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ORIGINAL PAPER

Runoff coefficient (*C* value) evaluation and generation using rainfall simulator: a case study in urban areas in Penang, Malaysia

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Abstract

The different peak discharge value estimated in the rational method (RM) model is caused by the various methods used to determine the runoff coefficient (C) parameter. The C value can be defined as the total amount of rainfall generated to become the runoff. Various studies have been conducted to produce C values that differ from one to another. For example, the C values suggested by the Manual of Storm Water Management (MSMA) and the American Society of Civil Engineers (ASCE) differed. To estimate C values, land use classification is confusing, unorganized, and not uniform, and therefore, the application of suggested C value is still doubtful to be applied in Malaysia. Thus, this research focused on estimating the C value based on the land use classification for urban areas in Penang using a rainfall simulator. The runoff coefficient will be generated from various surface types at a plot scale representing urban land use. The result obtained shows that the C values were 0.79–0.89 (asphalt), 0.85–0.92 (concrete), 0.77–0.89 (zinc), 0.73–0.85 (brick), 0.85–0.96 (asbestos), 0.8–0.93 (tiled roof), 0.17–0.63 (grass 2°–7°), and 0.35–0.69 (bare soil 2°–7°). The variation of the C value was influenced by the total amount of rainfall, surface imperviousness, soil moisture, soil and surface characteristics, slope, and vegetation cover. There were significant differences in the C value obtained in this study compared to the C value of MSMA (asphalt and brick) and the C value of ASCE (concrete and asbestos, grass, and exposed soil). Four factors that influenced the differences of C values in this research were environmental conditions, namely scale, surface physical condition, and soil antecedent moisture. The multiple comparison test showed a significant difference in the peak discharge estimated using RM compared to the gauged peak discharge. Nevertheless, peak discharge estimated from various C values in the RM did not show any statistical differences. In conclusion, this study found that the rainfall simulator could be used as a suitable and efficient modus operandi in terms of cost and time for runoff studies.

Keywords Discharge · Runoff coefficient · Rainfall · Land use · Rainfall simulator

Introduction

The continuous increase of the human population in the twenty-first century has led to modifications within catchments and dramatically changed the world's landscapes (Walsh, 2000). Irrespective of the cause, a study showed the exploitation and depletion of forested areas from 83% in 1972 to 60% in 1992 (Bernard & DeKoninck, 1997), and the Earth's land surface was more covered by anthropogenic constructions (Walsh, 2000; Kadioglu and Sen 2001). The increase of urbanization due to rapid economic development, especially in Southeast Asia, has increased impervious surfaces such as roads, parking lots, and rooftops. These impervious surfaces are well known for having the potential to create urban stormwater runoff and water quality problems (Lawrence et al. 1996). For instance, impervious areas reduce the land surface's capacity to absorb the rains, and almost 90% of the rains will run as surface runoff. The volume of runoff and the size of the flood peak resulting from each storm increase reduce the lag period between the rainfall and peak flow. Thus, the more the runoff, the more water enters drains and rivers, ending up with a greater frequency of flooding (Kafy et al, 2021). According to Roesner (1999), peak flows during the storm were generated by two to ten

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times greater than before urbanization. However, Schueler (1987) reported that the peak flow generated in residential areas was more significant than three times in a year and six times per year for commercial sites. Earlier studies had also proven that runoff is the main influencing factor for the degradation of stream water quality (Croke et al., 2005; Herngren et al., 2004; DeBano, 2000; Abu-Ashour & huang Lee, 2000).

Knowing the effects of storm runoff contributed to the catchments mentioned above (runoff quantity and quality) is crucial for estimating and analyzing the runoff peak flows. The rainfall–runoff relationship plays a vital role in any water resources planning, design, operation, and maintenance study (Sen et al. 2008). To date, there are many empirical models to estimate the storm peak discharge in catchments. Consequently, the rational method (RM) is the all-time favorite model since it was introduced by Kuichling (1889). Suitable to be applied in small ungauged catchments (not more than 2.5 km^2), the RM was popular for its simplistic relationship between the peak discharge, Q, intensity, I, area, A, and runoff coefficient, C. The most considerable modification that has been made in the typical RM was the addition of empirical relationship among the intensity, duration, and occurrence probability of the rainfall (Ben-Zvi, 1989). However, according to Ben-Zvi (1989), wide differences are found between discharges computed by different practitioners. He also agreed with McCune et al. (1984) that the source of differences in peak discharges was believed to lie in the diversity of the methods for determining the parameters C and t_c.

