twice through a 5.4 kg and a 3.2 kg rollers. The aim was to produce a compacted soil similar to that found in field conditions.

Figure 2. Soil erosion measuring facility with soil before testing

Soil penetration resistance after soil preparation was measured using a hand pushed spring-type Proctor penetrometer (ASTM, 1985). Bulk density was also measured each time. Wash erosion by overland flow was assessed using a factorial experiment involving the two soils with the four peat contents, and exposed to two slope gradients (9% and 30%) and two lengths of slope (1.54m and 2.62m) with two replications giving a total of 64 tests. A constant water overland flow rate of 0.28 L s^{-1} was maintained for 30 minutes for each test. The 0.28 L s^{-1} flow rate represented the lowest rate utilised by Zhang et al. (2002) and was sufficient to produce measurable values of erosion. The slope gradients were chosen to represent the ones prevalent in agricultural soils in Trinidad (Gumbs, 1987). Analysis of variance (ANOVA) of wash erosion values was performed using the MINITAB Statistical Software Release 13.20 by Minitab Inc., USA.

5. Results and Discussion

5.1 Factors Affecting Wash Erosion

Table 2 shows the values of wash erosion for the two soils. Peat was found to reduce wash erosion for all combinations of soil type and the two slope parameters. Wash erosion was higher for the 2.62m length of slope more than the 1.54 m for the two soils. For the 9% slope gradient, erosion was found to be higher in the clay soil than the sandy soil for the two slope gradients and the four peat contents. At the 30% slope, the reverse was obtained in that the most values of wash erosion in sand were now greater than those for clay soil. Table 3 shows the mean wash erosion for the main effects of soil type, peat content, slope gradient and slope length. While the mean wash erosion for the higher slope gradient and slope length was in each case greater than the values for the smaller slope parameters, mean wash erosion decreased with increasing peat contents. Sand had overall larger mean wash erosion than the clay soil.

Table 2. Values of wash erosion (kg) for two soils with four peat contents at two slope gradients and two lengths of slope

Soil Series	Peat Content (%)	1.54 m Length of Slope		2.62 m Length of Slope	
		9% slope	30% slope	9% slope	30% slope
Piarco sandy loam	0	0.85	3.71	0.88	6.75
	4	0.65	2.77	0.74	5.23
	8	0.33	1.83	0.48	5.20
	12	0.15	1.35	0.22	3.68
Talparo clay	0	1.13	3.21	2.18	6.55
	4	0.81	2.55	1.68	3.20
	8	0.73	2.12	1.43	2.03
	12	0.57	1.80	0.64	1.17

Table 3. Mean wash erosion for different experimental factors

Factor level	Mean Wash Erosion (kg) *	Factor level	Mean Wash Erosion (kg) *
Soil type		Slope gradient	
Piarco sandy loam	2.19	9%	0.84
Talparo clay	1.99	30%	3.31
LSD (P = 0.001)	0.44	LSD (P = 0.001)	0.44
Peat Content (%)		Length of slope (m)	
0	3.16	1.54	1.54
4	2.20	2.62	2.62
8	1.77	LSD (P = 0.001)	0.63
12	1.18		
LSD (P = 0.001)	0.36		

Remarks: * - Mean values for each factor were obtained by averaging the measured values over the levels of the other three experimental factors. Number of experimental points is 64 representing a factorial experiment with 2 soil types, 4 peat contents, 2 slope gradients, 2 lengths of slope and 2 replications.

The analysis of variance showed that the main effects of slope gradient, slope length and peat content were all significant at the 0.1% level of significance. The main effect of soil type was not significant. In addition, apart from the interaction between soil type and peat content (which was not significant), all the other interactions between the experimental factors were significant at 0.1% level. The most significant interactions were between soil type and slope gradient, slope length and slope gradient, and peat content and slope gradient in that order.

