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Date of Submission	03/08/2019
Date of Acceptance	02/09/2019
Date of Publication	01/10/2019
Page numbers	3362-3367(6 Pages)

Cite This Paper: Woei Keong Kuan, Muhamad H.H. Basri, Siti N.M. Saufi, Siti N.M. Ibrahim. Influence of Rainfall Characteristics and Land Surface Imperviousness on Rainfall-Runoff Relationship, 8(9), COMPUSOFT, An International Journal of Advanced Computer Technology. PP. 3362-3367.

ISSN:2320-0790

COMPUSOFT
An International Journal of Advanced Computer Technology

INFLUENCE OF RAINFALL CHARACTERISTICS AND LAND SURFACE IMPERVIOUSNESS ON RAINFALL-RUNOFF RELATIONSHIP

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Abstract: The changes of land surface imperviousness due to rapid development had contributed to the occurrence of flash floods. The runoff coefficient, *C* that represents the rainfall-runoff relationship in the catchment is one of important parameter being considered in estimating the peak discharge due to a rainfall event. This study aimed to investigate the influence of rainfall characteristics and land surface imperviousness on rainfall-runoff relationship. A series of laboratory experiments were conducted in a 2m x 1m sand flume to simulate the hydrological cycle in a laboratory scale catchment by varying the rainfall characteristics under different land cover conditions. The spatial distribution of rainfall was found to influence the flood peak and runoff volume in this study. The results revealed that the runoff coefficient was higher under non-uniformly distributed rainfall event. This study indicated that both spatial and temporal variations of rainfall should be considered to improve the accuracy in estimating the flood peak.

Keywords:runoff hydrograph; rainfall characteristic; Rational method; runoff coefficient

I. INTRODUCTION

The changes of land use due to development and its impact to water cycle have been identified as the major cause that lead to a flood event. Due to an increment of impervious surfaces such as roads, buildings and parking spaces, the risk and exposure of resident to floods has been increasing in urban area [1]. Thus, a proper drainage design should be implemented to convey the discharge in order to reduce flood occurrence. The runoff coefficient, *C* is one of important parameter that has been considered to estimate the peak discharge using Rational method in designing an appropriate capacity of drainage system [2]. In Rational method, the runoff coefficient is controlled by land use and the rainfall is assumed uniform in the estimation of peak discharge. However, the real rainfall varied temporally and occurs non-uniformly over the catchment; and the land use may not reflect the actual imperviousness of the development. The Rational method was also found to be subjectivity in application owing to the sensitivity of the input parameters [3]. In this study, investigation on the influences of rainfall characteristics and imperviousness of catchment to the runoff volume and catchment losses were conducted.

Numerous studies have attempted to develop rainfall and runoff relationship that involved collection of large number of hydrological data for a selected catchment area. Merz et al. [4] examined the spatial and temporal variations of runoff coefficients using large number of rainfall events. Their analysis showed that the spatial distribution of runoff coefficients was highly correlated with mean annual precipitation and only have little correlation with soil type and land use. Young et al. [5] conducted a study to investigate the relationship of runoff coefficient with recurrence interval of rainfall for several groups of stations. In their study [5], the rational *C* values was found to be higher for the larger recurrence intervals. Dhakal et al. [6] conducted a study on estimation of volumetric runoff coefficient, *C* for 90 watersheds in Texas using observed rainfall and runoff depths from more than 1,600 events observed in the watersheds. The results revealed that larger *C* values are derived for developed watersheds compared to undeveloped watersheds. The study of Savary et al. [7] based on past 30 years land cover data showed that the land cover changes has affected the runoff at watershed outlet using remote sensing and hydrological modelling. Sensitivity analysis using GIS conducted by Kusumastuti et al. [8] also indicated that the flood peaks was influenced by the impervious surface (green area). By adopting a statistical model, Mamun et al. [9] showed that the flood peak for ungagged catchment is related to the catchment area and mean annual rainfall. It is evident that the rainfall and runoff relationship is influenced by the catchment and rainfall characteristics that vary spatially and temporally.

