Sediment Erosion and Transport Experiments in Laboratory using Artificial Rainfall Simulator

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ABSTRACT: Catchments soil erosion, one of the most serious problems in the mountainous environment of the world, consists of a complex phenomenon involving the detachment of individual soil particles from the soil mass and their transport, storage and overland flow of rainfall, and infiltration. Sediment size distribution during erosion processes appear to depend on many factors such as rainfall characteristics, vegetation cover, hydraulic flow, soil properties and slope. This study involved laboratory flume experiments carried out under simulated rainfall in a 3.0 m long × 0.8 m wide × 0.7 m deep flume, set at 17° slope. Five experimental cases, consisting of twelve experiments using three different sediments with two different rainfall conditions, are reported. The experiments consisted of detailed observations of particle size distribution of the out-flow sediment. Sediment water mixture out-flow hydrograph and sediment mass out-flow rate over time, moisture profiles at different points within the soil domain, and seepage outflow were also reported. Moisture profiles, seepage outflow, and movement of overland flow were clearly found to be controlled by water retention function and hydraulic function of the soil. The difference of grain size distribution of original soil bed and the out-flow sediment was found to be insignificant in the cases of uniform sediment used experiments. However, in the cases of non-uniform sediment used experiments the outflow sediment was found to be coarser than the original soil domain. The results indicated that the sediment transport mechanism is the combination of particle segregation, suspension/saltation and rolling along the travel distance.

Keywords: Flume experiment, Simulated rainfall, Water retention function, Soil erosion, Sediment transport, Particle segregation

1. Introduction

Catchments soil erosion, one of the most serious problems in the mountainous environment of the world, consists of a complex phenomenon involving the detachment of individual soil particles from the soil mass and their transport, storage and overland flow of rainfall, and infiltration. Changes in land use and climate can act as triggers for soil erosion and catchment sediment yield (Wick & Bathurst 1996). Soil erosion is closely related to rainfall partly through detaching power of raindrops hitting the soil surface and partly through contribution of rain to runoff (Morgan, 2005). This applies particularly to erosion by overland flow and rills, for which intensity is generally considered to be the most important rainfall characteristic.

Sediment transport comprises the movement of sediment particles due to the combination of the gravity force, that acting on the sediment, and the overland flow in which the sediment is entrained. When sufficient energy is no longer available to transport, deposition takes place. In many studies (Rose, 1993; Haan et al., 1994), the sediment generation, transport and deposition process have been described well. Depletion of soil is caused by detachment and re-detachment by raindrops, and entrainment and re-entrainment by overland flow, accompanied by transport in sheet and rill flow (Rose, 1993). Rill erosion occurs when water moving over the soil surface flows along preferential pathways forming an easily recognizable channels (Rose, 1993). Rill initiation is controlled by the cohesive strength of the soil and the shear forces exerted on the soil. Flow in rills acts as a transporting agent for the removal of sediment downslope from rill and inter-rill sources, although if the shear stress in the rill is high enough the rill flow may also detach significant amounts of soil (Nearing et al., 1994). In contrast to rill erosion, gully erosion describes channels of concentrated flow that are too deep (Rose, 1993). The raindrop impact in gully flow is not an important factor in terms of flow resistance or in sediment particle detachment as in that of sheet and rill flows (Bennett, 1974).
Once runoff starts over the surface areas and in the streams, the quantity and size of material transported increases with the velocity of the runoff. The slope may decrease at some point, resulting in a decreased velocity and hence a decreased transport capacity (Haan et al., 1994). The sediment is then deposited, starting with the large primary particles and aggregates. Smaller particles are transported further down-slope, resulting in the enrichment of fines. The basic relationship describing sediment transport by overland flow is the sediment continuity equation, which relates the change in sediment storage over time, and the change in sediment flow rate along the hillslope to effective sources and sinks (Haan et al., 1994). Increased slope length and steepness produces higher overland flow velocities and correspondingly higher erosion (Haan et al., 1994).

The amount of sediment transport can be quantified using numerous available methods, in which the required data can be collected through field and laboratory experimental studies. Therefore, most of the scientific research has been conducted based on field and laboratory experiments.

