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Changes in sediment delivery from hillslopes affected by shallow landslides and soil armouring

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Abstract

Topsoil erosion and shallow landslides on steep hillslopes are often the main sources of sediment delivered to waterways, so understanding their interaction is critical for quantifying this sediment delivery. Shallow landslides can alter long-term topsoil erosion due to changes in topography, land-cover, and soil properties, as demonstrated by a series of experimental studies, field observations, and modelling simulations. On hillslopes with bare soil, soil erosion potential after failure is lower than before failure due to changes in slope and soil properties. On hillslopes covered with vegetation, slope failures remove the vegetation cover, which increases the hillslope's post-failure soil erosion potential. However, following a landslide, the re-distributed and exposed soil goes through a soil armouring process that reduces soil erosion rates over time until vegetation is re-established. Existing soil erosion models do not take soil armouring into account in their simulations and thus tend to over-predict sediment delivery from steep slopes. In this paper, we describe the development of a hillslope modelling framework called WEPP-SLIP (Water Erosion Prediction Project – Shallow Landslide Integrated Prediction) that predicts sediment delivery from hillslopes, including the representation of shallow landslides. The physically-based WEPP model is used to estimate pre-failure soil erosion, and an infinite-slope-based landslide model is then used to predict where a mass failure can occur along the hillslope. Changes in topography are estimated using simple soil redistribution equations, and the WEPP model is then used again for the new hillslope topography to predict post-failure soil erosion. The effect of armouring can be simulated within WEPP by changing soil erodibility parameters over time, but further research is needed to refine armouring processes as a function of rainfall intensity, soil type, and other factors. Results from flume-based experiments were used to demonstrate the soil erosion, landsliding, and armouring processes and to validate the model for loess and sandy type soils representative of many steep hillslopes in New Zealand. The proposed WEPP-SLIP is a 2D hillslope modelling framework, however, efforts are under way to create a spatially distributed model using GIS to predict sediment delivery to stream networks from hilly catchments.

Keywords

Hillslope processes, Landslides, Erosion, Armouring, WEPP, Sediment delivery

Introduction

Steep hillslopes have the potential to deliver vast quantities of sediment to streams and rivers in New Zealand through topsoil erosion and shallow landslides. Significant efforts have gone into studying topsoil erosion processes of rainsplash, sheet (or inter-rill), rill, and gully erosion (Hicks *et al.*, 2000; Gomez *et al.*, 2003; Parkner *et al.*, 2007). The prediction of shallow landslides has also been the subject of significant research over time (Crozier *et al.*, 1980; Crozier and Preston, 1999; Smale *et al.*, 1997; Page *et al.*, 1999; Brooks *et al.*, 2002; Hennrich and Crozier, 2004; Crozier, 2005; Preston, 2008). Although gullying and landsliding often occur together (Betts *et al.*, 2003), soil erosion and shallow landslides are usually studied independently of each other and there is much to learn about the interaction between them. For example, changes in soil erosion potential as a result of shallow landslides can be critical in quantifying sediment delivery from a hillslope profile. Shallow landslides can alter long-term soil erosion because failures result in changes in topography, vegetation cover and soil properties (Acharya *et al.*, 2009, 2011).

Although changes to topography and vegetation cover are readily modelled by most erosion models (Dymond *et al.*, 2006), changes to soil properties are rarely considered. During simulations with erosion models, soil input properties are usually kept the same throughout an entire simulation period. Field observations conducted by the authors in hilly terrain and mining sites around New Zealand, however, have shown that soil redistribution following landslides can lead to changes in the surface properties of soils and thus affect sediment yields. Surface soil properties can be changed as a result of soil armouring due to the selective removal of finer particles during rain, leaving an armoured layer of coarser particles which reduce further soil erosion. Soil armouring can occur after a change in vegetation cover or when the soil profile is disturbed, for example following shallow landslides, during restoration of slopes in open cast mines and construction sites, or at other locations that have the potential of delivering sediment in large quantities to nearby waterways.

