Comment on "Zhang, X. C. (2019). Determining and Modeling Dominant Processes of Interrill Soil Erosion. *Water Resources Research, 55*(1), 4-20. doi:10.1029/2018wr023217"

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Abstract

Zhang (2109) presented results from experiments where 4 sections in 1.8 m long flumes were sequentially exposed to rainfall during 15 minute periods during an hour where rainfall intensity and slope gradient remained constant. The upslope areas were protected by a tarp in one treatment, and a screen placed 5 cm above the soil surface to provide sheet flow protected to some degree from raindrop impact in another treatment. Zhang presented two equations, one for the screen experiments, one for the tarp experiments, for estimating the soil loss rates in the sections under steady state conditions. The equation used for the screen experiments is shown here to produce results that do not conform to well known long established rules that apply to the determination of erosion in a section. In terms of modelling sediment discharge, Zhang applied an equation developed by Zhang and Wang (2017). It is shown here that that equation was not well suited to predicting the discharges in the screen treatment. Zhang also observed sediment discharges were well correlated to stream power even though sediment concentrations were influenced by rainfall intensity. Considerable insights exists in respect to the detachment and transport mechanisms that operate in rain-impacted flows a few millimetres deep but the closeness of the flow surface to the soil surface has a major impact on sediment transport by saltation and rolling. Further study of sediment transport by very shallow rain-impacted flows is warranted

1. Introduction

In his study, Zhang (2019) used a silt loam soil in two replicate flumes 1.8 m long, 0.5 m wide, that were placed side by side with a 2.5 cm slot between them. The slot was used to collect splashed material. The soil came from Coshocton, OH in the USA and had 20.8 % sand, 58.6 % silt, 20.6 % clay. The rainfall simulator used in the experiments produced pulses of rain from 80150 nozzles 3 m above the eroding surfaces. Two treatments were used. In one treatment, a screen was suspended 5 cm above the soil surface to provide sheet flow protected from raindrop impact. In the other, a tarp was placed over the surface to prevent upslope runoff from flowing over the exposed surface. In the first 15 minutes of experiments lasting 1 hour, the bottom quarter of the flumes was exposed to rainfall produced by the rainfall simulator. In the 2nd 15-minute period, erosion by the rainfall occurred on the bottom half of the flumes. Three-quarters of the flume areas was exposed in the 3rd 15-minute period with the whole area being exposed in the 4th 15-minute period. In the first hour, 60 mm hr^{-1} rainfall intensity was used. In the 2nd hour, the exposure sequence was repeated with 90 mm hr^{-1} rainfall intensity, and 120 mm hr^{-1} rainfall intensity in the 3rd hour. The screen experiments were designed so that surface water flow conditions did not vary in the bottom section of the 1.8 m long surface as the number of exposed sections varied. In contrast, the tarp experiments were designed so that the transport capacity of rain-impacted flows in the bottom section varied as the number of exposed sections varied. The two treatments were applied on 9 %, 18 % and 27 % slopes. Newly prepared surfaces were used for a sequence of 3 one hour rainfalls varying in intensity from 60 mm hr^{-1} to 120 mm hr^{-1} and totalling 270 mm on for each slope gradient. Sediment-laden runoff was collected every 3 minutes.

In analysing the results from the experiments, Zhang concluded that the difference in sediment loads between two adjacent 15-min intervals may be considered the new contribution from the newly uncovered section for the corresponding period. For the tarp experiments, the differences were used to calculate steady state loss rates from section 1 during each 15-min interval but, for the screen experiments, the differences were used to calculate soil loss rates from the newly uncovered section. In addition, Zhang used comparisons between splash and flow transported sediment to determine whether detachment limiting or transport limiting conditions occurred, and evaluated a number of independent variable as predictors of sediment discharge. The following issues are considered in this comment

1. The approach adopted to analyse data from the screen experiments did not to produce reliable estimates of temporal and special variations in erosion on the inclined surfaces used.
2. There is a conceptual issue in the logic presented to interpret the effect splash on sediment transported in rain-impacted flows
3. The analytical approach adopted failed to identify differences in the abilities of the independent variables to account for variation in sediment discharges between the tarp and screen treatments
4. The apparent difference in stream power versus shear stress as predictors may in part be related to inaccurate determination of flow depth.

2. Determination of soil loss within each section

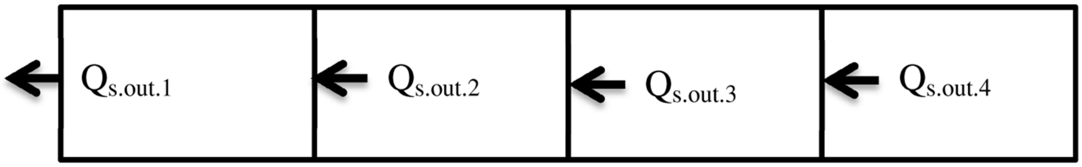

Figure 1. Schematic of the discharge of sediment between sections when the whole surface in the experiments by Zhang (2019) is exposed to rainfall. $Q_{s.out}$ is the amount of sediment discharged during a 15-minute period of time.