Rainfall simulators have been extensively used in the laboratory and field experimental soil erosion and sediment transport researches. By using rainfall simulator, Kilinc & Richardson (1973) evaluated the mechanism of soil erosion and concluded that slope and rainfall intensity had significant impact on soil erosion and sediment transport. Wischmeier & Smith (1978) and Govers (1991) noted an exponential relationship between the soil loss and slope gradient. Berger et al. (2010) reported that increasing rainfall intensity had larger effect on sediment yield than increasing slope. Hansen et al. (1999); Kamphorst et al. (2000) and Planchon et al. (2001) examined the impact of surface roughness on overland flow. It was determined that a higher degree of soil surface roughness enhances the infiltration rate of water through the soil surface and reduces overland flow, which in turn reduces the erosive capacity of runoff (Onstad, 1984; Huang & Bradford, 1990; Hairsine et al., 1992). Poessen & Ingelmo-Sanchez (1992) observed that sediment yield increased with surface flow while performing experiments by using a laboratory simulator spraying rainfall over different size of stones embedded into the soil.

Meyer et al. (1983) conducted a series of experiments to measure transport capacity of flow with combinations of different topographical slopes, flow rates, and sediment particle sizes; and found that the flow rate also affected sediment transport, although not so greatly as gradient. Sediment transport was increased as particle size decreased, but there was minor effect of rainfall on sediment transport capacity. Govers (1990) carried out a series of experiments on different slopes and flow rates to examine sediment transport capacity of overland flow; and it has been shown the possibility to predict sediment transport capacity using simple empirical relationships, which show considerable variation with grain size, but not with flow regime. Nearing et al. (1997) conducted experiments to investigate rill erosion as a function of slope gradient and flow rate. Stream power was found to be a consistent and appropriate predictor in calculating unit sediment load. Besides, Ali et al. (2012) examined the influence of flow rate, mean flow velocity, flow depth, and bed slope on sediment transport capacity, and obtained strong relationships between sediment transport capacity and unit stream power and effective stream power.

Sediment size distributions appear to depend on many factors such as rainfall characteristics, vegetation cover, hydraulic flow, soil properties and slope. Most of the researchers agreed that sediment leaving an area is finer than that of the soil under surface erosion; and the sediment transport mechanism is the combination of suspension/saltation and rolling. However, in this regard, there are still some conflicting and unexplained results. Many studies in the past were lacking to incorporate the interactions among catchment position, surface and subsurface hydrologic conditions, and erosion process. This paper presents the experiment results of laboratory flume based soil erosion due to rainfall carried out at two different rainfall intensities, using three different sediments. The experiments consisted of detailed observations of particle size distribution of the outflow sediment. Sediment water mixture outflow hydrograph and sediment mass outflow rate over time, moisture profiles at different points within the soil domain, and seepage outflow were also reported. This study investigated the soil erosion and sediment transport mechanisms based on direct observation during erosion and transport process, and the particle size distribution of the outflow sediment.

### 2. Experimental Method

This study involved laboratory flume experiments carried
out under simulated rainfall in a 3.0 m long × 0.8 m wide × 0.7 m deep flume. The flume was set at 17° slope by the chain pulley arrangement that was provided to adjust its longitudinal inclination. A rainfall simulator was set up above the flume to provide artificial rainfall. At the downstream end, the soil was supported by a wooden plate. To drain-out subsurface flow, 2.0 cm opening space was provided between the plate and the flume end. A filter mat supported by the wooden plate was used to retain the soil against the opening space. The schematic diagram of the flume including instrumentation and data acquisition system is shown in Fig. 1.

Three profile probes (PRs) were used to measure the temporal variation of moisture content at different locations inside the soil domain. The probe was profile probe type PR2 that consists of four sensors (SRs) in 10 cm spacing. Load cell, model KYOWA LT-50KG, was used to measure outflow sediment load. Servo type water gauge (Detector, KENEK NST-10) was used to obtain outflow sediment-water mixture, by measuring the increase in water level of the downstream container. For the purpose of getting temporal change in grain size distribution of the eroded sediment, 0.40 m × 0.30 m × 0.08 m sized sampler boxes were used to collect the out-flow sediment. At the downstream end of the flume a measuring cylinder was used to collect the seepage outflow through a drain pan. Two digital video cameras (VCs) were used to capture the erosion-deposition activities and seepage outflow. The shape and size of the soil domain with the arrangement of SRs is shown in Fig. 2.