Severe soil armouring on restored slopes with highly disturbed soil or subsoils has been observed and recorded by Cochrane *et al.* (2007) at mining sites in the West Coast, New Zealand (Fig. 1). This soil was classified as a Denniston series, according to New Zealand Soil Surveys, but contains a large percentage of pebbles and gravels due to excavation and grabbing of underlying rock during soil extraction (porosity 0.34 and density 2.23, 1.8 mm median size particles, 80% of particles under 9.5 mm). In this case, armouring on restored slopes seems to be directly related to rainfall intensity. Results from preliminary studies showed a reduction of over 75% in total erosion rates after extensive armouring. Research conducted at Australian mining sites has shown that the soil armouring rate is also related to parameters such as slope gradient and length of hillslope (Sharmeen and Willgoose, 2007). Recent field observations by the authors have revealed that armouring seems to occur in a

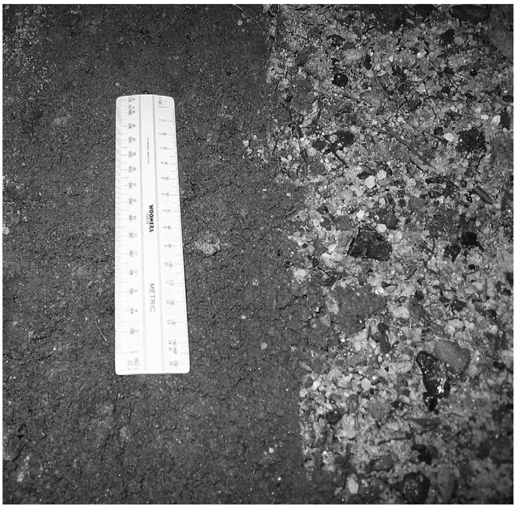

Figure 1 – A flume-based experimental comparison of Denniston-type fresh topsoil on the left and armoured topsoil on the right after 80 mm of simulated rainfall.

range of other soils in landslide-prone regions in New Zealand.

Although a wide range of models can predict soil erosion or shallow landslides independently, only a few can be used to predict both landslides and erosion under the same framework. One of these models is the sediment transport modelling system (SHETRAN), which predicts spatially distributed shallow landslides, soil erosion and sediment yield at larger catchment scales (Burton and Bathurst, 1998). This model identifies landslide potential and predicts sediment yield for large-scale applications, but there is a need to better understand hillslope processes involving shallow landslide generation, topography changes, and soil erosion prediction before and after landslides. Furthermore, the armouring effect needs to be incorporated into the modelling process. It is clear that if armouring rates are not taken into account, soil erosion modelling would over-predict sediment yields from hillslopes. By establishing the rate of armouring occurring and the reduction in erodibility, it is possible to adjust models such as the Water Erosion Prediction Project (WEPP) hillslope model (Flanagan and Nearing, 1995) to accurately reflect erosion rates in steep hillslopes following landslides.

The objective of this paper is to demonstrate the impact of shallow landslides and soil armouring on sediment delivery from hillslopes. We propose a modelling framework (WEPP-SLIP) that integrates shallow landslide prediction, soil redistribution, and soil erosion modelling and recommend a simple approach to simulating armouring. We demonstrate its applicability, point out current limitations, and propose future development goals.

Methods

Flume-based experiments

A series of flume-based experiments was conducted to understand and quantify sediment delivery from hillslope profiles influenced by interactions between soil erosion, shallow landslides and soil armouring (Table 1). The experimental setup consisted

Table 1 – Summary of experimental sloping configurations and profile preparations

Exp.	Soil	Upper Slope (°)	Lower slope (°)	Soil depth (mm)	Landslide triggered	Rainfall intensity (mm h^{-1})	Total kinetic raindrop energy over the simulation period (MJ m^{-2})	Porosity
E1*	Loess	35	10	100	No	20	0.90	0.41-0.42
E2	Loess	40	10	100	No		1.01	
E3	Loess	45	5	100	No		1.00	
E4	Loess	47	7	100	No		1.11	
E5*	Loess	35	10	100	No	40	2.05	0.41-0.42
E6	Loess	40	10	100	No		2.13	
E7	Loess	45	5	100	Yes	40	2.07	0.46-0.48
E8	Loess	47	7	100	Yes		2.24	
E9*	Sand	30	10	200	Yes	40	1.60	0.40– 0.41
E10	Sand	30	10	200	Yes		1.56	

* Sampling of top 1 cm of soil surface taken after experiments to determine changes in soil physical properties as a result of soil armouring.

Figure 2 – Experimental flume setup with rainfall simulator: a) side view and b) front view.

of a 0.3 m wide, 3.94 m long, two-section experimental flume, in which the slope of the upper 2.5 m long section could be varied between 30° and 47° and the lower 1.44 m long section between 5° and 10° (Fig. 2). Loess soils were used for experiments E1 through E8 and sandy soils for E9 and E10. The soils were uniformly placed and compacted in layers of 40 to 50 mm depth using a 40 kPa pressure mechanical mallet. Loess soils were compacted to what resulted in 0.41–0.42 porosity in E1–E6 for erosion simulations without triggering landslides and 0.46–0.48 porosity in E7–E8 to trigger shallow landslides. After layering and compacting the sandy soils, porosity values of 0.40–0.41 were obtained. Relevant physical and chemical properties of the soils were derived from standard laboratory tests (Table 2).