Figure 1 is a schematic of the discharge of sediment between sections when the whole of the surface is exposed to rainfall. It follows from Meyer and Wischmeier (1969), a paper cited by Zhang, that when the steady state occurs and the sediment discharge from a section is less than the sediment input into the section from upslope, all the sediment entering the section passes through the section, and the difference between the amounts of sediment entering and exiting the section results from erosion in the section. Conversely, when the sediment discharge is less than the sediment input from upslope then deposition occurs. In the Zhang (2019) experiments, only $Q_{s.out.1}$ is measured when each new section upslope of section 1 is exposed during the hour rainfall intensity was held constant. Even so, it can be assumed in the tarp experiments that the amount of sediment discharged into section 1 from section 2 in the 15-30 min period is equal to the amount of sediment discharged from section 1 during the 0-15 min period because there is no water or sediment entering section 2 from upslope during that 15-30 min period. Similarly, when section 3 becomes exposed, the amount of sediment discharged into section 2 from section 3 is equal to the amount of sediment discharged from section 1 during the 0-15 min period, and when section 4 is newly exposed, the amount of sediment discharged into section 3 from section 4 is equal to the amount of sediment discharged from section 1 during the 0-15 min period. As notes above, when the steady state occurs and $Q_{s.out} \geq Q_{s.in}$, all the material entering a section from upslope is transported through the section so that the rate soil material is discharged from the whole of eroding area is equal to the sum of the sediment discharges (g m^{-1} min^{-1}) from erosion in each of the contributing sections. Table 1 shows the result for 90 mm hr^{-1} rain on 18 % slope in the tarp experiments assuming steady state conditions.

In the case of the tarp treatment, Zhang concluded that steady state soil loss rates for section 1 during each 15 minute interval could be estimated from

, $$S1_{0\text{-}15} = L_{0\text{-}15} / A1 \quad (1a)$$

$$S1_{15\text{-}30} = (L_{15\text{-}30} - L_{0\text{-}15}) / A1 \quad (1b)$$

$$S1_{30\text{-}45} = (L_{30\text{-}45} - L_{15\text{-}30}) / A1 \quad (1c)$$

$$S1_{45\text{-}60} = (L_{45\text{-}60} - L_{30\text{-}45}) / A1 \quad (1c)$$

Eqs 1a-1c provide estimates of soil loss rates (g m^{-2} min^{-1}) that are consistent with the approach that generated the sediment discharges (g m^{-1} min^{-1}) presented in Table 1.

Table 1. Estimated sediment discharge (g m^{-1} min^{-1}) from erosion each section during the four 15-min periods for 90 mm hr^{-1} rain on 18 % slope in the tarp experiments assuming steady state conditions.

	sediment discharge from whole exposed area	sediment discharge from erosion in sect 1	sediment discharge from erosion in sect 2	sediment discharge from erosion in sect 3	sediment discharge from erosion in sect 4
0-15	9.09	9.09			
15-30	18.35	9.26	9.09		
30-45	29.36	11.01	9.26	9.09	
45-60	44.04	14.68	11.01	9.26	9.09

In analysing the data for the screen experiments, Zhang concluded that the steady state soil loss rates (g m^{-2} min^{-1}) from each section could be estimated from

$$S1_{0\text{-}15} = L_{0\text{-}15} / A1 \quad (2a)$$

$$S2_{15\text{-}30} = (L_{15\text{-}30} - L_{0\text{-}15}) / A2 \quad (2b)$$

$$S3_{30\text{-}45} = (L_{30\text{-}45} - L_{15\text{-}30}) / A3 \quad (2c)$$

$$S4_{45\text{-}60} = (L_{45\text{-}60} - L_{30\text{-}45}) / A4 \quad (2d)$$

where *S1*, *S2*, *S3*, and *S4* are the soil loss rates from sections 1, 2, 3, and 4 for the corresponding 15-minute interval in g min^{-1} m^{-2}, *L* is the average steady state delivery at the outlet (g min^{-1}) for the respective time interval, and *A1*, *A2*, *A3*, and *A4* are the projected areas of the respective sections.