Laboratory experiments always offer an effective alternative to the field investigation and have the advantage of allowing the investigator to minimize some of the variability inherent in environmental systems. In the experimental study of Moussouni et al. [10], the rainfall intensity showed a significant correlation within a range of intensity and Reynold numbers with runoff and sediment concentration. The study of Das et al. [11] indicated that no specific trend of rainfall intensity on runoff characteristics could be identified in their experiments. The laboratory investigation also revealed that the assumption of linearity between runoff volume and hydrograph ordinates was partially valid under non-uniform rainfall conditions. Ran et al. [12] investigated the impacts of rainfall characteristics on runoff generation and soil erosion. The experimental study of Ran et al. [12] demonstrated how the rainfall moving direction affected the rainfall-runoff relationship and soil erosion.

In this study, the laboratory experiments involved varying the spatial and temporal characteristics of rainfall and percentage of surface imperviousness were conducted to examine its effect to the runoff volume and catchment losses in a controlled environment.

II. METHODS

A. *Experimental Setup*

In this study, hydrology apparatus was used to simulate rainfall and surface runoff in the investigation of the effects of different rainfall patterns on runoff generation. The experiments were conducted using a 2m × 1m sand flume that equipped with rainfall simulators (manufactured by Gunt Hamburg, model HM 165 Hydrologie). The hydrology apparatus comprised of a closed water circuit with storage tank and pump. The core element was a sand-filled, stainless steel experiment tank with inclination adjustment. The sand was filled up in layer up to a depth of 0.14 m in the experiments (Figure 1).

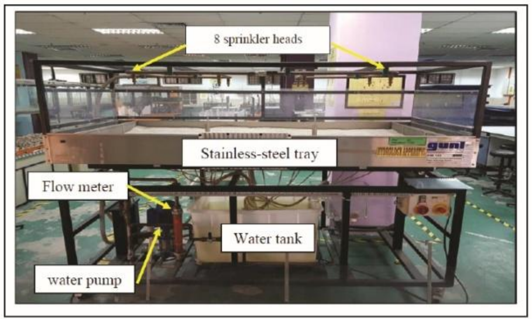

Figure 1 Experiment Apparatus and Setup

The rainfall simulating system consisted eight (8) sprinkle shower heads that acted as rainfall simulators. The water supply to the rainfall simulators was controlled by a valve and the required rainfall intensity was measured by flowmeter. Two (2) outlets were provided in the sand flume. The first outlet at the bottom of tray was used to drain subsurface (infiltration) flow andthe second outlet at the downstream channel was used to drain the surface runoff. During the experiment, part of the rainfall would infiltrate into the sand layer and the remained (excess rainfall) would become surface and subsurface runoff that discharge into the downstream channel at the lower end of apparatus as channel runoff. Lastly, the channel runoff discharged into the storage tank andthe water was pumped up in the storage tank as rainfall. The circulation of water was continued in this apparatus throughout the experiment. The experiments were conducted with a gentle slope of 0.5% (1:200).

B. *Experimental Procedures*

The flow meter that used to control (measure) the rainfall intensity generated by eight sprinkler shower heads was first calibrated to ensure its accuracy. Eight cylindrical plastic containers worked as rainfall collector were placed under the rainfall simulator to collect rainfall for 2 minutes. The diameter and height of each container were 8.00 cm and 24.5cm respectively. The calibration was conducted under a series of rainfall intensities. The results were then compared with the flow rate recorded by the flow meter. The left part of the apparatus is considered as upstream and the downstream is located on the right. The valve at the upper part of apparatus is used to control the water flow to the sprinklers located at downstream. In the case of equally distributed rainfall, the valve for all eight sprinkler heads is opened to allow water spraying on the whole catchment. The sprinkler valve at downstream will be closed in the case of unequally distributed rainfall in which the rainfall will be limited at upstream only. PVC board was used as land cover in the experiment. The percentage of imperviousness was determined by the area covered with PVC board on the catchment.