A two nozzle (Veejet 80100) Norton-type rainfall simulator (Norton and Brown, 1992) was used to provide rainfall coverage for the entire flume over an area of approximately 4 m × 2 m. The height of the nozzles in conjunction with the spray velocity allowed raindrops to reach terminal velocity before impact. Rainfall intensity from the simulator was set to 20 mm h^{-1} for experiments E1–E4 and

Table 2 – Physical properties of the soils

Selected soil properties	Loess soil	Sandy soil
Cohesion (kPa)	2.60	0
Angle of internal friction °	39.00	41
Organic matter content (OM) (%)	2.40	0.70
Initial moisture content (w) (%)	23.00	12.00
Mean grain size (D_{50}) (mm)	0.075	0.57
Effective grain size (D_{10}) (mm)	0.010	0.20
Specific gravity (G)	2.61	2.63
Cation exchange capacity (meq g^{-1})	0.19	NA

40 mm h^{-1} for E5–E10 and was applied for 6 to 8 hours during the experiments. These rainfall intensities were calibrated using a laser optical disdrometer (OTT Parsivel) (e.g., Löffler-Mang and Joss, 2000). The size of the raindrops ranged from 0.5 to 1.5 mm, with a mean size of 1 mm and a mean velocity of about 4 m s^{-1}. Furthermore, four cylindrical rain gauges were placed along each side of the flume to monitor the rainfall intensity and its spatial distribution every 30 minutes to verify consistency between the experiments. The total kinetic raindrop energy (MJ m^{-2}) calculated from the total amount of water falling in the flume over the simulation period is shown for each experiment in Table 1. Prior to application of rain in the loess soil experiments, the soils were saturated with simulated groundwater using three low-pressure porous pipes laid on the flume bed and connected by a precisely controlled regulator to an external water supply.

Runoff and sediment concentrations leaving the flume were sampled at regular intervals over a period of 6 to 8 hours for all experiments. For each experiment, the particle size distributions of the runoff samples collected at the end of experiment were analysed by sieving and by using a high-definition digital particle size analyzer (Micrometrics Saturn Digisizer 5200) (e.g., Meadows *et al.*, 2005). Shallow landslide occurrence, evolution, and the resulting profiles were recorded for experiments E7–E10. For experiments E1, E5, and E9, soil samples from the top 10 mm of the soil profile close to the outlet of the flume were collected immediately after each experiment. Particle size distributions were obtained for these samples to investigate physical changes to the topsoil as induced by the soil armouring process. Results from the soil erosion experiments (E1–E6), shallow landslide experiments (E7–E10), and information from literature were used in the development and validation of the WEPP-SLIP modelling approach.

WEPP-SLIP model formulation

A schematic diagram of the WEPP-SLIP modelling framework incorporating a soil armouring component is presented in Fig. 3. Model inputs are pre- and post-failure topography, soil properties, vegetation cover, and climate data. The WEPP-SLIP modelling framework combines the WEPP hillslope model, a slope stability model, a simple soil redistribution model, and a proposed simulation of soil armouring processes.

Predictions of pre-failure soil erosion and runoff are given by WEPP using the original hillslope topography. WEPP was selected for simulating soil erosion events because it is a well-established physically-based soil erosion model that has been widely used and validated for hillslope simulations. WEPP is able to simulate erosion and deposition processes along a hillslope in complex topography as well as to simulate final sediment delivery to channels. Laflen *et al.* (2004), for example, report on an extensive literature review of studies comparing observed soil loss to WEPP model predictions, and conclude that WEPP is well-suited for a wide range of soil erosion predictions. In a study using sixteen-hundred plot years of natural runoff plot data, it was found that WEPP performed as nearly well as empirical models (USLE and RUSLE) without calibration of any parameters (Tiwari *et al.*, 2000). WEPP, however, required further validation for simulations in steep hillslopes, which are presented here using the flume experiments. WEPP was applied using parameters from measured soil properties and the same soil depth as the flume experiments, including representing an impervious soil layer for the bottom of the flume. The observed initial soil water content in the flume was used to set the WEPP initial soil water content parameter and the hydraulic