A space was allowed in the 1.0 m upstream reach of the flume (Fig. 1) for providing runoff input essential for the development of surface erosion. The soil surface at 1.04 m downstream reach (sloping face of the soil domain) was made parallel to the flume slope. To bury at least two sensors of the profile probes in this reach, its upper limit thickness was designed to 30 cm (Fig. 2). The remaining 0.98 m upstream reach of the soil domain was longitudinally flat (horizontal length = 102.48 cm). Twelve experiments were carried out using different sediments with initially dry condition. The experimental program is outlined in Table 1. The sediment was placed on the rigid bed of the flume and compacted uniformly in layers of approximately 5 cm thick with a steel hand. The grain size distribution of the sediments is presented in Fig. 3. Fig. 4 shows the water retention curve of these sediments. Water retention data for the sediments used in the experiments was obtained through DIK-3423 Multi-Fold pF Meter. van Genuchten parameters (including residual moisture) were estimated by non-linear regression analysis of water retention data obtained by pF meter experiments. The saturated hydraulic conductivity of the considered sediments was measured through DIK-4012 Permeameter, 4 Fold Type, by the method of constant head. Some parameter values of the sediments used in the experiments are listed in Table 2.
Table 1. Experimental program

| Exp. Case | Exp. No. | Sediment | Initial condition | Pump supply | Avg. rainfall inside flume | Rainfall duration | Observation                      |
|-----------|----------|----------|-------------------|-------------|---------------------------|------------------|----------------------------------|
| 1         | 1        | S7       | Dry               | 98 ltrs/min | 93.06 mm/hr               | 39.50 min        | Erosion-deposition and water-sediment outflow |
|           | 2        |          |                   |             |                           |                  | Moisture profile and seepage discharge            |
| 2         | 3        | S7       | Dry               | 98 ltrs/min | 93.06 mm/hr               | 31.00 min        | Erosion-deposition and water-sediment outflow |
|           | 4        |          |                   |             |                           |                  | Moisture profile and seepage discharge            |
| 3         | 5        | Smix1-6  | Dry               | 98 ltrs/min | 93.06 mm/hr               | 55.00 min        | Erosion-deposition and water-sediment outflow |
|           | 6        |          |                   |             |                           |                  | Moisture profile and seepage discharge            |
| 4         | 7        | Smix4-7  | Dry               | 98 ltrs/min | 93.06 mm/hr               | 26.00 min        | Erosion-deposition and water-sediment outflow |
|           | 8        |          |                   |             |                           |                  | Moisture profile and seepage discharge            |
|           | 11       |          |                   |             |                           |                  | Temporal change in grain size distribution of out-flow sediment |
| 5         | 9        | Smix4-7  | Dry               | 60 ltrs/min | 67.47 mm/hr               | 26.25 min        | Erosion-deposition and water-sediment out-flow   |
|           | 10       |          |                   |             |                           |                  | Moisture profile and seepage discharge            |
|           | 12       |          |                   |             |                           |                  | Temporal change in grain size distribution of out-flow sediment |

S7 = Silica sand number 7, Smix1-6 = Silica sand number 1 to 6 are mixed in equal proportion by volume, Smix4-7 = Silica sand number 4 to 7 are mixed in equal proportion by volume.

In the experiments for case-1, the designed soil surface was horizontal in lateral direction. However, using initially dry sediment, it was practically difficult to make the soil surface perfectly smooth as per the design. Hence surface water flow path, initially from the head reach, was not observed identical in both the experiments for this experimental case.
Therefore, in other experimental cases it was designed to v-shape in lateral direction (Fig. 2) to achieve the identical surface water flow path through channelizing the flow towards v-notch initially from the head reach. The experiments were conducted using two rainfall conditions (98 and 60 liters/minute discharges from water supply pump). For these supply conditions, the rainfall intensity inside the flume was measured by using 21 bucks having opening diameter 20.75 cm. During these rainfall measurements, the flume was aligned perfectly horizontal. The measured average rainfall inside the flume was 93.06 mm/hr and 67.47 mm/hr in 98 and 60 liters per minute supply pump discharge, respectively. Figs. 5 and 6 show the arrangement of buckets inside the flume and a contour maps showing rainfall distribution over it for each rainfall condition, respectively.

