Analysis of sediment load under combined effect of rainfall and flow

S Shams, U Ratnayake, E K Abdul Rahman and A A Alimin
Faculty of Engineering, Universiti Teknologi Brunei, Gadong BE 1410, Brunei Darussalam
E-mail: shams.shahriar@utb.edu.bn

Abstract. An increase in sediment load resulting from extreme weather event can affect the capacity of existing water infrastructure, for example, decreasing reservoir capacities, creating obstacles and reducing the navigation depth, or eroding bridge piers by scouring actions. A number of studies have been carried out on factors affecting sediment yield and transport but only a few studies being done on the combination of both rainfall and flow on the sediment load. Therefore, the aim of this study is to identify the impact on sediment load comprising of well-graded silica sand due to combined effect of flow and rainfall. This research has two objectives; firstly, to study the relationship between flow, rainfall, and sediment load and secondly to devise an experiment to investigate how combination of flow and rainfall could affect sediment load with the help of Advanced Environmental Hydrology System. Thirty-six sets of experiments were conducted on a 2 m long, 0.2 m wide and 0.15 m deep channel, moulded in the Armfield S12 MKII on a 1% constant slope with six different readings of rainfall ranging from 6 to 72 mm/hr and by varying the flow ranging from 0.5 to 3.0 L/min to observe the different trends and changes to sediment load when rainfall and flow varies. This experimental study demonstrates a combination of both rainfall and flow resulted in a stronger linear correlation with sediment load.

1. Introduction
A river can erode the soil and rocks which form its channel and its bed by fluvial processes like corrosion, attrition, abrasion and hydraulic action. This eroded material carried by the river is known as sediment load. An area, where much sediment is deposited is often rich in nutrients [1] and hence in biodiversity since the living organisms feed on it to sustain their lives. It can be seen that the movement of water between the river channel and floodplain plays an important role in influencing the river ecosystem. The changes in the quantity and grain size distribution of sediment either too much or too little within river systems not only affect the physical structure of the channel but also the related habitat [2].

However, the changes in weather patterns give complex and improper impacts on many human and environmental systems as it affects the movement of sediment within watersheds [3]. Too much sediment load increases the size and frequency of flooding [4]. As the stream channels are filled with sediments, it reduces the depth of the river or channel and so the capacity of the channel decreases. This is what happened in Hekou-Longmen region, middle reaches of the Yellow River, the area have become a flood-prone due to excessive sediments it received [5]. A similar case happened in the Klang
River in the City Centre of Kuala Lumpur [6], the river became incapable of accommodating the excess flood and therefore overflowed the riverbanks causing flash floods in the City Centre.

It can be seen that the amount of sediment load is dependent on the power of fluvial processes in eroding the river bed and its carrying capacity. The power of fluvial processes in eroding the river bed and thus changing its carrying capacity is dependent on several factors such as the amount of precipitation and temperature, vegetation cover in the area, erodibility of materials in the drainage basin, relief and slope. Anthropogenic factors like mining, construction, clear-cutting, etc. could also influence the amount of sediment load being carried and deposited [7].

Energy is the result of mass and velocity which is related to the observed impact power value, and it characterises rainfall as kinetic energy [8]. Therefore, with rainfall intensity increasing, the observed impact power also increases. As impact power increases, erosion and sediment load increases. Thus, it can be seen that there is a positive correlation between sediment load and rainfall [9]. [10] found that amount of sediment load increases when the quantity of flow increases because there is more potential energy to transport the suspended sediment. The experiment conducted by [11] proved that the higher the inflow rate, the higher the suspended sediment concentration (SSC) along the river will be. [12] also stated that sediment would move only when flow exceeds the critical value of shear stress. [5] also observed that the reduction of river flow after the building of Longyangxia and Liujiatia reservoirs as a water storage supply for people living in Yellow River areas had reduced the amount of sediment load in downstream of Yellow river. Low flows do not contribute to sediment transport. These recent studies have shown that there is a positive correlation between sediment load and flow. [13] also found that sediment yield will increase as magnitude of flooding increases. [14] analysed that stream flow in the Cubuk River, Turkey and observed sediment load increased drastically after rainfall and in another study similar observation made in Xichuan Watershed in the Loess Plateau, China [15]. This means that the presence of rainfall will lead to flow and sediment load discharge. [16] also found out that the concentration of both rain intensity and flow velocity had a positive relationship with the concentration of sediment load. [17] has also found an almost stable relationship between rainfall and runoff from the last 120 years on their report.