According to Merz et al. (2006), the event runoff coefficient, C, is the portion of rainfall that becomes direct runoff during an event. Runoff coefficient is widely used as a diagnostic variable of runoff generation in process studies and an important input parameter in hydrologic design. In practice, the C values are typically obtained from tables of suggested values for a given soil, land use, and slope categories appropriate for a given watershed. Considerable judgment and experience are required in selecting satisfactory values of C for design. There are three ways to calculate and estimate the runoff coefficient in the literature: deterministic, probabilistic, and fuzzy logic approach. C values were traditionally determined using a deterministic approach in which the RM was used as a rainfall–runoff model to illustrate the peak discharge of an actual rainfall events situation observed. Therefore, in this case, the C values were determined as a group of various watershed physical parameters, together with area and rainfall rate. An alternative interpretation of C values probabilistically in RM was used to predict peak discharge for a specific return period. At the same time, the fuzzy logic approach was based on linguistic expression, which considers the hydrological parameters in a linguistic manner and subgrouping. The C values that the American Society of Civil Engineers has suggested are among the values that have been used for design purposes widely.

In Malaysia, engineers use the C values suggested by the Department of Irrigation and Drainage (DID) in 2000, adapted from Australian Rainfall and Runoff (1977). Interestingly, this manual does not justify the selected rational C values. Young et al. (2009) have reviewed a few research studies with estimated C values for watersheds. For instance, Shaake et al. (1967) estimated the C values at small urban watersheds used in Baltimore, MD. French et al. (1974) carried out a C value study for 37 watersheds in New South Wales, Australia, ranging in size up to 250 km^2. In 1995, Hotchkiss and Provaznik estimated the C values for 24 rural watersheds in south-central Nebraska. Young et al. (2009) also established appropriate rational C values for rural watersheds in Kansas with areas up to 30 mi^2. Keya and Hama Karim (2020) discovered that when rainfall intensity and slope increased, so did the rate of runoff and sedimentation. Silty clay soil with a 15% slope provided the best performance at a 20 mm h^{-1} intensity. A digital filter, used by Cardoso et al. (2019), was used to separate the direct runoff from the overall flow, allowing them to calculate C. For instance, a field rainfall simulator was used to determine the protective effect of agricultural crops on the soil erosion process by Davidová et al. (2015).

Recent studies by various researchers show the differences in C values. For example, C values that have been suggested are inconsistent, used different and confusing land use classification, and the reliability and suitability of these values to be applied in Malaysia is unknown or questionable (Table 1). Nevertheless, the research on the characteristics of urbanized and urbanizing catchments areas is relatively scarce, especially within Malaysia itself. Thus, there appears an urgent need to solve these issues. This study estimates

Table 1 Different C values for urban land uses suggested by MSMA and ASCE

Land use	Runoff coefficient (C)	
	MSMA (2000)	ASCE (1969)
Residential	0.8–0.9	0.3–0.7
Roofs	0.8–0.9	0.75–0.95
Road/ asphalt	0.8–0.9	0.7–0.95
Pavement	0.6–0.9	0.7–0.95
Parks	0.1–0.63	0.1–0.35
Bare soil	0.4–0.85	-
Unimproved area	0.1–0.63	0.1–0.3
Open space	0.1–0.5	-
Industrial (light)	-	0.5–0.8
Industrial (heavy)	-	0.6–0.9
Commercial	0.6–0.9	0.5–0.95

the *C* values according to various urban land uses, specifically in Penang, Malaysia. The *C* values were derived from different surfaces such as asphalt, concrete, different types of roofs (zinc, asbestos, concrete), and bricks under a pressurized rainfall simulator. The *C* values obtained from this experiment will be compared to the *C* values suggested by DID and ASCE.

Data and methodology

In this study, the "*C*' values according to the values given in MSMA and ASCE will be reviewed and evaluated, as well as the procedure of determining the runoff. Table 1 shows the different *C* values for urban land uses, which are suggested by MSMA and ASCE. However, the approach for determining runoff processes has been modified. Fieldwork was conducted using an experimental rainfall simulator approach instead of using a gauging approach during the storm event. Secondary data collection is vital in this study, mainly on the rainfall intensities in Malaysia and other natural rainfall characteristics studied by previous researchers as references to conduct the rainfall simulator calibration to get similar characteristics as the natural rainfall in Penang, Malaysia. Using the rainfall simulator, sampling will be carried out to evaluate the current "*C*" values from various surface studies. Gauging storm events in this study was done only to compare the *C* values derived from the rainfall simulator and the actual situation by determining the peak discharge, whereas statistical analysis was used to compare the mean differences in *C* values from this study (C_{test}) with *C* values from the literature (C_{ASCE} and C_{MSMA}).