The main effects and these three interaction effects are described below:

1) *Peat content*: Wash erosion decreased with increasing levels of peat content in the two soils. This was true irrespective of the slope gradient and slope lengths that the soils were exposed to. The decrease in wash erosion by peat can be attributed to its reduction of soil compactibility. Table 4 shows that peat reduced values of bulk density and penetration resistance, which are indices of soil compactibility (Ekwue and Stone, 1995). Peat reduces bulk density of soils by diluting the soil matrix with its own less dense material (Ekwue and Stone, 1995). This also ensured that it reduced soil penetration resistance, whose value increases with bulk density. This reduction in soil compactibility ensured that peat increased the infiltration capacity of the soil, and thus reduced runoff and wash erosion.

Table 4. Values of bulk density and penetration resistance of soils prior to testing of wash erosion

Soil Series	Peat content (%)	Bulk density (Mg m^{-3})	Penetration Resistance (kPa)
Piarco sandy loam	0	1.10	183.6
	4	0.90	163.4
	8	0.82	155.2
	12	0.75	149.1
Talparo clay	0	1.00	173.7
	4	0.89	166.3
	8	0.79	161.8
	12	0.70	154.4

Ekwue (1987) reported increases in infiltration rates as a result of peat incorporation into the soil. The interaction obtained between peat content and slope gradient shows that the effect of peat in reducing wash erosion will be more effective in steep rather than in gentler terrains (see Figure 2).

2) *Soil type:* The main effect of soil type was not important on wash erosion, but the interaction obtained between soil type and slope gradient (see Figure 3), shows that the effect of soil type on wash erosion depends on the slope gradient. It was reported that at 9% slope gradient, there was greater wash erosion in the Talparo clay than in the Piarco sandy loam. This was as expected because it is well known that wash erosion is greater in clay than in sandy soils (Luk, 1979). This is because, the particle size of sand is greater than that of clay, and therefore it is more difficult for overland flow to transport eroded materials in the sandy loam soil. Moreover, the larger size of the sandy loam soil will lead to greater presence of few large pores in the sandy loam soil than the clay soil, which is known to have many tiny pores. Large pore space is expected to cause a greater infiltration in the sandy soil. This will lead to lower surface runoff and hence lower wash erosion in the sandy loam soil.

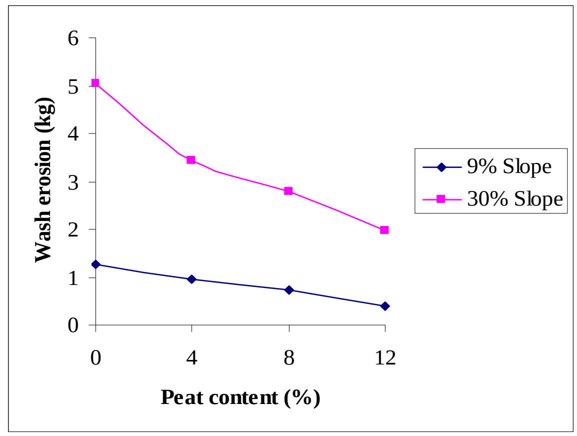

Figure 2. Effect of interaction between peat content and slope gradient on mean wash erosion

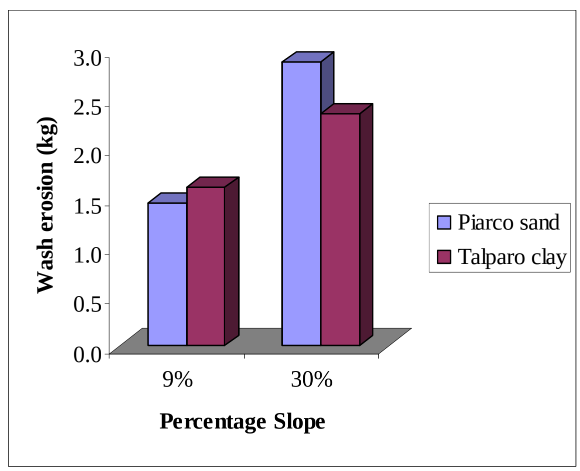

Figure 3. Interaction between slope gradient and soil type on mean wash erosion

However, at 30% slope gradient, the wash erosion was greater in the Piarco sandy loam soil. This may be because this larger slope gradient did not allow enough time for water to infiltrate in the sandy loam soil. This caused the water to flow down the slope at a higher velocity and eroded the more loose sandy loam particles. Sand particles are held more loosely than clay soils (Quansah, 1981; Poesen, 1985). At this higher slope gradient, the erosion in clay could have been decreased by the known greater cohesive nature of clay particles. Although soil texture may be the main factor affecting soil erodibility (Wischmeier and Smith, 1978), the results presented here indicate that the effect of soil texture on wash erosion by overland flow depends on the degree of slope in the field.