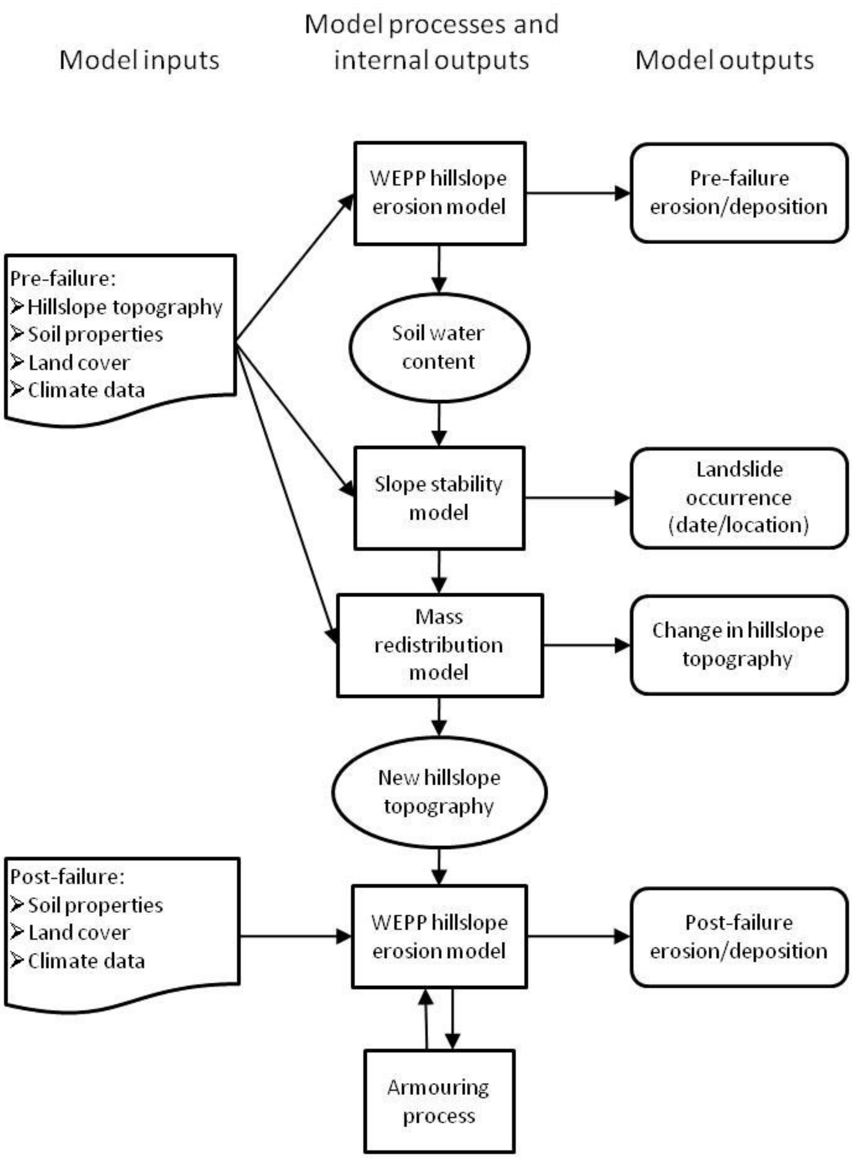

Figure 3 – Integrated hillslope modelling of shallow landslides, erosion, and armouring processes (modified from Cochrane and Acharya, 2009).

conductivity was adjusted to represent the WEPP-required "effective" hydraulic conductivity. Rill and inter-rill erosion were simulated under constant rainfall for the experiment period.

For slope failure, an infinite slope method was used which assumes that shallow landslides occur along a soil profile resulting from the interaction between two major opposing forces: the resistance of soil to shearing (shear strength) and shear stresses, which act to shear the soil along a potential failure plane. The ratio of this relationship is expressed as a factor of safety, F. The factor of safety can be calculated using an equation by Skempton and DeLory (1957), as described in greater detail by Cochrane and Acharya (2009). A slope with a value of F less than 1.5 is categorized as an unstable slope (Montgomery and Dietrich, 1994).

To determine the changes in hillslope topography following a predicted landslide event, a mass redistribution model consisting of a set of simple rules was used. Runout distance, failure depth (which in our experiments were the full soil depth), and final runout slope were estimated, as presented in Acharya *et al.* (2011).

WEPP was then run again using the new hillslope topography to predict post-failure soil erosion. The soil armouring process was added to account for changes in soil properties and cover resulting from the failure event by changing soil erodibility or rock cover in multiple subsequent simulations using WEPP. The success of the model was tested by comparing the observed and predicted values. For example, the measured runoff was compared with the WEPP predicted runoff for both pre- and post-failure cases. Total measured sediment yields were compared with the WEPP predicted sediment yields for the experiment duration. A factor of safety value, in response to pore pressure measurements from a pore pressure transducer, was calculated. The factor of safety at the time of peak pore pressure was compared with the observed landslides. Runout distances were computed using the empirical equation described in Acharya *et al.* (2011) and compared with the modelled values.