Before the experiments were started, the catchment was sprinkled with water by the rainfall simulator to make it in wet soil condition. When the runoff produced by the preceding rainfall has stopped, the valve was opened and adjusted to the desired flow rate (rainfall intensity) measured by flowmeter. The time was measured once the pump started. The surface runoff was formed when the infiltration has achieved its infiltration capacity and the rainfall excess was drained into the downstream channel. The runoff and infiltration rate were measured by volumetric method. The outflow of water (runoff volume) at downstream channel and infiltrated water were collected respectively at an interval of 1 minute using measuring cylinder for a duration of 15 seconds. The rainfall stopped after 30 minutes but the runoff and infiltration rate were continuously measured until the outflow ceased. The amount of rainfall was determined from the flow rate recorded by flow meter.

C. Study Cases

Four study cases were developed, in which 2-4 experiments were conducted in each study case to investigate the influence of rainfall characteristics and land surface imperviousness on rainfall-runoff relationship (Table 1). In study case 1, experiment 1A (1/1A) was conducted under constant rainfall intensity (CU) whilethe rainfall was varied temporally (VU) in experiment 1B. The temporal pattern of the rainfall in experiments 1B and 4A-4D followed the fraction of normalized temporal pattern of Penang (Region 3), Malaysia as stated in Urban Stormwater Management Manual for Malaysia - 2nd Edition [2]. The rainfall intensity was varied at interval of 5 minutes over the rainfall duration of 30 minutes. The total rainfall volume in both experiments were identical. In the second study case, the spatial variation of rainfall distribution was applied in which constant rainfall was distributed either equally (uniform, CU)or unequally (non-uniform, CN, rainfall applied at upstream only)over the catchment.In the third and fourth study cases, the catchment was covered by PVC board to represent surface imperviousness at 0, 25%, 50% and 75% under constant and temporally varied rainfall conditions respectively.

Table 1 Experimental Cases

Study cases/ Experiments	Rainfall types/ Duration (min)	Flow rate (L/hr)	Rainfall intensity (mm/hr)	% of impervious surface
1/1A[1]	CU/30	500	250	0
1/1B[2]	VU/30			
	0-5	474	237	0
	5-10	483	242	0
	10-15	630	315	0
	15-20	519	260	0
	20-25	474	237	0
	25-30	423	212	0
2/2A[1]	CU/30	500		0
2/2B	CN/30	500		0
3/3A[1]	CU/30	500		0
3/3B	CU/30	500		25
3/3C	CU/30	500		50
3/3D	CU/30	500		75
4/4A[2]	VU/30	as in study case 1/1B		0
4/4B	VU/30	as in study case 1/1B		25
4/4C	VU/30	as in study case 1/1B		50
4/4D	VU/30	as in study case 1/1B		75

[1] Experiments 1/1A, 2/2A and 3/3A are identical. [2] Experiments 1/1B and 4/4A are identical. CU, VU, and CN indicated constant and uniform (equally distributed), temporally varied and uniform, constant and non-uniform rainfall respectively.