According to Zhang, "*By assuming that the same slope length (i.e., the same runoff rate) yields the same amount of sediment load, the difference in sediment loads between the two adjacent intervals may be attributed to the loss from the lowest section (S1) rather than from the newly uncovered section because the sediment loads for the same slope (or flow) length tend to cancel out. For example, the flow length of S3 + S2 during the 30- to 45-min interval is 90 cm, which is equivalent to the length of S2 + S1 in the previous interval, and thus, the difference in sediment loads between the two intervals reflects the loss from the segment of 90 to 135 cm (i.e., S1)*". According to Zhang (pers com), the purpose of Eq. 2 was to produced values of APPARENT NET LOSS which reflect whether the sediment transport capacity has been reached in S1, *"***nothing more".** This approach is questionable. As shown in Table 2, the "apparent" net soil losses generated by Eq.2 are not consistent with net soil losses based on the scheme shown in Figure 1, a scheme which, as noted above, follows from Meyer and Wischmeier (1969). Also, there is actually no need for Eq, 2 to exist for the purpose stated by Zhang. The impact of the new exposures in the screen experiments can be shown by determining the differences between successive discharges from S1. There is no need to divide those differences by the area of the new section exposed.

Table 2. Soil loss rates (g m^{-2} min^{-1}) in each section during the 45-60 min periods in the tarp and screen treatment on the 18 % slope estimated using the scheme shown in Figure 1 and Eq. 2. The results for the screen experiments using the scheme shown in Figure 1 assume that the relative contributions of the sections to sediment discharges in the screen experiments follow the same spatial pattern as observed in the tarp experiments. No data exists to determine the actual soil loss rates directly in the screen experiments.

rainfall intensity (mm/hr)	sediment discharge from sect 1 (g/m/min)	Sect 1 (g/m^2/min)	sect 2 (g/m^2/min)	sect 3 (g/m^2/min)	sect 4 (g/m^2/min)
TARP experiments using Fig. 1 scheme					
60	25.0	22.4	13.5	11.0	8.7
90	44.0	32.6	24.5	20.6	20.2
120	77.9	66.9	41.5	33.1	31.5
SCREEN experiments using Fig.1 scheme					
60	45.7	40.9	24.6	20.1	15.8
90	75.6	56.0	42.0	35.3	34.7
120	103.9	89.4	55.4	44.2	42.0
SCREEN experiment using Eq.2					
60	45.65	59.85	18.86	15.40	7.34
90	75.58	151.38	1.90	10.40	4.29
120	103.91	198.38	16.94	15.19	0.41

Given that for the screen treatment, surface flow discharges in each section remained constant throughout each 1 hour rainfall event due to the fixed drainage areas, questions arise as to why small but positive impacts of adding newly exposed sections upslope were observed whereas there should be none given that the sediment transport capacity of the rain-impacted flow did not change during the one hour of rain. It is generally accepted that coarse particles detached by raindrop impact may travel downstream in rain-impacted flow by raindrop induced saltation (*RIS*), raindrop induced rolling (*RIR*), flow driven saltation (*FDS*) and flow driven rolling (*FDR*). These 4 transport mechanisms are known to have a limited capacity to transport soil material, and this may be especially true in very shallow flows. However, fine particles move in the flow as suspended load at concentrations which are well below any transport limit. No particle size data were collected but it is possible that the small positive changes in $Q_{s.out.1}$ between 15 min periods result from increases in fine material being discharged as the areas exposed to raindrop impact increased as suggested by Zhang.