Rainfall simulators are devices to duplicate the physical characteristics of natural rainfall. The primary purpose of the layout of nozzle of rainfall simulator and pumping system is to simulate natural rainfall accurately and precisely. Desirable characteristics for rainfall simulators used in erosion and hydrological studies include the rainfall intensity, spatial rainfall uniformity over the entire test plot, the drop size, its distribution and terminal velocity (Aksoy et al., 2012). Therefore, the layout of nozzles of the rainfall simulator and pumping

### Table 2. Some parameter values of the sediments considered

| Parameters                           | S7    | Smix1-6 | Smix4-7 |
|--------------------------------------|-------|---------|---------|
| Saturated moisture content, $\theta_s$ | 0.42  | 0.276   | 0.325   |
| Residual moisture content, $\theta_r$  | 0.038 | 0.022   | 0.027   |
| van Genuchten parameter, $\alpha$     | 1.86  | 9.56    | 3.54    |
| van Genuchten parameter, $\eta$       | 4.82  | 2.73    | 2.98    |
| Saturated hydraulic conductivity, $K_s$ (cm/sec) | 0.00872 | 0.0278 | 0.01075 |
| Mean grain size, $D_{50}$ (mm)        | 0.182 | 1.113   | 0.284   |
| Porosity, $n$                        | 0.42  | 0.276   | 0.325   |
system should be carefully considered to get equal energy and amount of rainfall over the test bed, otherwise, the results are biased to specific area, where received more rainfall comparing to other part of the test bed. However, in this study, the distribution of rainfall is not uniform (Fig. 6). The experiments were conducted in the Ujigawa Open Laboratory, Kyoto University, Japan, where the rainfall generation system was already fixed permanently.

3. Results and Discussions

Besides the climatic factors, the soil factors such as soil water content and matric potential relationship ($\theta - h$), hydraulic conductivity and water content relationship ($K - \theta$), saturated hydraulic conductivity ($K_s$), and porosity ($n$); are the controlling factors of the soil water movements in the unsaturated zone. The surface runoff and infiltration phenomena of a particular soil, due to a rainfall event, are directly connected to the physics of the soil water movement of that particular soil. The water retention function and hydraulic conductivity function proposed by van Genuchten (1980) are respectively as follows.

$$S_e = \frac{(\theta - \theta_r)/\theta_s - \theta_r}{\theta_s - \theta_r} = \left[ 1 + (\alpha |h|)^\eta \right]^{-m} \quad \text{for } h < 0$$

$$= 1 \quad \text{for } h \geq 0$$

(1)

$$K = K_s S_e^{1/2} \left[ 1 + \left( 1 - S_e^{1/m} \right) \right]^{2}$$

(2)

where $S_e$ is the effective saturation; $\alpha$ and $\eta$ are empirical parameters; $\theta_s$ and $\theta_r$ are saturated and residual moisture content, respectively; and $m = 1 - 1/\eta$.

The value of $n$ for the sediments Smix1-6 (case-3), Smix4-7 (case-4 and 5) and S7 (case-1 and 2) are 0.276, 0.325 and 0.42; respectively. Similarly, the value of $K_s$ for these sediments are 0.0278, 0.01075 and 0.00872 cm/sec; respectively. Higher the value of $K_s$, faster the soil water movement. Soil water movement was faster in coarser sediment soil domain and high rainfall condition (Table 1, and Figs. 3 and 7). This phenomenon was also directly reflected to the seepage outflow (Fig. 8). In each sensor (SR) of PRs, moisture increase rate due to the wetting front contributed only by the rainfall intensity above it was comparatively slow before reaching the sharp wetting front through lateral inflow from upstream overland flow (Fig. 7). In case of sensors 1, 5 and 9 for all the experimental cases, sharp wetting front through lateral inflow reached prior to the wetting front through rainfall intensity above it so that sudden raise of moisture from its initial value was observed.