III. RESULTS AND DISCUSSIONS

A. *Influences of rainfall characteristics*

In this study, the flow rate was controlled in the range of 400-600 L/hr. The base flow rate of 500 L/hr was applied which was equivalent to a rainfall intensity of 250 mm/hr. In study case 1, two experiments were conducted under constant (250 mm/hr) and temporally varied rainfall intensities. The magnitude of peak discharge and time to peak were varied in both experiments 1A and 1B (Figure 2a). These differences were induced by distribution of rainfall temporal pattern applied in both experiments. In experiment 1A, the peak discharge was achieved after 28 minutes with discharge magnitude of 50.0 cm^3/s under steady rainfall intensity (Figure 2a). The peak discharge occurred when the infiltration rate had reached its infiltration capacity of approximately 60.0 cm^3/s in Experiment 1A (Figure 2b). The highest infiltration rate occurred after 21 minutes while peak discharge occurred after 28 minutes in experiment 1A. In experiment 1B, the discharge achieved its peak at 45.3 cm^3/s after approximately 24 minutes. The percentage of difference in peak discharge was approximately 9.86%. In both experiments, there was no significant change in peak discharge. The accretion of runoff started earlier in experiment 1A (constant rainfall) compared to the experiment 1B (temporally varied rainfall). This was happened because the initial rainfall intensity applied in the experiment 1A was larger than in the experiment 1B at the beginning of the experiment. The time to peak in temporally varied rainfall condition (experiment 1B) is shorter than the constant rainfall condition (experiment 1A). This might due to the temporally varied rainfall intensity that applied in experiment 1B. The rainfall intensity achieved its peak at 10-20 minutes in experiment 1B which was higher than the constant rainfall intensity applied in experiment 1A. Both experiments showed similar decrement trend of runoff rate. The runoff ceased after 22 minutes in experiment 1B when the rain stopped. It was 3 minutes faster than in experiment 1A. The runoff coefficients for experiments 1A and 1B were determined as 0.2119 and 0.2138 respectively. Since the percentage of difference between both runoff coefficients were less than 1%, there was not significant changes of runoff coefficient in both experiments. Therefore, the temporal variation of rainfall intensity was not critical in affecting the runoff volume in this experiment.

In study case 2, the spatial distribution of rainfall was varied under constant rainfall condition. In experiment 2B, the peak discharge was determined as 74.3cm^3/s when rainfall only occurred at upstreamcompared to the peak discharge of 50.0cm^3/s under constantly distributed rainfall in experiment 2A (Figure 2c). The difference of peak discharge was 24.3cm^3/s which is 39.1%. The result showed that there were significant changes in peak discharge between uniformly (2A) and non-uniformly (2B) distributed rainfall. The rainfall volume was identical in both experiments in study case 2 but the distribution of rainfall was concentrated at upstream in Experiment 2B. The non-uniformly distributed rainfall had generated higher rainfall intensity at upstream that led to higher peak discharge in experiment 2B. The beginning of runoff accretion was lagged by 9 minutes in experiment 2B when compared to experiment 2A. This was due to the non-uniform distribution of rainfall that caused the runoff at upstream to travel longer distance to reach the outlet in experiment 2B. The times to peak in both experiments were almost identical which was recorded after 28 minutes and 27 minutes in experiment 2A and 2B respectively. This was also happened to the decrement of runoff when the rainfall stopped. The falling limb indicated similar decrement rate of runoff after 30 minutes of the rainfall event.

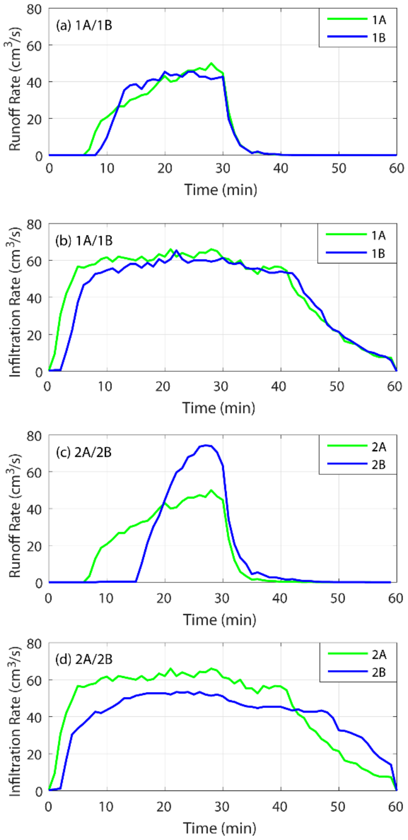

Figure 2 Comparison of runoff rate (a and c) and infiltration rate (c and d) under constant (1A) and temporally varied (1B) rainfall events; Uniform (2A) and non-uniform (2B) rainfall events.