Table 3 – Summary of measured and modelled soil loss.

Exp	Measured soil loss (kg m^{-2})	WEPP soil loss (kg m^{-2})	Measured mean runoff (l min^{-1})	WEPP mean runoff (l min^{-1})
E1	4.68	4.70	0.278	0.303
E2	5.03	4.92	0.311	0.332
E3	5.02	4.83	0.308	0.322
E4	5.24	5.13	0.340	0.316
E5	12.57	14.94	0.630	0.699
E6	12.85	15.77	0.657	0.711

Results and discussion

Steep slope erosion validation

The soil erosion simulation component of WEPP-SLIP was validated with experiments E1–E6 for steep slopes (Table 3) because these simulations did not result in any landslides. Results of experiments E1–E4 showed a good correlation between measured and WEPP simulations of both sediment loss and runoff (below 4% and 9% variation respectively). However, under the high intensity rainfall of 40 mm h^{-1} (experiments E5 and E6) WEPP predicted up to 18.5% higher soil loss than the measured values. This significant difference is attributed to the armouring process, which is not accounted for in the WEPP simulations, but which occurred on the bare soil over the eight-hour rainfall. The difference between simulated and measured soil loss can be reduced if the process of armouring is considered, as discussed later in the paper.

Failure and mass redistribution

Failure and soil redistribution for experiments E7–E10 that resulted in shallow landslides were compared against the WEPP-SLIP predictions. The factor of safety values for landsliding calculated using the infinite slope method ranged from 1.29 to 0.74 and gave clear indications that shallow landslides would occur in these experiments. As expected, the location of failure was at the intersection of the slopes, where the model predicts the highest pore pressure. Predicted runout distances, however, were on average 38% smaller than the measured values, with measured values in metres ranging from 0.44 to 1.45 and predicted values ranging from 0.36 to 1.24. The under-prediction can be attributed to the continuous rainfall during the experiment, which triggered not just one landslide, but in some cases multiple retrogressions of the slide. The empirical equation could be adjusted to improve predictions for this case. As expected, for these experiments the failure depth was equal to the soil profile depth for all cases. The bottom section of the failure slope (final runout slope) was between 12° and 13° for all experiments regardless of soil type. The angle of the upper section of the failure slope was between 25° and 27° for loess soils and 23° for sandy soils, which is comparable to values reported in the literature (e.g., Johnson *et al.*, 2000). Although the overall predictions seem to coincide with observed results, further improvements in how landslides and mass movements are predicted are warranted. Further details on the validation of failure and soil redistribution of these experiments and others can be found in Acharya *et al.* (2009) for sandy soils, and Cochrane and Acharya (2009) and Acharya *et al.* (2011) for loess soils.

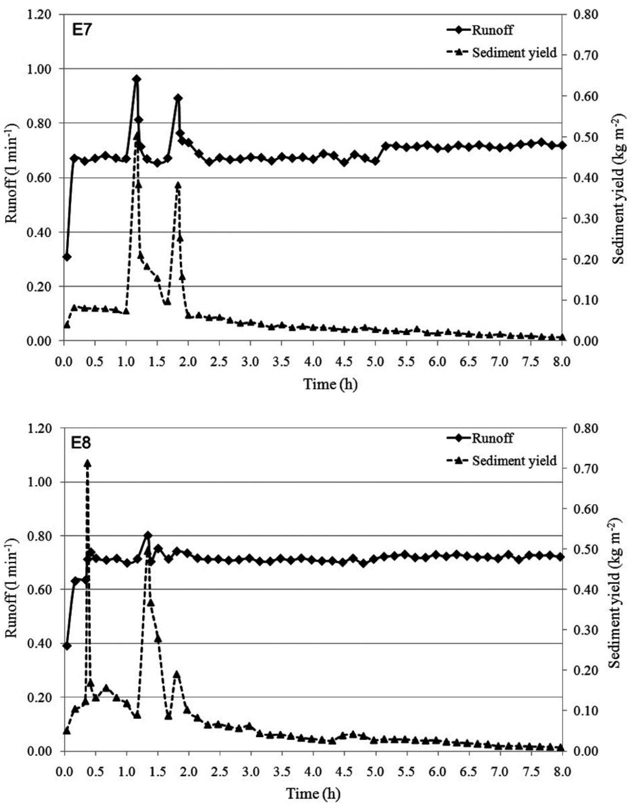

Figure 4 – Measured sediment yield (kg m^{-2}) and runoff (l min^{-1}) from experiments E7 and E8 sampled every 10 minutes for the entire experiment duration (8 h) showing periods of significant sediment yield related to shallow landslide events.