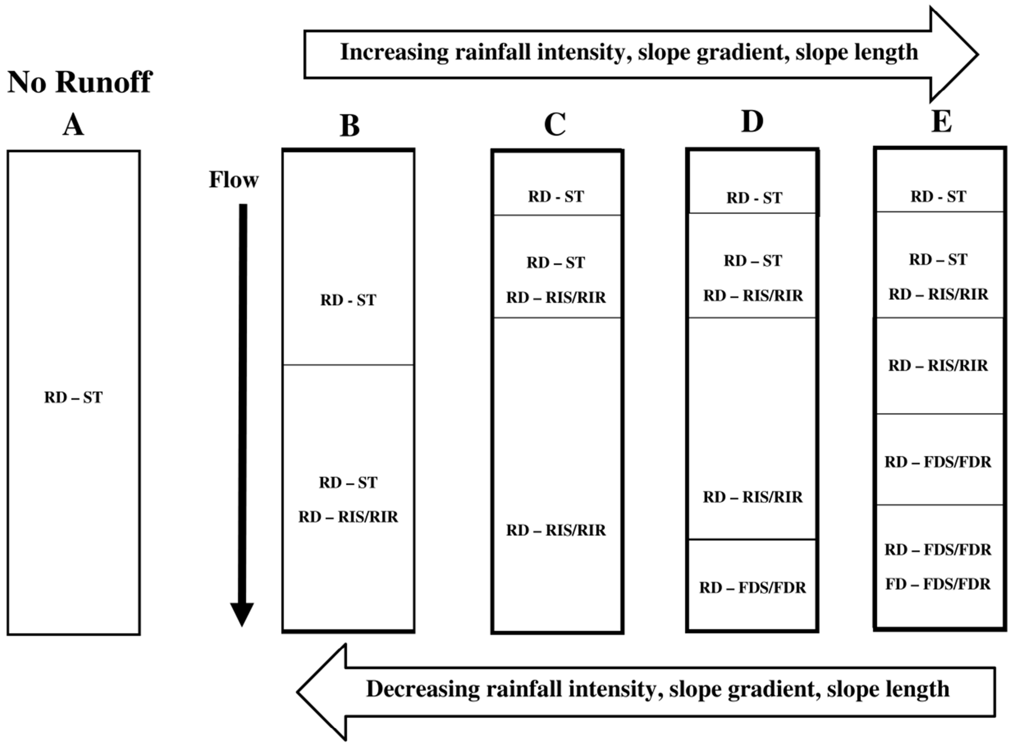

Figure 2. Schematic of spatial variations in the detachment and transport mechanisms operating on surfaces eroding as the result of detachment by raindrop impact and surface water flow when rilling does not occur. Modified from (Kinnell, 2012)

3. Splashed material as an indicator of detachment limiting and transport limiting conditions

Figure 2 illustrates how rainfall intensity, slope length and gradient can influence the detachment and transport mechanisms that operate on surfaces eroding under rainfall. In all cases, raindrop impact plays a major role in detaching and transporting soil material in the upper parts of the eroding slope. As noted above, a slot between the two flumes was used to collect splashed material. According to Zhang (2019), "*If slot splash is greater than flume wash, it can be inferred that interrill erosion rate is limited by sediment transport. Otherwise, interrill erosion is limited by soil detachment*". However, although the material splashed to the slot represents splashed material falling onto the rain-impacted flow from the air, it is not an absolute measure of the material available for transport by the rain-impacted flow. Not all materials detached by raindrop impact become airborne. It has been well demonstrated by Moss and Green (1983) that the ratio of material splashed and material transported by raindrop induced saltation decreases greatly as flow depth increases so that sediment transport by rain-impacted flows can be transported limited even when the slot splash is less than the flume wash. Theoretically, the mass lifted into the air by a drop impact is given by

$$M_{m.A} = a\, M_m \qquad (3)$$

where M_m is the mass of soil material lifted vertically from the soil surface under the water layer by the impact of a raindrop, and the mass that remains in the flow

$$M_{m.F} = b\, M_m \quad (4)$$

where $a + b = 1.0$ (Kinnell, 2020). Although a tends towards 1.0 as flow depth decreases its value is not known to be 1.0 in the shallow flows that occur in the Zhang experiments. Also, the mass of material that is mobilised by a drop impact and made available for transport in both the flow and the air comes from two sources, soil material from the matric soil detached by the impacting raindrop and the mobilization of loose material sitting on the soil surface detached by previous drop impacts. In theory M_m is given by

$$M_m = M_d\,(H\,\text{-}1) + H\, M_{pd} \quad (5)$$

where M_d is the mass detached directly by the current drop impact, M_{pd} is the loose material sitting on the surface that has been detached by previous drop impacts, and H is the degree of protection provided by the loose material sitting on the surface. If no soil material is transported downslope from the site of the drop impacts then H increases until ultimately only pre-detached material is mobilized by drop impacts. M_d is controlled by both the ability of the drop impact to cause detachment and the ability of the soil to resist detachment. The latter will always be a limiting factor but detachment will also be limited when $H > 0$. $H > 0$ will occur whenever sediment is being transported by saltation and rolling. Consequently, unless sediment is so fine that all the detached material is transported in complete suspension, both detachment and transport limiting conditions operate at the same time to control sediment discharge when raindrop induced saltation and rolling occur in rain-impacted flows.

As indicated in Figure 2, it is possible that as rainfall intensities and slope gradients increased, the discharge of sediment from the eroding slope may become controlled by flow driven transport mechanisms (Figure 2D). It may also be possible for flow detachment to to occur on high slopes under high rainfall intensities to produce the situation depicted in Figure 2E. Apart from the data comparing splash and wash rates, Zhang provided no information about what actual detachment and transport mechanisms control sediment discharge from S1. Also, transitions between raindrop induced transport and flow driven transport are particles size and density dependent so that, for example, the situation depicted in Figure 2C may apply to the larger heavies coarse particles while, as the same time, the situation depicted in Figure 2D may apply to the smaller lighter coarse particles. Even if all the coarse particles are discharged by flow driven transport mechanisms, the sediment discharged from S1 will contain particles that enter S1 by raindrop driven transport mechanisms operating upslope. Similarly, if flow detachment occurs in S1, some of the sediment discharged from S1 will come from detachment by raindrop impact not just in S1 but from upslope of S1. The notion that soil lost from erosion on a slope is either detachment limited or transport limit is overly simplistic.