Study area

Penang Island was chosen to conduct and determine the ability of the rainfall simulator to replicate natural rainfall for runoff coefficient study, which can mostly be representable in the urban characteristics of Malaysia. Penang Island in Malaysia (5° 21′ N, 100° 19′ E) encompasses an extensive, rapidly expanding area of 645,000 people (in the year 2005), located over limestone and granite with a thin alluvium surface. It has an area of 299 km^2 consist of 36% of highland (>76 m), which is not suitable for urbanization, while 35.7% (107 km^2) of low land are urban areas. The climate is warm and humid throughout the year, as characterized by the equatorial climate with a mean annual rainfall of 2301 mm (year 2000–2005). The rainfall is subjected to localized and convective storms generated by the inter-monsoon seasons or Sumatra wind system in the months of April/May and October/November. The southwest monsoon (normally from May to September) produces less rain on the west coast of the Peninsular. Average daily temperatures range from a minimum of 25 °C to a maximum of 33 °C in the study area. Becoming one of the earliest urban areas in Malaysia, the rapid development of Penang Island over the past 50 years has led to an extensive urban area characterized by a heterogeneous landscape consisting of residential, commercial, industrial, agricultural, transportation, and institutional. The urban core of Penang city consists of a mosaic of land use types that include a significant impervious surface cover. Urban land-use type classifications were obtained from the Urban and Rural Planning Department (JPBD), topography maps, and Penang Municipal Council (MPPP) to be evaluated and compared for new urban land use categorization. Runoff coefficient will be derived from different surfaces such as asphalt, concrete, different types of roofs (zinc, asbestos, concrete), bricks, and grass. Table 2 shows the land use classification and proposed plots from the various surface of Malaysia's urban area, which will be used in this study. These surfaces were selected at the Universiti Sains Malaysia site, located at 5° 25′ N, 100° 19′ E (Fig. 1). Stormwater gauging at the outlet of the study area was done for runoff coefficient verification derived from the rainfall simulator. Having a sum area of 0.37 km^2, six types of urban surfaces cover dominantly by asphalt (0.032 km^2), concrete (0.183 km^2), bricks (0.027 km^2), roofs (zink, 0.012 km^2; clay, 0.092 km^2), and grass (0.023 km^2). Data will be collected from these various surface studies and will be analyzed afterwards. (Fig. 2)

Rainfall simulator

It was well known that a rainfall simulator is an alternative approach to produce rainfall that is controllable in time and space and allows the repetition of many years of rainfall in a concise period. This study uses a pressurized type rainfall simulator (Fig. 3) that satisfies specific criteria such as runoff sample collection efficiency, rainfall intensity, and event duration for runoff experiment purposes. Calibration of rainfall simulator is essential in order to produce rainfall simulations that have similar characteristics of natural rainfall.

The simulator devices for this experiment consist of a triangular frame mast with a height of 3 m, an arm of 3 m length mounted at the top of the mast, and 3 nozzles spaced 1.1 m apart are installed at the nozzle boom, such that the height of the nozzle is 2.4 m. According to Duncan (1972), this height is adequate for creating terminal velocities like natural rainfall for all drop sizes. Full jet type nozzles with wide-angle square spraying, model 1/2HH-50WSQ (Spraying Systems Co. USA) were chosen for their wide spraying angle, the square wetted zone, and the high uniformity of the spray. Water under adequate pressure was supplied to the nozzle by a 13-hp water pressure pump. Intensity and uniformity were measured using 500-ml beakers (5 cm diameter) kept in a grid pattern and measuring the rainfall

Table 2 Land use classification and proposed plots from the various surface of Malaysia's urban area