Landslide-driven sediment yields

Sediment yields during landslides were high for all experiments. Sharp increases in measured sediment yields (Fig. 4) were directly related to landsliding occurring in E7 and E8. The initial landslide resulted in up to a 10-fold increase in sediment yields, whereas subsequent landslides, which occurred further from the outlet, resulted in lower sediment yields. Similar results were obtained for sediment yields during landslides in sandy soils.

Post-failure sediment delivery

Changes in topography make post-failure sediment delivery lower than pre-failure delivery because of changes in the slope gradient of the soil profile. Post-failure validation of the WEPP-SLIP model was done using E7–E10 (Table 4). To determine the relative importance of the

Table 4 – Summary of measured and modelled soil loss in the post-failure phase over approximately 6 hours following the last landslide.

Exp	Measured soil loss (kg m^{-2})	WEPP soil loss (kg m^{-2})	% difference in soil loss	Measured runoff (l min^{-1})	WEPP runoff (l min^{-1})	% difference in runoff
E7	9.54	10.22	6.65	0.636	0.694	8.36
E8	9.81	10.55	7.01	0.690	0.717	3.77
E9	0.032	0.059	45.76	0.656	0.715	8.25
E10	0.031	0.048	35.42	0.640	0.697	8.18

armouring phenomenon, WEPP-predicted values without simulating armouring were compared against measured soil loss for the loess soil experiments after landslides. The values were within 7%, indicating that the effect of armouring in this case seems to be minimal, due to a post-failure reduction in slope. Steeper slopes tend to increase armouring rates, as smaller particles are more readily washed off. However, values for measured soil loss in sandy soils were up to 45% lower than WEPP-simulated values without simulating armouring. Lower values of measured soil loss were attributed to post-failure soil armouring in the lower slope, particularly for the sandy soils. These results indicate that armouring is also clearly dependent on soil type. Predicted runoff was up to 8.36% higher than measured runoff for all experiments.

Soil armouring

The soil armouring process was quantified for both loess and sandy soils by observing changes in sediment yields over time and by measuring the resulting particle size distribution of the soils and runoff. Observed runoff and sediment yields in experiments E1 and E5, where landslides did not occur, are compared in Fig. 5. Steady runoff rates were observed in both experiments, however, sediment

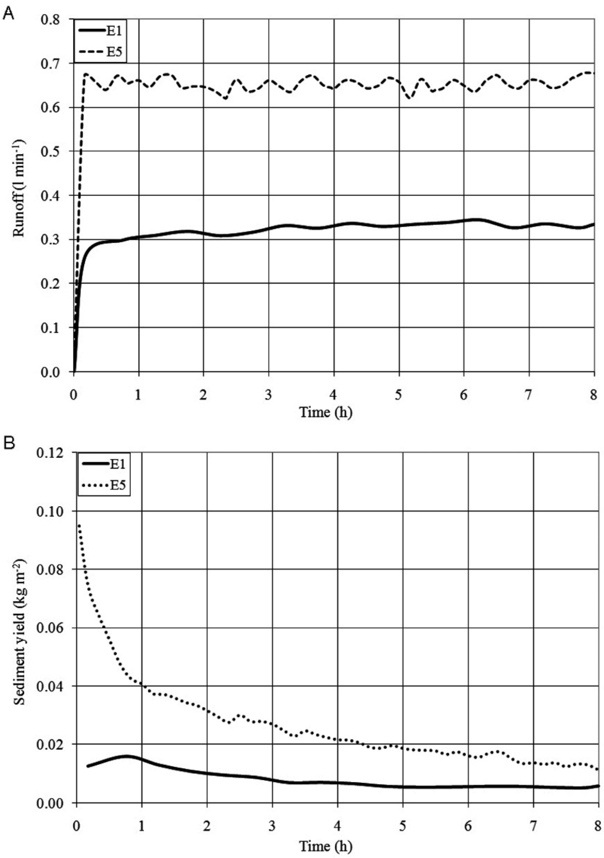

Figure 5 – Measured runoff (A) and sediment yields (B) for experiments E1 and E5 over 8 hours for 20 and 40 mm h^{-1} rainfall respectively.