The study on sediment transport and deposition of sediment is essential for the land and water management. The knowledge on the status of the natural balance of the coasts and sediment transport can be used for long-term planning and protection of river basin [18]. An investigation was being made on the sediment distribution along the Yangtze River by [11] to meet the increasing demand on freshwater and to improve the water quality of Taihu Lake by building the first one-dimensional rainfall-runoff model to calculate and analyse the influence of flow rate and the suspended sediment concentration (SSC) on the sediment transport. Then [3] in their research, have used river basin sediment transport models as a standard component of frameworks providing the technical underpinning to policy programs aimed at reducing pollution of freshwater and coastal ecosystems. Such study is useful for civil engineering activities, forestry applications, hazard mitigation like flooding and soil erosion, and sustainable river basin management, channel stability and agriculture. This is because understanding the sediment load transportation and estimating the correct amount of sediments are both needed for the design, management, maintenance and operation of dams and canals.

Currently, there are very few studies being conducted on the combination of both rainfall and flow to sediment load. Therefore, the aim of this study is to identify the effect of sediment load transportation underflow and rainfall with two objectives; (i) study the relationship between flow, rainfall, and sediment load (ii) devise an experiment to investigate how a combination of flow and rainfall could affect sediment load on a plain flat land with the help of Advanced Environmental Hydrology System.

2. Methodology
A laboratory experiment is carried out to determine the relationship between flow, rainfall and sediment load by using Armfield Advanced Environmental Hydrology System SK12MII (Figure 1) in
Water Resources Lab, University Teknologi Brunei (UTB). This equipment is used to demonstrate, on a small scale, the physical process specifically associated with sediment transport.

![Figure 1. Armfield S12 MKII hydrology apparatus.](image)

The apparatus is equipped with a water storage tank having a basin 2 m long x 1 m wide x 0.2 m deep stainless-steel tank comprises of fine sand (0.8 mm) as shown in Figure 2. It is also connected to the dual-linked jacking system so that the slope can be varied between 0 to 5%. The equipment comprises of a pumping system where the flow can be set between 0 to 5.0 L/min and rainfall can be set between 0 to 3.0 L/min corresponding to rainfall intensity between 0 to 90 mm/hr. There are eight stainless steel spray nozzles with on/off valve to control the intensity of the rainfall. These nozzles produce drop sizes and distributions close to those of natural rainfall. These nozzles are positioned right on the platform tank which heights are up to 0.6 m to give an equal distribution of rainfall across the tank surface with height of the gantry can be easily adjusted (Figure 3).
Figure 2. Water basin having a channel of 2 m long, 0.20 m wide and 0.15 m deep.

Figure 3. Handle and jack system to adjust slope.

For this research, a total of thirty-six sets of experiments were conducted on this hydrology apparatus by using the parameters as illustrated in Table 1.