Even though, the seepage water flow in case-3 was faster than case-4; and case-4 was faster than case-2 (these cases have same geometry and rain fall intensity), the movement of fore-front of the overland flow in case-2 was slower than
Fig. 7. Moisture content profiles

others, before passing the ridge line (Table 3 and Fig. 9). Even its movement is slower than case-4, after passing the ridge line. However, the movement of fore-front of the overland flow in case-4 was faster than case-3 (before and after passing the ridge line). Also being the same geometry in case-5, rainfall intensity was smaller than others. But, the movement of fore-front of the overland flow in case-2 was even delayed than case-5. The moisture retention capacity of S7 is higher than Smix1-6 and Smix4-7 (Fig. 4). Smix4-7 has also moisture retention capacity higher than Smix1-6, but the difference is not so much in comparison to S7. Therefore, the movement of fore-front of the overland flow in case-2 was slower. The timing of seepage out-flow initiations for all the cases were delayed than the initiation of out-flow of the overland flow. In experimental case-3, the overland flow was totally ceased to infiltration before reaching the downstream end (Table 3 and Fig. 9).

The bed of the fore-front of the overland flow was unsaturated in each experiment. Therefore, its movement was observed intermittent nature in each. After the bed being saturated (fulfilled the full retention capacity within the soil domain), in these experimental cases, the movement of overland flow in case-2 should be faster than other two cases. And, the movement of overland flow in case-4 should be much faster than case-3, even it was faster before reaching the full retention capacity. The effect of the rate of movement of overland flow was directly reflected to the SRs closer to the soil surface, SR6 and SR10 (Figs. 7 (c) and 7 (e)). At these sensors, increase in moisture was earlier in case-4 than case-3; and in case-2 it was comparatively closer to case-3. However, for SR1, SR5 and SR9, which are closer to the flume bottom, increase in moisture was earlier in case-3 than other cases (Figs. 7 (a),
Table 3. Results summary

| Case | Sediment | Rainfall Intensity (mm/hr) | Seepage outflow start time (second) | Time to approach overland flow | D₅₀ (mm) |
|------|----------|---------------------------|-----------------------------------|-------------------------------|----------|
|      |          |                           |                                   | Ridge (second)                | Outlet (second) | Original soil domain | Outflow sediment |
| 1    | S7       | 93.06                     | 2,340                             |                                | 1,285                | 1,845                | 0.182           | 0.185 |
| 2    | S7       | 93.06                     | 1,500                             |                                | 820                  | 1,370                | 0.182           | 0.184 |
| 3    | Smix1-6  | 93.06                     | 960                               |                                | 671                  | 930                  | 0.284           | 0.335 |
| 4    | Smix4-7  | 93.06                     | 1,200                             |                                | 466                  | 1,020                | 0.284           | 0.350 |
| 5    | Smix4-7  | 67.47                     | 1,500                             |                                | 526                  | -                   | -               | -     |

Fig. 8. Seepage outflow (cm³/sec)

Fig. 9. Observed time to approach ridge line and outlet point by the overland flow

Fig. 10. Sediment water mixture outflow hydrograph

Fig. 11. Sediment mass flow rate over time

7 (b) and 7 (d)).