Classification	Land uses (local plan)	Surface type
1. Buildings	- Residential	Roofs
	- Industrial	- Concrete
	- Institution (educational, hospital, religion, etc.)	- Zinc
	- Business/commercial	- Asbestos
		- Clay
2. Surfaces/texture/pavement	- Transportation	- Asphalt
	- Roads, highways	- Simen
	- Airports	- Grass
	- Bus station	- Concrete
	- Car parks	- Bricks
	- Open areas	- Scrubland/meadows
	- Scrubland/meadows/park lawns	- Bare soil
	- Unimproved areas	- Grasscrete
	- Construction site	- Kerb concrete
	- Open space and recreational	- Gravel
	- Parks, cemeteries	
	- Playground	
	- Field/ grass areas	
	- Pedestrian	
	- Stadium	
	- Drives and walks	
	- Tin mining land	
3. Soil texture/slope	- Open areas/bare soil	- Lawns/sandy soil (2–7%)
		- Lawns/heavy soil (2–7%)

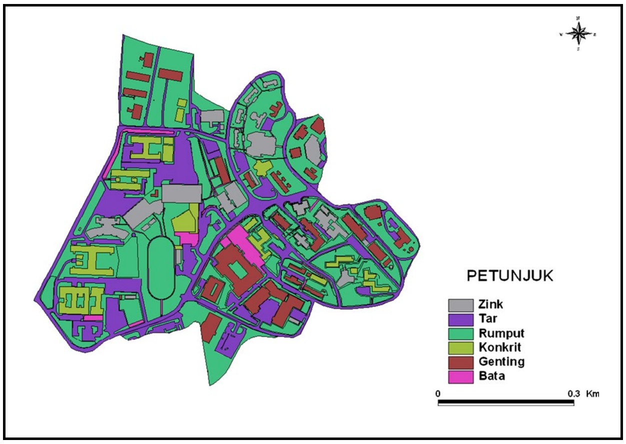

Fig. 1 Experimental surfaces at the study area

volumes collected over various intensities and durations. The rainfall simulator provides the intensity of 70 mm/h, 88 mm/h, 148 mm/h, 165 mm/h, 190 mm/h, and 210 mm/h for this study, which is within the range of 2-year average recurrent interval (ARI) for severe natural rainfall in Penang. The chosen plot area had dimensions of 2 × 1.5 m and an average coefficient of uniformity (Cu) of 80 to 95%, which were exceeded the minimum value of a disperse irrigation system (Christiansen 1942). The Cu is defined as the deviation of individual observations from the mean over the mean value and number of observations. A high Cu value indicates a small deviation from the mean intensity. The impact of rainfall intensity on Cu was found to be negligible. The simulated rainfall's drop size distribution (DSD) was measured using the flour pellet method described by Hudson (1963).

Fig. 2 Urban surfaces for rainfall simulator experiment

Fig. 3 Pressurized rainfall simulator

The DSD obtained for this rainfall simulator ranged from 0.8 to 4.1 mm for tropical raindrop size (Tew Kia Hui, 1999). The median drop size for the simulated rainfall was calculated as 1.3 to 2.0 mm. The kinetic energy was determined to be 0.29 MJ ha^{-1} mm^{-1} based on tropical rain (Hudson, 1965). The runoff water was collected in a trough and was vacuumed continuously into a 28L container for runoff volume measurement.

Data analysis

The sampling strategy in this study can be divided into three parts. Firstly, the estimation of runoff coefficient was derived from rainfall simulator on various urban surfaces. Each surface consists of three replicates of obtained *C* values, representing each intensity of the rainfall simulator experiment. An average of *C* value from the three replicate data was used for analysis. Secondly is the application of runoff coefficients derived from the rainfall simulator (C_{test}) and runoff coefficients from the literature (C_{MSMA} and C_{ASCE}) into the RM formula. Analysis in this part involving the mean differential percentage was calculated from these *C* values. Thirdly, the comparison of peak discharge estimates was derived directly from the application of RM and estimates derived from actual storm events. Statistical Package for Social Sciences (SPSS) software version 16.0 was used to run the statistical test analysis. The main statistical data analysis involving descriptive analysis will highlight and describe the data as a whole, including the mean, median, variance, standard deviation, kurtosis, and skewness. Tukey honestly significant difference test (Tukey HSD) will determine the significant difference of multiple comparisons between mean peak discharge with different *C* values application in RM and real events peak discharge gauging estimation.

Result and discussion

Experimental C value estimation

The methodology outlined in the "Data and methodology" section was used to estimate the rational *C* values for average recurrent intervals of 2 years from various urban surfaces (asphalt, zinc, concrete, tiled roofs, grass, and bare soil). The amount of rainfall simulation that becomes runoff in a 3 m^2 plot is used to determine *C* values in this study. Figure 4 shows the distribution of RM *C* values that were determined in this study for each urban surface, as mentioned earlier. The tendency of increasing *C* values obtained was influenced by the intensity of the rainfall simulation provided. The higher the rainfall intensity, the higher the *C* values obtained.