Table 1. Parameters for sediment transport simulations.

| Parameter | Details |
|-----------|---------|
| Sediment  | Uniform sand was used to ensure homogeneity of the material. The median grain size for the sediments that already being prepared in the lab is 0.8 mm. |
| Flow      | Six flow readings were chosen as the variable parameter for this study; 0.5 L/min, 1.0 L/min, 1.5 L/min, 2.0 L/min, 2.8 L/min, 3.0 L/min to see the different trends of the sediment load as the flow is increased using flow meter (Figure 4). |
| Rainfall  | Six different rainfall intensities from the rainfall simulator were chosen as the variable parameter for this study; 0.2 L/min (6 mm/hr), 0.6 L/min (18 mm/hr), 1.2 L/min (36 mm/hr), 1.6 L/min (48 mm/hr), 2 L/min (60 mm/hr), 2.4 L/min (72 mm/hr) to see patterns of the sediment load as rainfall intensity is increased. |
| Slope     | The experiment focuses only on a plain flat land condition with no vegetation cover on a consistence slope at 1% because most river slope in flood plains is between 1 - 2%. Moreover, this research focuses on rainfall and flow only. |
| Channel   | The straight river channel 2 m long, 0.2 m wide and 0.15 m depth. |

Sediment load is collected using a fine cloth placed and positioned beneath the weir chute or diffuser and it is replaced every 15 minutes (Figure 5). Each set of experiments takes about 1 hour with the fine cloth being replaced four times; 15 minutes, 30 minutes, 45 minutes and 60 minutes to
see a clearer pattern of sediment load with more accuracy. Collected sediment samples are dried and weighed separately as shown in Figure 6.

![Figure 4. Flowmeters for the flow and rainfall.](image1)

![Figure 5. Sediment collection process.](image2)

![Figure 6. Collection, drying and weighing of sediment.](image3)

3. Results and Discussion
The observed sediment loads of the thirty-six sets of experiments are shown in Table 2. The results demonstrate that total sediment load increases with increasing rainfall and flow as shown in Figure 7. When both rainfall (6 mm/hr) and flow (0.5 L/min) was at the lowest rates, the total amount of sediment load removed from the channel was also at the lowest i.e. 52.03 g, while both rainfall (72 mm/hr) and flow (3.0 L/min) was at the highest, the total amount of sediment load carried away from the channel was at the highest, i.e. 2503.64 g. The relationship indicated that sediment load was directly proportional to rainfall and flow.
Table 2. Sediment load based on the variation of flow and rainfall.