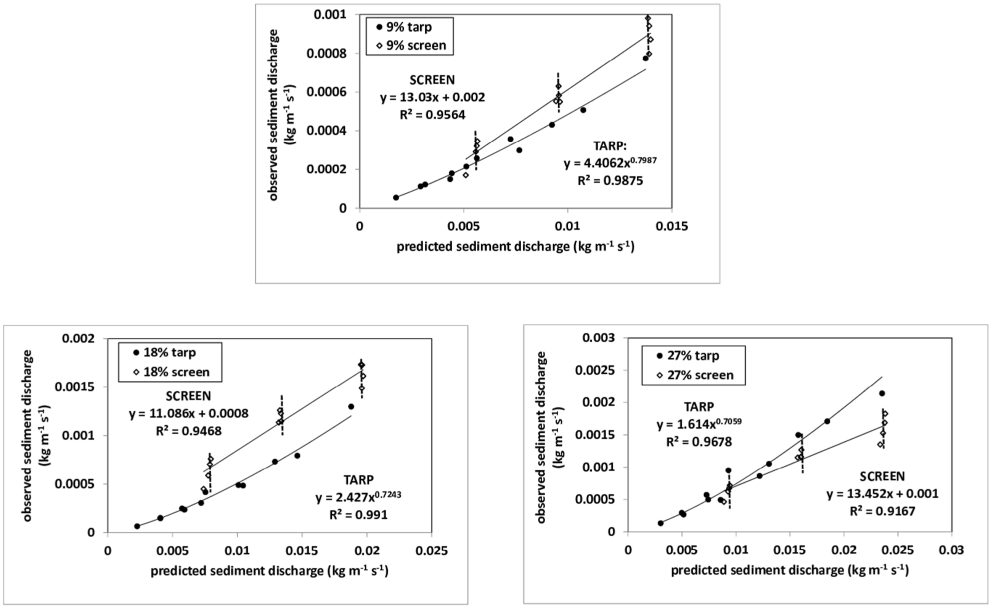

Figure 3. The relationships between values predicted by Eq.6 and average sediment delivery rates observed during the 15 min periods for the three hours of rain applied when the slope gradients were maintained constant in the trap and screen experiments.

4. Modelling sediment discharges

The tarp experiments provided data on 4 slope lengths (0.45 m, 0.9 m, 1.35 m, 1.8 m) on 3 slope gradients (9 %, 18 %, 27 %) under 3 rainfall intensities (60 mm hr^{-1}, 90 mm hr^{-1}, 120 mm hr^{-1}). Previously, Zhang and Wang (2017) undertook a series of 1 hour experiments where slopes ranging length from 0.4 m to 2.0 m, on gradients ranging from 17.6 % to 57.7%, eroded under rain with intensities ranging from 48 mm hr^{-1} to 170 mm hr^{-1}. The soil was a loessial soil from the Ansai County in Shaanxi Province, China and had 39 % sand, 45 % silt, 16 % clay. In the experiments, rain was supplied continuously from pendant drop formers (DJK-6000 rainfall simulator, Japan) 8.7 m above the target rather that intermittently from sprays in the Zhang (2019) experiments. Analysis of the data from the 250 experiments generated by Zhang and Wang (2017) produced the equation

$$D_s = K_i\, I\, S_f\, R^{0.242}\, L^{0.963} \qquad (6)$$

where K_i is a soil related factor, D_s is the sediment delivery rate (kg m^{-1} hr^{-1}), I is rainfall intensity (mm hr^{-1}), R is runoff rate (mm hr^{-1}) and L is slope length (m) and S_f is given by

$$S_f = 1.05 - 0.85e\text{-}4(\sin \theta) \qquad (7)$$

where θ is slope angle (Liebenow, Elliot, Laflen, & Kohl, 1990). The relationship between the 15 min mean sediment discharge data from the Zhang (2019) experiments and Eq. 6 using the value of K_i obtained for the Zhang and Wang (2017) experiments produced a value of the

Pearson correlation coefficient (r) of 0.948 when both screen and tarp were considered together. X. C. Zhang (2019) did not test the relationship in respect to the goodness of fit Eq. 6 in respect to his experiments. However, when Eq.6 is applied to predict the discharges in each 15 min period for each slope gradient (Figure 3), it is apparent that mathematical form of observed to predicted relationships for the screen treatment differs from that for the tarp experiments. It should also be noted that the predicted values are about an order of magnitude greater than the observed sediment discharges.