The infiltration volume was higher in experiment 2A (Figure 2d). The difference of infiltration volume between two experiments was 19,800 cm3 which was 12.81%. The time taken for the infiltration rate to reach the infiltration capacity at upstream was shorter due to higher rainfall intensity in experiment 2B compared with the uniform rainfall in experiment 2A. The non-uniform rainfall had resulted higher runoff volume and hence higher runoff coefficient. The runoff coefficients for experiments 2A and 2B were determined as 0.2119 and 0.2313 respectively. The difference of runoff coefficient was 8.75%. The results showed that the variation in spatial distribution of rainfall had affected the runoff volume. The rainfall that concentrated at upstream had contributed to higher excess rainfall (surface runoff) and caused the increment in runoff coefficient.

B. *Influences of land surface imperviousness*

Study cases 3A-3D were conducted under constant and uniform rainfall condition (SU) that the rainfall intensity was fixed at 250 mm/hr for 30 minutes and equally distributed over the catchment. The impervious surface area was varied at 0%, 25%, 50% and 75% in study cases 3A-3D respectively. In study cases 3A-3D, the rising limb of hydrographs shows a gradually increment of flowrate with slightly fluctuations. There were no significant changes of peak discharge in study cases 3A-3C. However, the study case 3D has recorded highest peak discharge of 53.3 cm^3/s. After 30 minutes of rainfall event, the falling limb of the hydrographs shows a steep drop of flowrate in all study cases (Figure 3a). In study case 3A and 3B, the infiltration rate increased sharply and reached a relatively constant rate of approximately 60.0 cm^3/s after 5 minutes of rainfall. When the percentage of impervious surface increased in study cases 3C and 3D, a longer duration of approximately 20 minutes was taken to achieve a relatively constant infiltration rate of 60.0 cm^3/s (Figure 3b).

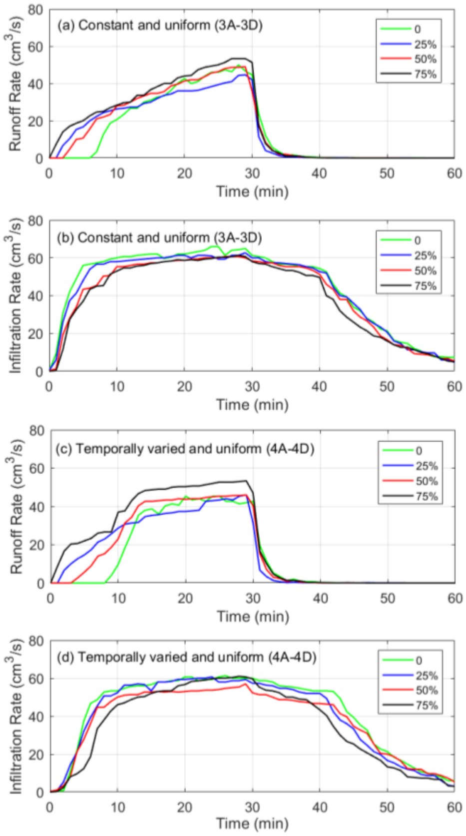

Figure 3 Comparison of runoff rate (a and c) and infiltration rate (b and d) for 0, 25%, 50% and 75% surface imperviousness under constant (a and b) and temporallyvaried (c and d) rainfall events.

Study cases 4A-4D were conducted under temporally varied and uniform rainfall (VU) condition. The total rainfall volume and duration were identical in both study cases in which the rainfall volume applied in study cases 3A-3D was distributed at 5 minutes interval in study cases 4A-4D (Table 1). In study cases 4A-4D, the rising limb of hydrographs shows a relatively sharp increment of flowrate at the beginning of 15 minutes when compared to study cases 3A-3D. The peak discharges for study cases 4A-4C was almost identical at approximately 46.0 cm^3/s. The peak discharge for study case 4D was recorded at 53.3 cm^3/s which was higher than study cases 4A-4C. No significant change in peak discharge was observed at 0, 25% and 50% of impervious surface except at the higher imperviousness of 75% in both constant and temporally varied rainfall conditions. This might due to the high infiltration capacity of the sand used in the experiment. Similar trend of the changes of infiltration rate in study cases 3A-3D can be observed in study cases 4A-4D. The infiltration rate has increased sharply at the beginning of rainfall and reached a relatively constant rate of 55.0 – 60.0 cm^3/s after 10 minutes of rainfall in study cases 4A-4D (Figure 3d). After 30 minutes of rainfall event, the falling limb of the hydrographs shows a steep drop of flowrate in all study cases 4A-4D (Figure 3c).