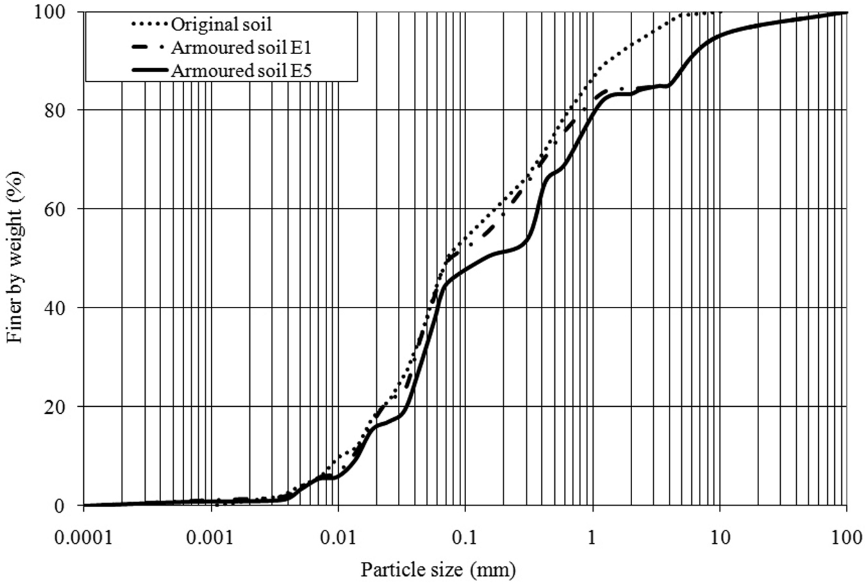

Figure 6 – Comparison of particle size distribution of original loess soils before experiments and particle size distribution of armoured soil close to the outlet of the flume in experiments E1 and E5.

yield rates decreased gradually over time. The reduction of sediment yield rates is attributed to armouring of the soil surface as a result of selective removal of finer transportable materials by rainsplash and overland flow. The average rates of decrease in sediment yields were about 0.002 and 0.009 kg m^{-2} h^{-1} in E1 and E5 respectively, with a significant decrease in yields for E5 in the first hour. Based on these results, it was inferred that rainfall intensity strongly influenced the soil armouring rate; the experiment with higher intensity rainfall resulted in quicker armouring due to increased runoff and sediment loss rate. Similar results were obtained for the sandy soil.

A comparison of particle size distribution from the original soil and soil samples from the top 10 mm of the soil collected immediately after each experiment from close to the outlet of the flume is shown in Fig, 6. A summary of the comparison of mean particle size betweenthe original and armoured soil is shown in Table 5. The mean particle size (D_{50}) in experiment E5 under high rainfall intensity was 0.142 mm. This was significantly larger median particle size than the original soil, which had a D_{50} of 0.075 mm, and E1 which had a D_{50} of 0.082 mm.

The particle size distribution of the runoff sample from E5 was compared with the original

Table 5 – Comparison of median particle size between original and armoured soil.

Exp	Soil	Rainfall ($mm\ h^{-1}$)	Flume slope (°)		Median particle size (D_{50}) (mm)	
			Upper	Lower	Original	Armoured
E1	Loess	20	35	10	0.075	0.082
E5	Loess	40	35	10	0.075	0.142
E9	Sand	40	30	10	0.57	1.36

soil material. Results showed that although the mean particle size of the sediment in runoff (D_{50} = 0.082 mm) did not significantly differ from the original soil (D_{50} = 0.075 mm), the range of eroded particle sizes was different and the largest particle in the runoff was about 0.8 mm, which is significantly smaller than that of the original material (Fig. 7). Similar results were obtained for the other experiments.

Modelling changes in cover and armouring

The experimental simulations using the flume were conducted without vegetation. Vegetation, however, can have a significant effect on sediment delivery. Using our proposed WEPP-SLIP modelling framework, we analysed and compared pre- and post-failure soil loss and runoff under bare soil, grass cover (w/sheep grazing), and regeneration of grass after failure for experiments E7 and E8 (Table 6). The simulation was conducted over a single year and the grass regeneration was simulated using growth rates typical of Canterbury. The hillslope erosion component (WEPP) was run on a daily continuous simulation mode, with a total annual precipitation of 857 mm for all simulations. Results clearly show that post-failure soil loss is lower than pre-failure soil loss for bare soil (no cover) on the hillslope. However, if the failure occurs in hillslopes with grass cover, pre-failure soil loss would be significantly less than post-failure loss, because failure of the slope would imply that the grass cover would be lost and therefore have to regenerate over time. For our example simulations when armouring is not considered, pre-failure soil loss on grass-covered hillslopes would be only 0.02 kg m^{-2}, compared to a post-failure situation where grass had to regenerate over time, yielding 0.300 kg m^{-2}. When armouring for these types of soils is considered, there is a reduction in soil loss over time.