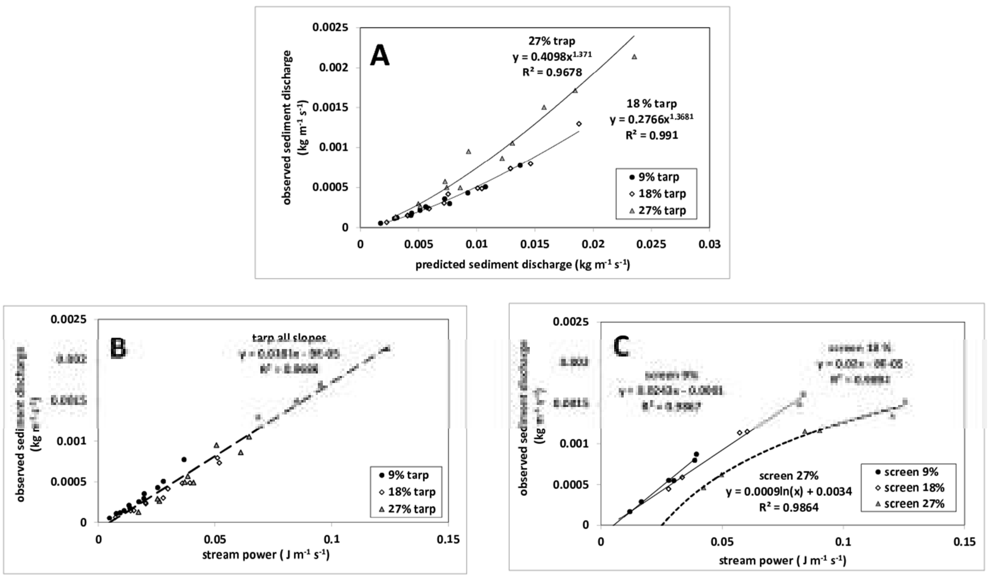

Figure 4 (A) The relationships between average sediment discharge rates during 15 min periods in the tarp experiments and the values predicted by Eq.6, (B) the relationships between average sediment discharge rates during 15 min periods in the tarp experiments stream power and (C) the relationships between average sediment discharge rates during 15 min periods in the screen experiments stream power during the three hours of rain applied when the slope gradients were maintained constant.

Figure 4 shows the relationships between the sediment discharges for each of the 3 slope gradients used in the tarp experiments and the values predicted by Eq. 6 and stream power. When Eq.6 is used in tarp experiments, the 27% slope appears to produce greater sediment discharges than expected from applying Eq. 6 to the 9 and 18 % slopes (Figure 4A). However , that is not the case when stream power is used as the independent variable (Figure 4B). When stream power is used as the independent variable in the screen experiments, the 27 % slope appears to produce much lower sediment discharges than expected from the 9% and 18% slope slopes (Figure 4C) These issues were not detected in the analyses undertaken by Zhang on the combined the data from the screen and tarp experiments. Failure to examine the mathematical form and goodness of fit the relationships between dependent and independent variables can lead to misplaced confidence in the value of certain independent variables in accounting for variations in the observed sediment discharges. It should also be noted that with high rainfall intensities, flow discharges are highly correlated with rainfall intensity so that stream power and rainfall intensity are highly correlated in the screen experiments.

Zhang also examined shear stress and unit stream power as predictors of sediment discharge when the data for the tarp and screen experiments were combined. Sediment deliveries in the tarp and screen experiments were less well correlated with shear stress (Pearson $r = 0.545$) and unit stream power (Pearson $r = 0.867$). The primary factors associated with shear stress are slope gradient and flow depth whereas, for unit stream power, the primary factors are slope gradient and flow velocity. Flow velocities were measured by Zhang using a dye method and flow depths were determined for the knowledge that flow discharge is given by product of flow depth and velocity. However, dye methods for measuring flow velocity may not produce accurate results in rain-impacted flow because raindrops impacts disperse the dye making visual timing difficult. Flow discharge is more accurately measured and this may have contributed to a better correlation being observed for stream power (directly proportional to slope gradient and flow discharge) than shear stress (directly proportional to slope gradient and flow depth) and unit stream power (directly proportional to slope gradient and flow velocity).