The result indicates that grass plots gave the lowest mean *C* value of 0.41 with a range of *C* values from 0.17 to 0.63, followed by bare soil plot, 0.54, ranging from 0.35 to 0.69. Bricks pavement has a mean of 0.80 (range from 0.73 to 0.85), while the mean value for roofs with zinc surfaces was 0.84 (range 0.77 to 0.89). The mean of *C* values for asphalt surfaces was 0.85 (range 0.79 to 0.89). Roofs tiled with clay surfaces have an average C value of 0.88, ranging from 0.80 to 0.93. Concrete surfaces have quite a high value of mean *C*, 0.89 (range 0.85 to 0.92). The highest value of mean *C* in this experiment was derived from roofs tiled with the asbestos surface, which was 0.92 (range 0.85 to 0.96). Point to be noted that the mean values were slightly lower than the median and that the *C* values were larger than the mean, where smaller *C* values were highly further distributed (Table 3). Among the surfaces tested in this study, the standard deviation for the grass plot gave the most significant value (0.181), indicating a larger spread of scores within the *C* values. Descriptive statistics analysis also has proved that the distribution of *C* values derived from this experiment was negatively skewed.

A non-linear correlation between the rainfall intensity and runoff coefficients highlights the uncertainty and variability in the experimental *C* value estimates. The trend of increasing *C* values was influenced by the rainfall depth and surface impermeability characteristic factor. Impervious surfaces

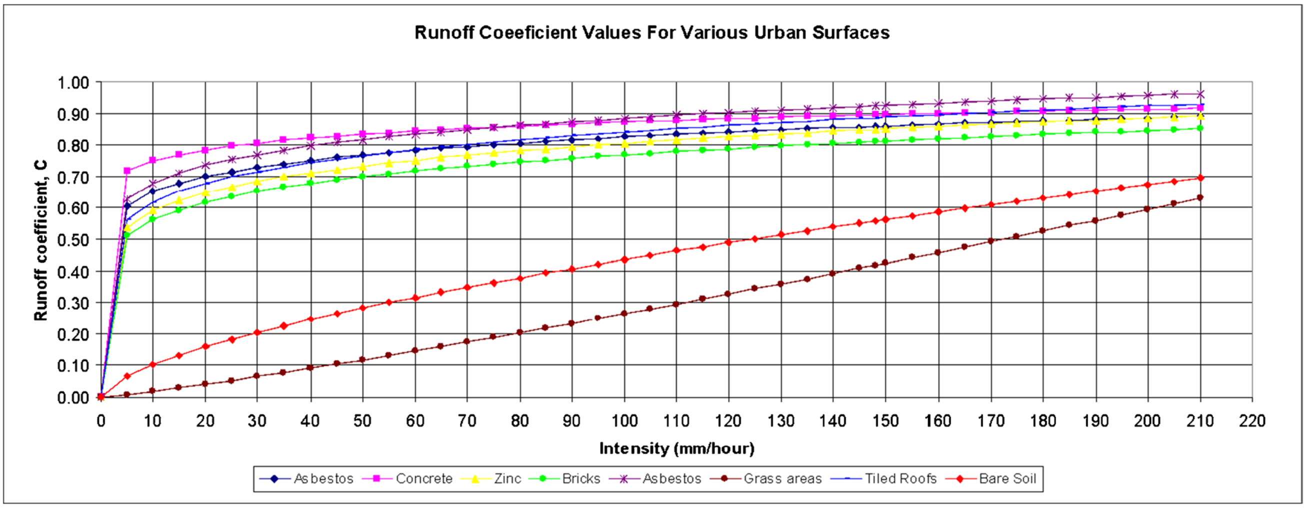

Fig. 4 Runoff coefficient for various experimental surfaces

Table 3 Summary of descriptive statistics for rational *C* values

Descriptive statistics	Surfaces							
	Asbestos	Bricks	Tiled roofs	Concrete	Grass	Bare soil	Asphalt	Zinc
Mean	0.92	0.8	0.88	0.89	0.41	0.54	0.85	0.84
Median	0.93	0.815	0.895	0.9	0.445	0.58	0.865	0.855
Standard deviation	0.045	0.049	0.052	0.028	0.181	0.137	0.040	0.049
Range	0.11	0.12	0.13	0.07	0.46	0.34	0.1	0.12
Skewness	−0.708	−0.689	−0.796	−0.716	−0.355	−0.596	−0.813	−0.689