WEPP can be adapted to simulate soil armouring by changing the soil erodibility parameter over time. For our example, we chose to change only the inter-rill erodibility

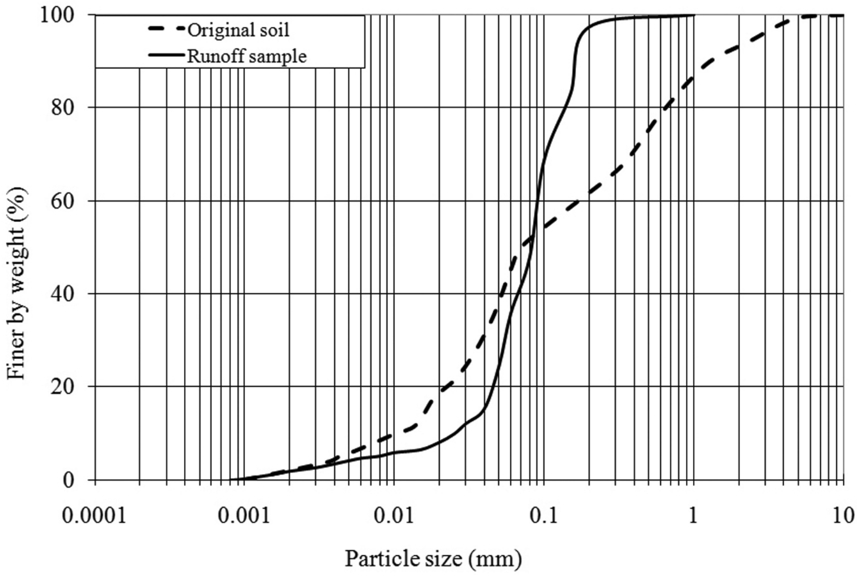

Figure 7 – Particle size distribution of original soil versus a typical runoff sample collected after 8 hours of rainfall during experiment E5.

Table 6 – WEPP-SLIP simulated pre and post-failure annual soil loss and runoff as impacted by landcover.

Exp.	Topography	Landcover	Annual soil loss without armouring (kg m^{-2})	Annual runoff (mm)
E7	Pre failure	none	0.452	167.45
E7	Post failure	none	0.386	170.53
E7	Pre failure	Grass (w/ sheep grazing)	0.020	34.23
E7	Post failure	Grass regeneration	0.300	109.19
E8	Pre failure	none	0.455	166.50
E8	Post failure	none	0.387	172.21
E8	Pre failure	Grass (w/ sheep grazing)	0.020	33.70
E8	Post failure	Grass regeneration	0.302	111.65

from a value of 3.0e+06 to 2.79e+06 kg s m^{-4} to account for a 7% reduction in erodibility for this type of soil before vegetation is re-established. By doing this, we have assumed that this type of soil is less prone to the armouring that occurs in rills. Modelling results indicate that there would be an annual post-failure soil loss of 0.279 and 0.281 kg m^{-2} for E7 and E8 respectively with combined grass regeneration and armouring, which also represents an overall reduction in annual soil loss of about 7%.

Although this preliminary research shows that the soil armouring can be a significant component leading to changes in soil erodibility, relationships are still needed to quantify the armouring process as a function of rainfall intensity, duration, slope, soil types, and rill and inter-rill erosion erodibility over time.

Conclusions

Results from flume-based experimental studies show that water-induced shallow landslides and armouring processes can significantly affect sediment delivery from the hillslope profile. During shallow landslide events, sediment yields from the flume increased up to 10-fold. Post-failure topography resulted in changes in slope gradient that resulted in lower erosion after the failure. Armouring was observed in both loess and sandy soils, but had a significantly larger impact on sandy soils, where reductions of up to 45% in soil loss occurred over a 6-hour period after the last landslide. The WEPP-SLIP model was proposed as a tool for quantifying pre- and post-failure soil erosion on hillslopes, which would account for both of these processes. The armouring component, however, needs development and validation with a range of soil types and conditions. Applications of the WEPP-SLIP model on a hillslope with no vegetation cover show that shallow landslides may cause a reduction in soil erosion because the changes in topography result in a reduced slope gradient. In grass-covered hillslopes, post-failure soil erosion is significantly greater until vegetation is re-established, however the armouring process will reduce the sediment yield over time. Preliminary application of the WEPP-SLIP modelling framework with flume-based experiments were encouraging, but further improvements in modelling shallow landslides, soil redistribution, and soil armouring processes are necessary to better quantify interactions with different soil types, cover, and rainfall.

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