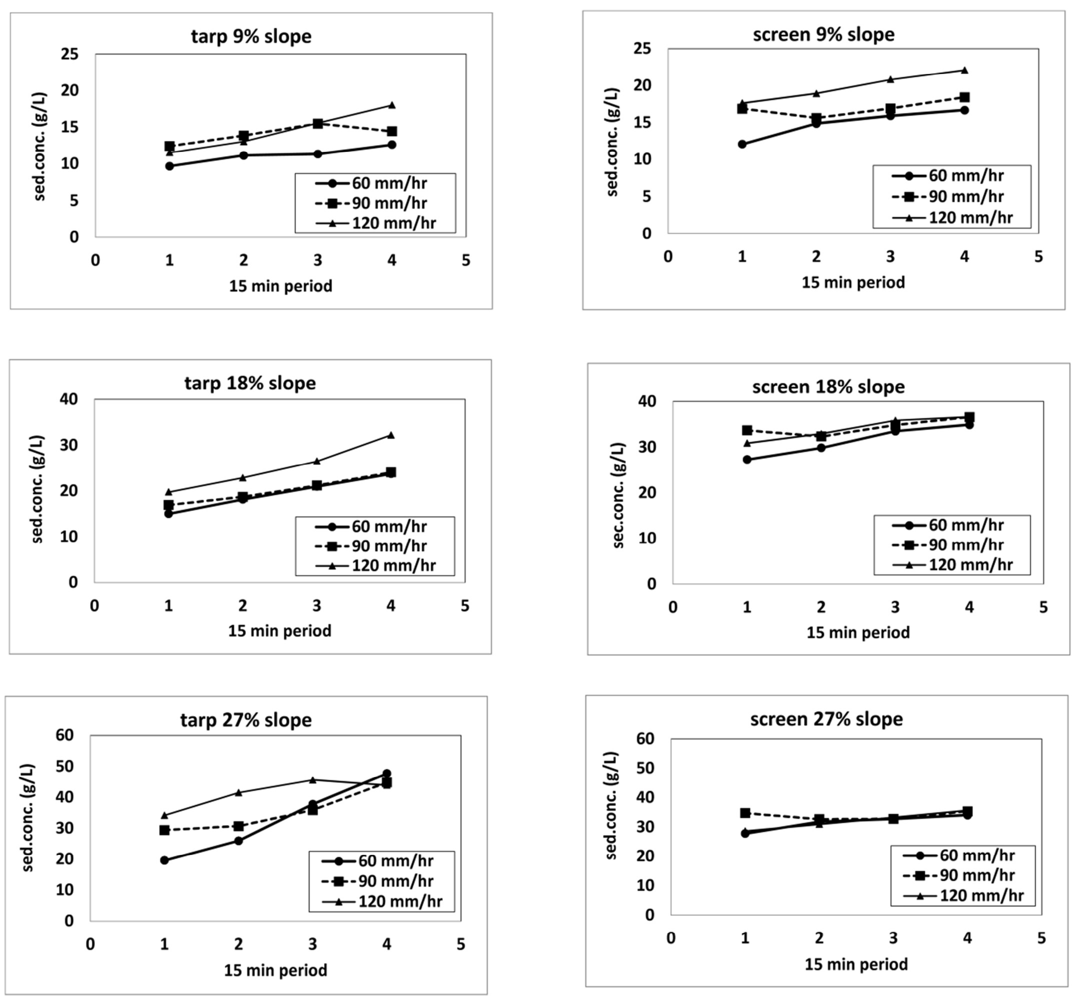

Figure 5. 15 min sediment concentrations produced on slopes with different gradients during the 1 hour rainfall events where rainfall intensity was held constant.

4. Variations in sediment concentration

In analysing runoff and soil loss data, it is useful to consider that sediment discharge is given by flow discharge and sediment concentration, the mass of soil material discharged per unit quantity of water. When stream power is used as a predictor, sediment concentrations are assumed to vary with **only** slope gradient. However, when sediment transport occurs by raindrop induced saltation in flows a few millimetres deep, sediment concentrations vary directly with rainfall intensity (Kinnell, 2005). In addition, Eq.6 obtained for the shallow flows that occurred in the Zhang and Wang (2017) experiments support the expectation that sediment concentrations should increase with rainfall intensity in the Zhang (2019) experiments. As shown in Figure 5, the 15 min sediment concentrations for 120 mm hr^{-1} rainfall in the tarp experiments tended to be higher those for the 60 mm hr^{-1} rainfall. Period 4 on the 27 % slope was an exception. 90 mm hr^{-1} rainfall did not produce consistent intermediate sediment concentrations. It is apparent from Figure 5 that rainfall intensity should be considered as an independent factor in determining sediment discharge in addition to stream power.

Figure 5 also shows that, when slope gradient and rainfall intensity are held constant, the sediment concentration for the sediment discharged during each 15 minute period tends to increase as the number of exposed sections increases in both the tarp and the screen experiments. When sediment transport by raindrop induced saltation (*RIS*) occurs in flows a few millimetres deep, sediment concentrations decline with flow depth when rainfall intensity is held constant (Kinnell, 2005). Although some doubt may be cast at the accuracy of the data on flow depths and velocities obtained in the tarp experiments, those data (Figure 6) do not provide any support for the notion that temporal variations in sediment concentrations shown in Figure 5 are dependent on flow depth.