However, we have calibrated the flow meter prior to the experiment, there was still discrepancy between the measured (by flow meter) and actual rainfall volume (estimated by submission of runoff and infiltration losses using volumetric method) at approximately 3-5%. In the following analysis, the actual rainfall volume was considered. In the experiment, the infiltration loss was high due to the characteristics of the sand used. The infiltration loss has achieved 76% of total rainfall volume in the base case (experiment 1A/3A) at 0% of impervious surface under constant rainfall condition. In the temporally varied condition, the infiltration loss has reduced to 75%. The infiltration loss was corresponded inversely to the increment of the imperviousness of surface (Figure 4a). At 75% of imperviousness, the infiltration loss has reduced to 68% and 63% for constant and temporary-varied rainfall conditions respectively (Figure 4a). The results have indicated that the infiltration loss was lower under the temporally varied rainfall event. This discrepancy was more significant when the surface imperviousness increased. This was contributed by the inconsistent of temporal rainfall distribution where the rainfall intensity was lower at the beginning and end of rainfall event in temporally varied rainfall condition when compared to the constant rainfall case that limited the infiltration loss. This phenomenon also reflected in the runoff coefficient for the catchment. The runoff coefficient was higher under temporally variedrainfall condition compared to constant rainfall condition (Figure 4b). The rainfall intensity of temporally varied rainfall was higher than the average rainfall intensity of constant rainfall in the middle of a rainfall event. This increment of rainfall intensity had contributed higher excess rainfall (runoff) to the catchment in the temporally varied rainfall condition.

The results indicated that the runoff coefficient was linearly corresponded to the percentage of surface imperviousness and was higher in temporally varied rainfall events (Figure 4). However, the runoff coefficient as suggested in Rational method [2] is based on specific land use which does not reflect the exact percentage of impervious surface and do not consider the temporal variations of rainfall. Such simplicity could lead to inaccuracy in estimating the flood peak.

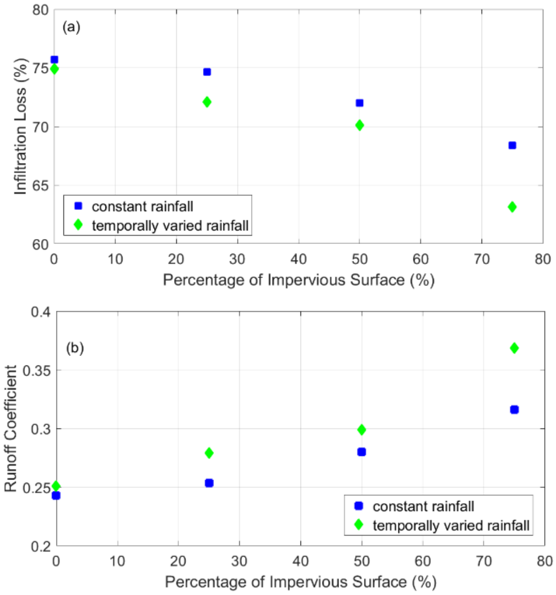

Figure 4 (a) Infiltration Loss and (b) Runoff Coefficient for 0, 25%, 50% and 75% surface imperviousness.

IV. CONCLUSIONS

Development has led to increasing of impervious surface and could be a major cause of flood in developed area as less water infiltrating into the soil surface. Runoff coefficient as one of the parameters used in estimating peak discharge, the accuracy of the parameter is thus crucial in drainage design. A series of experiment were conducted to investigate the influence of rainfall characteristics and percentage of imperviousness to the runoff.