such as all types of roofs (zinc, asbestos, and clay), concrete, asphalt, and bricks estimate higher *C* values than impermeable surfaces (bare soil and grass). Impervious surfaces tend to be saturated with high rainfall volume and easily create surface runoff. According to Tan Boon Tong, high-quality bricks used for building construction in Malaysia have an impermeable rate of not more than 1/6 of a brick volume. This means that an excess of 1/6 of rain will automatically create surface runoff. However, saturated surfaces will result in less *C* variability and become much more constant in the end. This situation can be referred to the roof surfaces, asphalt, bricks, and concrete in the figure at high intensity. Opposite from impervious surfaces, the *C* values of less impervious surfaces (bare soil and grass) were influenced by rainfall depth, soil structure, soil antecedent moisture content, and vegetation cover, which will also affect the soil infiltration rate and runoff occurrence.

High *C* values estimated from bare soil surfaces compared to grass surfaces may be due to the rainfall compaction of soil aggregate. Particles can be packed together in laminar sheets, with small and large particles interacting with one another. Sandy loam soil has been used in this experimental purpose. Sandy soils are generally porous, but they may appear massive when containing a certain amount of silt and clay. Silt is tight, has small pores, and drains poorly. This process leads to less infiltration into the soil, whereas increases the amount of surface runoff.

The comparison of C values

A comparison of *C* values has been made between the *C* values derived from this experiment (C_{test}) and the *C* values that have been suggested by ASCE (C_{ASCE}) and MSMA (C_{MSMA}). To make the comparison, C_{MSMA} values were obtained from the runoff coefficient graph of Australian Rainfall and Runoff (1977) based on the intensities 70, 88, 148, 165, 190, and 210 mm/h. In the meantime, C_{ASCE} values were obtained from the ASCE manual, and the values for the comparison purposes were taken as suggested by McCune (1998) since the *C* values were presented in range values. Figure 5 shows the mean differences of these *C* values accordingly to different surfaces. Clearly, it indicates that C_{test} mean values produced the intermediate values from C_{ASCE} and C_{MSMA}. The C_{ASCE} gave the lowest mean values among all, while C_{MSMA} estimated much higher mean values most of the time for all surfaces. The largest discrepancies of tested values (C_{test}) were for grass and bare soil, which differed by 19% and 22% for C_{MSMA}, 107% and 317% for C_{ASCE}. Tested asphalt,

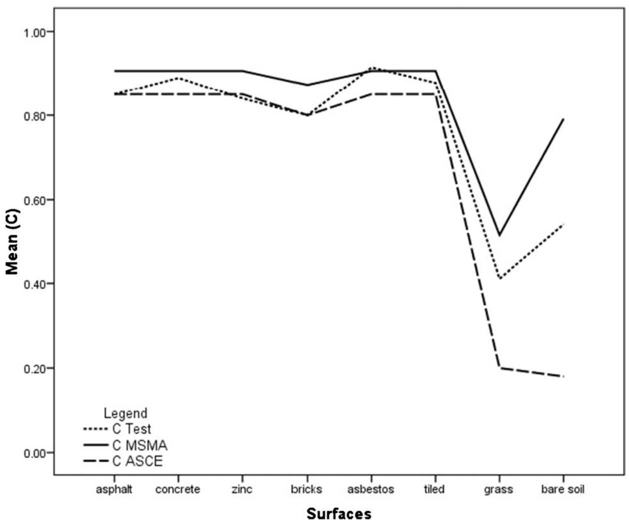

Fig. 5 The comparison of experimental mean *C* values

concrete, zinc, bricks, and tiled roof surfaces derived from the rainfall simulator gave much lower mean values compared to C_{MSMA} with the decrement of 6%, 2%, 7%, 8%, and 3%, respectively. Only tested asbestos surface gave 1% increment of percentage when compared to C_{MSMA}. Higher mean *C* values were derived from rainfall simulators on concrete, asbestos, and tiled roof surfaces. The C_{test} for concrete, asbestos, and tiled roofs gave a different percentage of 5%, 8%, and 3% compared to C_{ASCE}, respectively. However, the mean C_{test} values for asphalt and brick surfaces remained unchanged. Unlike others, zinc had a reduction of 1% when comparing C_{test} to C_{ASCE}. (Table 4).