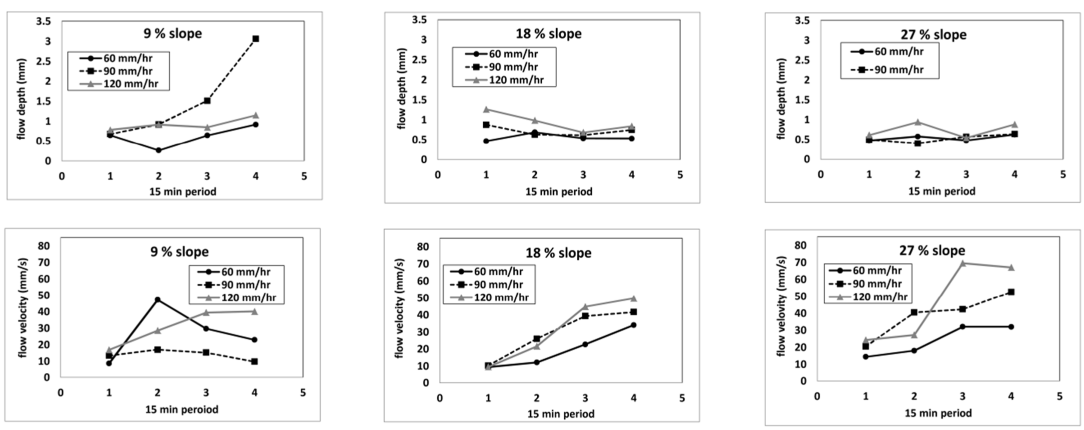

Figure 6. Average flow depths and velocities in section 1 during 15 min periods when slope gradient and intensity were held constant in the tarp experiments.

Although sediment concentrations during a one hour rainfall event may be better correlated with flow velocity, the increases in sediment concentration may be associated with the sequential exposure of the 4 sections. As noted earlier, Eqs. 1 and 2 are considered to apply when steady state conditions occur. However, the area exposed to erosion by rain-impacted flows in both the tarp and screen experiments changes every 15 minutes. Consequently, the experiments when the section 4 is exposed to rain impacted flow last for

15 minutes, that 15 mins may not be long enough for the slowest moving particle detached at the top of the slope to reach the bottom and be discharged as is required for the steady state. Inevitably, coarse material in transit over the soil surface before a change in exposed area or rainfall intensity will continue to move down stream after the change and get discharged under different conditions to when first detached. The continual increase in sediment concentrations throughout each hour of exposure to rain observed by in Figure 5 may be a consequence of the fact that the effect of a change in exposed area on sediment discharged by the rain impacted flow is not complete during the associated 15 min period. It may also be a consequence of the fact that the rainfall system produced pulses of high intensity rainfall which meant that detachment and transport of coarse material was highly intermittent while the transport of fine material was more continuous. It also needs to be kept in mind that each 15 min "event" on a given section is, in effect, a pre-treatment for the next 15 min "event" on that section. Consequently, the results obtained during each 1 hour rainfall event depends on what happened during the previous rainfall event. Changing the sequencing (eg. high intensity first and low intensity last) may produce quite different results. Hysteretic loops in sediment fluxes have been observed when rainfall intensities have been varied stepwise from low to high and back again (Cheraghi, Jomaa, Sander, & Barry, 2016).

6. Conclusion

The experiments reported Zhang (2019)) are unique in that the length of the area exposed to raindrop impact changes every 15 mins during 3 hours of rainfall where rainfall intensity was changed hourly. While using the tarp may seem an attractive alternative to experiments where, like in Zhang and Wang (2017), a new surface is used for each combination of slope length, gradient and rainfall intensity, coarse material in transit over the soil surface before a change in exposed area or rainfall intensity will continue to move down stream after the change and get discharged under different conditions to when first detached. This may have influenced the results. Considerable insight exists in respect the movement of particles in rain-impacted flows a few millimetres deep but not in very shallow flows where the closeness of the flow surface to the soil surface has a major impact on sediment transport by saltation and rolling. Given that it is well known that the size of the primary particles and aggregates being transported in rain-impacted flows an few millimetres deep influence sediment discharge, data on the actual particles sizes and densities discharged by the flow should augment data on sediment discharge if better understanding on how shallow rain-impacted flows transport detached soil material. Independent tests on the susceptibility of soil surface to detachment by flow are also warranted given that in some circumstances flow conditions may cause detachment by flow to occur. The submerged vertical jet method has been used to determine erodibility in respect to flow (Haddadchi et al., 2018; Rose, Olley, Haddadchi, Brooks, & McMahon, 2018) and the critical shear stress on non-cohesive soils (Sang, Allen, & Dunbar, 2015). Further study of sediment transport by very shallow rain-impacted flows is warranted but currently factors such as flow depth and flow velocity are difficult to control and measure to the same extent as in deeper flows.

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