| CODE | FLOW (L/min) | RAINFALL (mm/hr) | 15 min | 30 min | 45 min | 60 min | Total sediment load (g/hr) |
|------|--------------|------------------|--------|--------|--------|--------|--------------------------|
| 1.A  | 6            | 4.97             | 5.88   | 30.50  | 10.68  | 52.03  |
| 1.B  | 18           | 9.45             | 179.64 | 33.49  | 279.45 | 502.03 |
| 1.C  | 36           | 6.90             | 189.22 | 78.84  | 360.95 | 635.91 |
| 1.D  | 48           | 225.47           | 529    | 193.23 | 127.58 | 805.28 |
| 1.E  | 60           | 785              | 525    | 218.16 | 206.27 | 1734.35 |
| 1.F  | 72           | 152              | 845    | 615    | 460    | 2027   |
| 2.A  | 6            | 34.98            | 58.82  | 37.56  | 52.27  | 185.63 |
| 2.B  | 18           | 65.10            | 21.23  | 43.83  | 312.71 | 442.87 |
| 2.C  | 36           | 609              | 347.99 | 157.13 | 103.19 | 1222.2 |
| 2.D  | 48           | 524              | 236.45 | 132.30 | 150.31 | 1042.06 |
| 2.E  | 60           | 187.36           | 799    | 212.09 | 108.08 | 1306.53 |
| 2.F  | 72           | 795              | 702    | 323.99 | 296.78 | 2107.77 |
| 3.A  | 6            | 66.79            | 193.52 | 80.31  | 118.11 | 458.72 |
| 3.B  | 18           | 52.55            | 23.42  | 449.28 | 142.66 | 667.91 |
| 3.C  | 36           | 13.78            | 461.37 | 76.96  | 185.23 | 825.35 |
| 3.D  | 48           | 53.29            | 313.17 | 382.33 | 76.56  | 1563   |
| 3.E  | 60           | 312              | 385    | 432    | 434    | 1563   |
| 3.F  | 72           | 704              | 448.60 | 510.30 | 450.92 | 2113.82 |
| 4.A  | 6            | 100.85           | 218.24 | 104.31 | 142.73 | 566.13 |
| 4.B  | 18           | 85.52            | 48.04  | 473.28 | 167    | 773.84 |
| 4.C  | 36           | 47.57            | 485.99 | 100.96 | 209.85 | 844.37 |
| 4.D  | 48           | 87.08            | 337.79 | 406    | 101.18 | 932.05 |
| 4.E  | 60           | 345.97           | 409.62 | 456.63 | 458.62 | 1670.84 |
| 4.F  | 72           | 737              | 473.22 | 634.92 | 375.54 | 2220.68 |
| 5.A  | 6            | 137              | 243.77 | 124.13 | 162.55 | 667.45 |
| 5.B  | 18           | 121.47           | 73.57  | 522    | 167    | 884.04 |
| 5.C  | 36           | 83.52            | 200.96 | 611.52 | 109    | 1005   |
| 5.D  | 48           | 123.75           | 363.32 | 406    | 121    | 1014.07 |
| 5.E  | 60           | 382              | 435.15 | 556    | 382.01 | 1647.16 |
| 5.F  | 72           | 772.95           | 492.75 | 634.92 | 475.54 | 2376.16 |
| 6.A  | 6            | 174.93           | 273    | 156.12 | 187.17 | 791.22 |
| 6.B  | 18           | 159.4            | 103.58 | 553.99 | 191.62 | 1008.59 |
| 6.C  | 36           | 121.5            | 230.97 | 643.51 | 133.07 | 1129.05 |
| 6.D  | 48           | 161.68           | 393.33 | 437    | 145.91 | 1137.92 |
| 6.E  | 60           | 419.93           | 465.16 | 588.09 | 407.52 | 1880.68 |
| 6.F  | 72           | 810.88           | 522.76 | 666    | 504    | 2503.64 |
Figure 7. Sediment load resulting from variations of flow and rainfall after 60 minutes (1 hour).

Figure 8, 9, 10, and 11 shows a combined effect of flow and rainfall with different flow and rainfall on the amount of sediment load after 15, 30, 45 and 60 minutes respectively. It was observed that at the end of the first 15 minutes for any rainfall and flow, the total sediment load carried and deposited gave almost a similar trend apart from flow 0.5 and 1.0 L/min respectively. This is because most of the rainfall is infiltrated rather than overland flow. Therefore, all the sediment load is at its lowest amount after the first 15 minutes compared to sediment load weight after 30, 45 and 60 minutes.

The amount of collected sediment load at the end of 30, 45 and 60-minute periods started to fluctuate. This was because most of the soils have already being carried and eroded depending on the flow and rainfall. After the first 15 minutes, most of the soil was saturated therefore most of the water were moving horizontally (overland flow), instead of vertically (infiltrating), hence greater transport of sediment and erosion resulting higher amount of sediment load after 30 minutes was observed.

The channel became more active with water flow after 30 minutes period resulted in a drastic increase in the amount of sediment load as shown in Figure 9, 10 and 11. This is due to the fact that the soil is saturated, and the water starts to pool, and stagnant water can be seen on both sides of the banks as shown in Figure 12. As more rainfall water is added, pooled stagnant water escaped form the riversides forming gullies towards the centre of the river channel. [19] have also described an almost similar case for a real scenario at Bonea Stream, southern Italy where strong erosion at the delta, shore and bar at the studied area was because of a combined effect of rainfall and flow.

Figure 8. Sediment load with the combined effect of flow and rainfall after 15 minutes.
Figure 9. Sediment load with the combined effect of flow and rainfall after 30 minutes.