The tremendous differences in *C* values estimated from experimental plots and *C* values from the literature are most likely due to differences in surface properties. The four main factors that influenced the disagreements of *C* values are (1) environment situation, (2) scale, (3) physical characteristics of surfaces, and (4) antecedent moisture and soil water table. As mentioned earlier, this study uses a rainfall simulator to generate runoff and estimate *C* values on different surfaces. Different from the *C* values that have been estimated in this experiment, the *C* values that have been suggested by the Department of Irrigation and Drainage (2000) and American Society of Civil Engineers (1969) were based on real storm events' rainfall–runoff data. The experiment situation, which is obviously different in terms of weather conditions, may undoubtedly influence the collected results. For example, the rainfall simulator experiment took place on a sunny day with an ambient relative humidity percentage from 35 to 85%. The process of infiltration and evaporation influenced the experimental runoff data collection. The evaporation process did not influence the real storm events, for the air has reached its maximum humidity and less infiltration as the rainfall increase.

The rainfall simulator experiment in this study only measures the runoff on a plot scale of 3 m^2. Unlike the plot scale experiment situation, real storm events measure runoff at catchment scale, creating more runoff than small plot scale. This may be the reason for the high increasing percentage of experimental C values, compared to *C* values that ASCE has suggested.

Besides that, experimental runoff plots need to consider the physical surface condition. Lower average *C* values obtained from the experimental plots comparing to C_{MSMA} and C_{ASCE} may be caused by the crack surface of bricks. Crack surfaces will increase the amount of infiltration into the soil and reduce the amount of surface runoff.

Furthermore, the increment of experimental mean *C* values comparing to C_{ASCE} for grass and bare soil plots were resulted from soil antecedent and soil water table factor. The use of rainfall simulation on these plots on a daily basis has increased soil moisture content and influenced the rise of the soil water table. High soil moisture content will decrease the infiltration rate whenever the experiment occurs, thus contributing to more surface runoff.

The reliability of experimental C values

A study conducted by Hayes and Young (2006) found that the runoff coefficient did not appear to vary with rainfall intensity but with peak discharge, which is highly correlated

Table. 4 The different percentage of experimental *C* values

Surface type	Runoff coefficient (C)			Different percentage (%)	
	Test	MSMA	ASCE	Test and MSMA	Test and ASCE
Asphalt	0.85	0.91	0.85	−6	0
Concrete	0.89	0.91	0.85	−2	5
Zinc	0.84	0.91	0.85	−7	-1
Bricks	0.80	0.87	0.80	−8	0
Asbestos	0.92	0.91	0.85	1	8
Tiled roofs	0.88	0.91	0.85	−3	3
Grass (2°–7°)	0.41	0.51	0.20	−19	107
Bare soil (2°–7°)	0.54	0.70	0.13	−22	317

with rainfall intensities. This means that there is a strong relation between peak discharge and runoff coefficient, which, therefore, using an insufficient *C* value may overestimate or underestimate storm peak discharges. Determination of parameters used in the design method (storm, basin, and runoff characteristics) will assess the accuracy of design peak discharge. Justifications on the reliability of experimental *C* values that have been derived from the rainfall simulator experiment are essential in this study. Determination of experimental *C* value reliability will justify how good the applicability of these values in the computation of design peak discharge estimation using the RM. In order to do so, peak discharges with the application of *C* values (experimental *C* values, C_{MSMA}, and C_{ASCE}) in the RM are compared to 29 events storm peak discharge estimation of the USM study area. According to Table 5, the highest peak discharge value obtained from the real storm event gauging was 3.93 m^3/s, giving a total rainfall depth of 157 mm for 22 min. The lowest peak discharge value was 0.03 m^3/s with a total rainfall of 15 mm for 27 min.