This study revealed that non-uniform rainfall has influenced the generation of runoff volume and peak discharge. The non-uniform rainfall has led to higher excess rainfall (surface runoff). It was due to concentrated rainfall intensity on the upstream of catchment. The infiltration loss decreased when the percentage of surface cover (indicated as development) increased in this study. As a result, the runoff coefficient increased due to less infiltration through the soil surface. The study revealed that the rainfall temporal pattern has affected the runoff coefficient. The runoff coefficient for temporally varied rainfall event was higher compared to the uniform rainfall event. However, there was no significant changes in peak discharge between both constant and temporally varied rainfall conditions.

This study demonstrated that the runoff coefficient based on land use might not represent the real hydrological characteristics of a catchment and the assumption of uniform distributed rainfall may underestimate the peak discharge and runoff coefficient. However, the laboratory scale of the investigation and the type of soil may not represent the complexities at the field scale, further investigation is needed for different scale of catchment and soil characteristics.

ACKNOWLEDGEMENT

The authors acknowledge the assistance and laboratory facilities provided by UniversitiTeknologi MARA (Pulau Pinang Branch).

V. REFERENCES

[1] N.W. Chan, “Impacts of Disasters and Disaster Risk Management in Malaysia: The Case of Floods” in *Economic and Welfare Impacts of Disasters in East Asia and Policy Responses,ERIA Research Project Report 2011-8*, Jakarta, pp. 503-51, 2012.

[2] Urban Storm Water Management Manual For Malaysia - 2nd Edition. *Department of Irrigation and Drainage (DID) Malaysia*, Kuala Lumpur, Malaysia, 2012.

[3] S. Grimaldi, and A. Petroselli, “Do we still need the rational formula? An alternative empirical procedure for peak discharge estimation in small and ungauged basins”, *Hydrological Sciences Journal*, 60(1): p. 67-77, 2015.

[4] R. Merz, G. Blöschl, J. Parajka, “Spatio-temporal variability of event runoff coefficients”. *Journal of Hydrology*, vol. 331, pp. 591-604, 2006.

[5] C.B. Young, B.M. McEnroe, A.C. Rome, “Empirical Determination of Rational Method Runoff Coefficients”, *Journal of Hydrologic Engineering*, vol 14, pp.1283-9, 2009.

[6] N. Dhakal, X. Fang, T.G. Cleveland, D.B. Thompson, W.H. Asquith, L.J. Marzen, “Estimation of Volumetric Runoff Coefficients for Texas Watersheds Using Land-Use and Rainfall-Runoff Data”, *Journal of Irrigation and Drainage Engineering*, vol. 138, pp. 43-54, 2012.

[7] S. Savary, A.N. Rousseau, R. Quilbé, “Assessing the Effects of Historical Land Cover Changes on Runoff and Low Flows Using Remote Sensing and Hydrological Modeling”, *Journal of Hydrologic Engineering*, vol. 14, pp. 575-87, 2009.

[8] D. Kusumastuti, D. Jokowinarno, S. N. Khotimah and C. Dewi, “The Use of Infiltration Wells to Reduce the Impacts of Land Use Changes on Flood Peaks: An Indonesian Catchment Case Study”,*Pertanika Journal of Science & Technology*, 25(2), 2017.

[9] A.A. Mamun, A. Hashim, and Z. Amir, “Regional Statistical Models for the Estimation of Flood Peak Values at Ungauged Catchments: Peninsular Malaysia”,*Journal of Hydrologic Engineering*, 17(4): p. 547-553, 2011.

[10] A. Moussouni, L. Mouzai, M. Bouhadef, “Laboratory experiments: Influence of rainfall characteristics on runoff and water erosion”, in *International Journal of Civil and Environmental Engineering*, *Waset*, vol. 68, pp. 1540-3, 2012.

[11] P. Das, K. Mahmud, S. Karmaker, “Surface-Runoff Characteristics under Simulated Rainfall Conditions”, Progressive Agriculture, vol. 24 (1-2), pp. 219-227, 2014.

[12] Q. Ran, D. Su, P. Li, Z. He, “Experimental study of the impact of rainfall characteristics on runoff generation and soil erosion”, *Journal of Hydrology*, vol. 424-425, pp. 99-111, 2012.