Figure 10. Sediment load with the combined effect of flow and rainfall after 45 minutes.

Figure 11. Sediment load with the combined effect of flow and rainfall after 60 minutes.

Since the soil surface was bare, with no vegetation cover to protect the sands, bank collapse was inevitable as seen in the experiments and shown in Figure 12. This was also contributed to the increase
and fluctuations of the amount of sediment load. The forces of rainfall intensity and saturated soil lead to bank collapse and along with the combination of the flow, it became easier for sediments to be eroded and carried away.

Figure 12. Stagnant water (left), bank collapse (right)

Figure 13 illustrated the average sediment load versus time for different rainfall. The amount of sediment load increased and peaked at 30 minutes for flow of 0.5 L/min while it peaked at 45 minutes for flows of 1.0, 1.5, 2.0, 2.8 and 3.0 L/min. This is when gullies are usually created, and stagnant water contributed to the fast-flowing of pooled water. The sediment discharge started to decrease right after it reached the peak point; this is because the condition at the watershed is stable with most of the pooled water are already out of the basin.

Overall results show that each rainfall intensity and flow rate highly influenced the erosion. The estimated erosion rate when both rainfall and flow are the lowest was 0.33 g/min and the estimated erosion rate when both rainfall and flow are the highest can be up to 54.06 g/min. It also suggests that the combination of both rainfall and flow resulted a stronger linear correlation with sediment load.

Figure 13. Average sediment load with respect to time for various flows.

However, between these two parameters, the study suggests that rainfall has stronger effect to erosion than flow. This is because the flow detached and transported sediment only along the channel bed but rainfall detached and transported from the surface of whole catchment or watershed area. Thus, one of the important factors in storm characteristic is rainfall intensity as it has a close relationship with erosion [20] since soil loss are formed as a result from kinetic energy from raindrops impacting on soil surface [8]. The higher the rainfall intensity, the stronger the rainfall energy to
detach the soil particles. Furthermore, it will increase in the rate of water flow in the catchment area, hence more energy is created to carry and erode the sediment as suggested in the previous study [21].

4. Conclusion
The study has demonstrated that there is a strong correlation between flow, rainfall, and sediment load. As rainfall intensity increases, flow increases and hence sediment load increases. The estimated erosion rate for both lowest rainfall and flow is the lowest (0.33 gram per minute) and the estimated erosion rate for both highest rainfall and flow is the highest (54.06 gram per minute). In terms of kinetic energy, an increase in rainfall intensity will increase the kinetic energy thus at higher intensities more sediment will be produced. Therefore, a combination of both rainfall and flow resulted in a stronger linear correlation with sediment load. It is also observed that for low rainfall intensities the sediment load yield is at the lowest within the first 15 minutes compared to sediment load weight after 30, 45 and 60 minutes. The limitation of this research is that the observations are applicable to levelled new catchment surface prior to development of gullies and rills.