3) *Slope Parameters:* As expected, soil loss increased, in each case with increasing slope gradient and slope length. The increase of soil loss with slope length was because the increase in length meant more soil on the slope and a greater exposed surface area to overland flow. Also, at a higher slope gradient, there was an increase in the velocity of water over the surface resulting from lower infiltration into the soil as indicated above. This led to an increase in the volume of overland flow. The increase in water velocity resulted in a greater erosive power of the water. The combination of these resulting effects increased the wash erosion by overland flow. The interaction between slope gradient and length of slope indicates that the effect of length of slope on wash erosion will be higher on a steeper more than on a gentle terrain (see Figure 4).

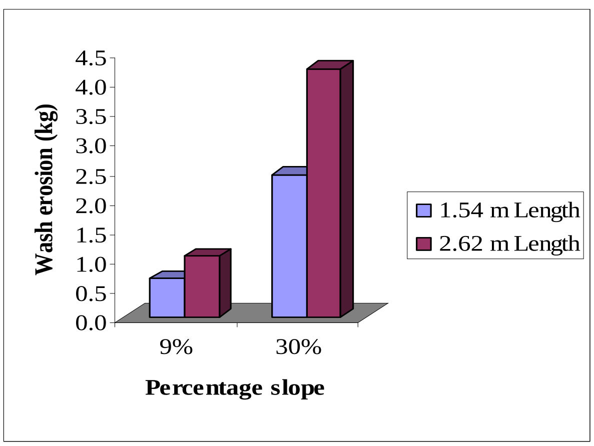

Figure 4. Effect of the interaction between slope gradient and slope length on mean wash erosion

5.2 Derivation of Regression Equation Relating Wash Erosion to Experimental Factors

The wash erosion for the two soils with different peat contents, percentage slopes and lengths of slope was used to generate a multiple linear regression equation that could be used to predict wash erosion. The equation is of the form:

$$E_w = -1.15 - 0.00639\, C_t(\%) + 1.00\, S_L(m) + 0.118\, S_p(\%) - 0.159\, P_t(\%)$$

$R^2 = 0.749$; $N = 64$

Where: E_w is wash erosion (kg); C_t is the percentage clay content of the soil (%); S_L is the slope length in metres; S_p is the slope gradient (%); P_t is the percentage peat by mass; R^2 is the coefficient of multiple determination; and N is the number of experimental data points. The signs of the experimental factors obtained confirm how the factors affected the wash erosion. The R^2 is significant at the 0.1% level.

6. Conclusions

Based on experimental testing, the new constructed soil erosion research apparatus was found to be user friendly and easy to operate. The facility allows for small incremental changes to be made in the slope length as well as the slope gradient; it allows for the efficient separation of the eroded sediment from the runoff water during testing. This also allows for the efficient removal of infiltrated water during testing. Wash erosion measured with the apparatus decreased with increasing peat content in all cases and was smaller for the sandy loam soil than the clay soil at the lower slope percentage.

The reverse occurred for the higher slope percentage where the clay soil had lower wash erosion than the sandy soil. This implies that the effect of soil texture on soil erosion depends on slope gradient. In all cases, wash erosion increased with increasing slope gradient as well as length of slope, although it was found that the maximum effect of slope length on soil erosion would be on steep rather than gentle slopes. The implication of this result is that while land use zoning of soils based on slopes is very essential in soil conservation, the incorporation of peat in steep arable slopes would greatly minimise soil erosion by water.

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