Water-sediment mixture out-flow hydrographs and sediment mass out-flow rates over time are presented in Figs. 10 and 11, respectively. Fig. 12 shows the soil domain sloping face pictures observed at different time during surface erosion/deposition caused by overland flow. Pictures snapped towards upstream and downstream reach after the rainfall in experiment number 8 was shown in Fig. 13. Fig. 14 presents the pictures of soil domain after each experiment. Runoff contributed from upstream of the sloping face induced minor rills and a major gully was observed in the experiments (Fig. 14). Since the overland flow for case-3 was totally ceased to infiltration before reaching the downstream end, no out-flow hydrograph was observed in this experimental case (Fig. 10). So, there was minor surface erosion and deposition in comparison to other cases (Figs. 12 (c) and 14 (c)). Fig. 15 compares the grain size distribution of the out-flow sediment with the original soil domain. In the experimental case-1 and case-2, the difference of grain sizes of original soil bed and the out-flow sediment was insignificant. But in the case of case-4 and case-5, the outflow sediment was observed coarser than the original soil bed. To see the temporal change in grain size distribution of the out-flow sediment, in case-4 and
Fig. 12. Pictures showing soil domain sloping face observed at different time during surface erosion/deposition caused by overland flow (contd.)
case-5, one more experiments were performed in each case (Table 1). The comparison of temporal change in grain size distribution of the out-flow sediment and the grain size distribution of the original soil domain, for the experimental cases 4 and 5, are presented in Fig. 16 and Fig. 17, respectively.
There is common view among most of the researchers that sediment leaving an area is finer than that of the soil under surface erosion; and the sediment transport mechanism is the combination of suspension/saltation and rolling. However, in this study the out-flow sediment was not finer than that of the original soil domain, in the cases of non-uniform sediment.

Fig. 14. Pictures showing soil domains observed after erosion/deposition
used experiments. For these cases in the intermittent nature of out-flow, the grain size distribution was much coarser, resulting from particle segregation along the travel distance. Besides the intermittent nature of the out flow, the sediment transport mechanism was the combination of suspension/saltation and rolling.

In experimental case-4 and case-5, the outflow sediment was observed coarser than the original soil bed (Fig. 15). In the intermittent nature of out-flow, before 1,105 sec in case-4 and before 1,155 sec in case-5 (Fig. 10), the grain size distribution was observed much coarser (Figs. 16 and 17). In the case of case-1 and case-2 (the sediment of the soil bed was uniform), the difference of grain sizes of original soil bed and the out-flow sediment was insignificant (Fig. 15). Takahashi (1980), in his study for the case of stony type of debris flow, emphasized the particle segregation concept. If the gradient of the bed is steeper (>15°), a bore of sediment-water mix flow is formed due to the sudden supply of water from the upstream. In the flowing layer of such a mixed flow, larger particles move upward. As the upper layer velocity is faster than lower layer, larger particles moved upward are also transported upward, faster than the progressive velocity of the forefront. On reaching the fore-front these particles tumble down the bed and are buried in the following flow. But, soon after that, the buried particles are larger than the surrounding particles. It appears again on the top of the flow and moves ahead. Repeating such processes, result in particle segregation along the travel distance.

In the present study, the soil bed gradient downstream of ridge (i.e., sloping face) was also steeper (17°). While passing the overland flow from ridge to its downstream, there was sudden flow of water, and the experimental observations were also looked consistent to the particle segregation phenomena as explained by Takahashi (1980). Thus, the outflow sediment was observed coarser than the original soil bed (Case-4 and Case-5). Channel towards the downstream end, the deposited sediments in either banks and inside it were also observed coarser than the original soil bed (Fig. 13 (b)). Channel towards the upstream end (before ridge line), the observed deposited sediments were somehow finer than the original soil bed (Fig. 13 (a)). Larger the sediment particle in comparison to the mean particle size, the faster the upward velocity becomes (Takahashi, 1980). For the cases of uniform sediment particles soil bed (Case-1 and Case-2), the movement of the sediment particles was slow and the deposited sediments in the flow front obstructed the flow, thereby diversion of flow from its main course was observed through the head reach of the sloping face (Fig. 12). In other cases, the flow diversion was comparatively minor.