References
[1] Talbot C J, Bennett E M, Cassell K, Hanes, D M, Minor E C, Paerl H, Raymond P A, Vargas R, Vidon P G and Wollheim W 2018 The Impact of Flooding on Aquatic Ecosystem Services Biogeochemistry 141(3) pp 439-461
[2] Griffiths R E and Topping D J 2017 Importance of Measuring Discharge and Sediment Transport in Lesser Tributaries When Closing Sediment Budgets Geomorphology 296 pp 59-73
[3] Wilkinson S N, Dougall C, Kinsey-Henderson A E, Searle R D, Ellis R J and Bartley R 2014 Development of a Time-Stepping Sediment Budget Model for Assessing Land Use Impacts in Large River Basins Sci. Total Environ 468 pp 1210-1224
[4] Vanniere B, M Magny M, Joannin S, Simonneau A, Wirth S, Hamman Y, Chapron E, Gilli A, Desmet M and Anselmetti F 2013 Orbital Changes Variation in Solar Activity and Increased Anthropogenic Activities: Controls on the Holocene Flood Frequency in the Lake Ledro Area Northern Italy Climate of the Past 9 pp 1193-1209
[5] Shi H, Hu C, Wang Y, Liu C and Li H 2017 Analyses of Trends and Causes for Variations in Runoff and Sediment Load of the Yellow River International journal of sediment research 32 pp 171-179
[6] Dominic J A, Aris A Z and Sulaiman W N A 2015 Factors Controlling the Suspended Sediment Yield During Rainfall Events of Dry and Wet Weather Conditions in a Tropical Urban Catchment' Water Resour. Manage 29 pp 4519-4538
[7] Das T K, Halder S K, Gupta I D, and Sen S 2014 River Bank Erosion Induced Human Displacement and Its Consequences Living Review of Landscape Research 8 pp 1-35
[8] Yuan J, Liang Y and Cao L 2014 Preliminary Study on Mechanics-Based Rainfall Kinetic Energy Int. Soil Water Conserv. Res 2 pp 67-73
[9] Zhang Y, Wang P, Wu B and Hou S 2015 An Experimental Study of Fluvial Processes at Asymmetrical River Confluences with Hyperconcentrated Tributary Flows Geomorphology 230 pp 26-36
[10] G Zhao, X Mu, Z Wen, F Wang, P Gao, Soil Erosion, Conservation, and Eco-Environment Changes in the Loess Plateau of China Land Degradation & Development 24 499-510 (2013)
[11] Gong Z, Zhang C, C Zuow, Wu W 2011 Sediment Transport Following Water Transfer from Yangtze River to Taihu Basin Water Sci. Eng. 4 pp 431-444
[12] Ferguson R I 2012 River Channel Slope Flow Resistance, and Gravel Entrainment Thresholds Water Resour. Res. 48
[13] Joyce H M, Hardy R J, Warburton J and Large A R G 2018 Sediment Continuity through the Upland Sediment Cascade: Geomorphic Response of an Upland River to an Extreme Flood Event Geomorphology 317 pp 45-61
[14] Duru U, Wohl E and Ahmadi M 2017 Factors Controlling Sediment Load in the Central Anatolia Region of Turkey: Ankara River Basin Environ. Manage. 59 pp 826-841
[15] Li T and Y Gao Y 2015 Runoff and Sediment Yield Variations in Response to Precipitation Changes: A Case Study of Xichuan Watershed in the Loess Plateau China Water 7 pp 5638-5656
[16] Sajjadi S A and Mahmoodabadi M 2015 Sediment Concentration and Hydraulic Characteristics of Rain-Induced Overland Flows in Arid Land Soils J. Soils Sediments 15 pp 710-721
[17] Crooks S M and Kay A L 2015 Simulation of River Flow in the Thames over 120 Years: Evidence of Change in Rainfall-Runoff Response? J. Hydrol. Reg. Stud. 4 pp 172-195
[18] Ginesu S, Carboni D and Marin M 2016 Erosion and Use of the Coast in the Northern Sardinia (Italy) Procedia Environmen. Sci. 32 pp 230-243
[19] Budillon F, Violante C, Conforti A, Esposito E, Insinga D, Io-rio M and S Porfido S 2005 Event beds in the recent prodelta stratigraphic record of the small flood-prone Bonea stream (AmalfiCoast, Southern Italy) Mar. Geol. 222–223 pp 419-441
[20] Mohamadi M A and Kavian A 2015 Effects of Rainfall Patterns on Runoff and Soil Erosion in Field Plots International Soil and Water Conservation Research 3 pp 273-281
[21] de Assunção Montenegro A A, dos Santos Souza T E M, de Souza E R and Montenegro S M G L 2018 Temporal Dynamics of Soil Moisture and Rainfall Erosivity in a Tropical Volcanic Archipelago J. Hydrol. 563 pp 737-749