Depending on the source of eroded sediment, soil erosion by water is commonly divided into rill and inter-rill components (Meyer & Wischmeier, 1969; Laflen et al., 1991). Inter-rill soil erosion results in selective removal of fine particles, whereas rill erosion is less selective (or nonselective) after a specific critical flow shear stress is exceeded (Gabriels &
Moldenhauer, 1978; Meyer et al., 1980; Mitchell et al., 1983; Loch & Donnellan, 1983; Miller & Baharuddin, 1987; Proffitt & Rose, 1991; Durnford & King, 1993; Sutherland et al., 1996; Slattery & Burt, 1997; Wan & El-Swaify, 1998; Hairsine et al., 1999; Hogarth et al., 2004; Malam Issa et al., 2006; Asadi et al., 2007a; Asadi et al., 2007b; Romero et al., 2007). The general agreement is that eroded materials are enriched in clay and silt-sized particles relative to the original soil where the erosion event commenced. The eroded materials gradually become coarser over time, and its composition becomes very similar to that of the original soil at final steady state condition (Asadi et al., 2011). But in some cases, the observed transported sediment by inter-rill erosion was coarser than the original soil (Young & Onstad, 1978; Meyer et al., 1992). It has also been noted that in soil erosion due to rainfall there are dynamic changes in both the concentration and size distribution of sediment (Hairsine et al., 1999). Asadi et al. (2007b), found that the mass fraction of different sediment sizes is bimodal distribution resulted from two different transport mechanisms of suspension and saltation, and rolling. However, there are still some conflicting and unexplained results regarding sediment size distribution during erosion processes.

Shi et al. (2012) suggested that total soil loss is the sum of suspended, saltating and contact (rolling) loads. Suspension/saltation, which affects fine particles, is the main erosion mechanism at work during inter-rill erosion processes. However, after rill development on the hillslope, suspension/saltation becomes less dominant, and bed-load transport by rolling of medium to large-sized sediment particles becomes an increasingly important transport mechanism. Concentration of rolling size fractions often showed short-term fluctuations due to both the intermittent nature of some sediment inputs and the intermittent nature of the movement involved. The relative importance of these two types of sediment transport mechanisms was related to stream power. While the relative importance of suspension/saltation decreased with increasing stream power, rolling became more important at higher stream powers. Figs. 10, 13, 16 and 17 indicate that the sediment transport mechanism is the combination of particle segregation, suspension/saltation and rolling along the travel distance.

In the experiments for case-1, the soil surface was horizontal in lateral direction, but in other cases it was v-shape (Fig. 2). So that the overland flow was channelized towards v-notch, and also the average depth of soil domain was lesser in the other cases. Hence, the experimental out-puts for case-1 were comparatively delayed than case-2, even other experimental conditions were same for the both. Similarly, the experimental outputs for case-5 were comparatively delayed than case-4. In the case-5 experiments the rainfall was less than case-4, but the geometry of soil domain and type of sediment used to prepare it were same in both the cases.

In the case of a real watershed, several soil and land cover related factors affect erosion rates. However, this study does not take into account these factors. Therefore, the soil erosion and transport characteristic of the real watershed may different from this type of laboratory scale experimental results. Further studies based on numerical analyses and additional experiments compatible to actual watershed characteristics are necessary.

4. Conclusions

This study involved laboratory flume experiments carried out under simulated rainfall in a 3.0 m long × 0.8 m wide × 0.7 m deep flume, set at 17º slope. Five experimental cases, consisting of twelve experiments using three different sediments with two different rainfall conditions, are reported. Moisture profiles, seepage out-flow, and movement of overland flow was clearly found to be controlled by water retention function and hydraulic function of the sediment used in the experiments.

Runoff contributed from upstream of the sloping face induced minor rills and a major gully was observed in the experiments. The results indicated that the sediment transport mechanism is the combination of particle segregation, suspension/saltation and rolling along the travel distance. The difference of grain size distribution of original soil bed and the out-flow sediment was found to be insignificant in the cases of uniform sediment used experiments. However, in the cases of non-uniform sediment used experiments the out-flow sediment was found to be coarser than the original soil domain. In the intermittent nature of out-flow, the grain size distribution was much coarser caused by particle segregation due to the sudden supply of water from the upstream.

For the uniform sediment particles soil bed, the movement of the sediment particles was slow and the deposited sediments in the flow front obstructed the flow, thereby diversion of flow from its main course was observed through the head reach of the sloping face. In contrast, for the non-uniform
sediment particles soil bed, the movement of the sediment particles was faster and the flow diversion was comparatively minor.

The soil erosion and transport characteristic of the real watershed may different from this type of laboratory scale experimental results. Further studies based on numerical analyses and more experiments (varying soil bed slope, soil types and rainfall conditions) compatible to actual watershed characteristics as well are necessary to verify this conclusion further more.

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