Table 5 shows the result for peak discharge comparison between the application of the RM and real storm event peak discharge. The result indicates no significant difference between all of the RM applications when $p > 0.05$. However, there is a significant difference between real event peak discharge and RM. This demonstrates that the experimental

Table 5 Real storm event and RM peak discharge

Time begin	Time end	Rainfall duration (min)	Rainfall total (mm)	Peak water level (m)	Peak discharge gauging (m^3/s)	RM peak discharge, Qp (m^3/s)		
						experiment	MSMA	ASCE
11/6/08 13:45	11/6/08 14:12	27	15	0.20	0.03**	0.54	0.67	0.87
11/25/08 13:45	11/25/08 14:15	30	109	1.38	2.34**	6.34	7.57	6.42
11/26/08 15:50	11/26/08 16:10	20	104	1.32	0.79**	5.94	7.17	6.13
1/1/09 17:30	1/1/09 17:55	25	13	0.18	0.05**	0.46	0.55	0.78
1/2/09 15:30	1/2/09 15:45	15	26	0.35	0.12**	1.03	1.33	1.55
2/13/09 9:00	2/13/09 9:38	38	63	0.81	1.76*	3.06	3.92	3.70
2/20/09 16:38	2/20/09 17:38	60	27	0.36	0.17	1.08	1.41	1.58
2/21/09 20:25	2/21/09 21:30	65	31	0.42	0.23	1.18	1.53	1.71
2/23/09 22:35	2/24/09 2:07	212	54	0.52	0.35	0.54	0.67	0.91
2/25/09 0:51	2/25/09 1:13	22	157	1.85	3.93	10.66	11.88	9.28
2/26/09 18:40	2/26/09 19:20	40	41	0.66	0.55	1.79	2.33	2.44
2/28/09 1:25	2/28/09 2:30	65	45	0.41	0.22	1.79	2.33	2.44
2/28/09 18:25	2/28/09 18:40	15	26	0.35	0.16	1.03	1.33	1.54
3/4/09 3:42	3/4/09 6:40	178	27	0.37	0.18	0.30	0.36	0.53
3/5/09 14:57	3/5/09 15:20	23	59	0.89	1.22**	2.81	3.64	3.48
3/11/09 17:30	3/11/09 18:45	75	81	0.81	1.46**	3.19	4.08	3.85
3/15/09 16:00	3/15/09 17:45	105	19	0.34	0.16	0.38	0.45	0.65
3/19/09 12:00	3/19/09 12:30	30	33	0.45	0.26	1.37	1.79	1.97
3/20/09 13:30	3/20/09 14:30	60	135	1.79	3.69	8.56	9.87	8.01
3/24/09 20:20	3/24/09 22:05	105	15	0.32	0.14	0.30	0.36	0.52
3/26/09 15:27	3/26/09 15:30	3	22	0.30	0.12	0.85	1.08	1.31
3/28/09 18:50	3/28/09 19:20	30	124	1.24	1.82	7.59	8.93	7.32
4/24/09 19:30	4/24/09 19:40	10	62	0.50	0.82*	3.00	3.82	3.70
4/27/09 10:50	4/27/09 11:10	20	49	0.50	0.98*	2.23	2.89	2.91
4/29/09 10:03	4/29/09 10:49	46	83	1.30	2.48**	4.38	5.47	4.94
4/30/09 11:15	4/30/09 12:05	50	80	1.21	2.27**	4.17	5.23	4.75
5/4/09 15:02	5/4/09 15:17	15	38	0.81	1.24*	1.63	2.14	2.28
5/13/09 12:36	5/13/09 13:04	28	61	0.95	1.25**	2.94	3.76	3.61
6/24/09 14:00	6/24/09 15:00	60	144	1.51	2.67	9.40	10.67	8.55
n	29	29	29	29	29	29	29	
Mean	51	60	0.76	1.08	3.05	3.70	3.37	
Maximum	212	157	1.85	3.93	10.66	11.88	9.28	
Minimum	3	13	0.18	0.03	0.30	0.36	0.52	
Standard deviation	47.78	41.62	0.49	1.12	2.94	3.35	2.57	

C values used to estimate peak discharge are similar to the peak discharge applications of C_{MSMA} and C_{ASCE}. It also appears that the experimental *C* values obtained using the rainfall simulator provided relevant values and were approachable for peak discharge estimates. However, peak discharges using RM provided slightly higher estimated values than the real storm peak discharge.

In general, practices in Malaysia, for example, have far relied very much on slight adaptation or even direct use of temperate region-based urban runoff coefficients and models. This study shows clearly that the widely used *C* values (MSMA and ASCE) give different *C* values to be applied in the catchments scale. Even though MSMA has already suggested *C* values for Malaysia, these values were still based on Australian Rainfall and Runoff (1987) standards to suit Malaysian tropical conditions (Table 6). Thus, from this experiment, the runoff coefficient values derived from the urban area, Penang, using a rainfall simulator give reliable and sufficient *C* values to suit the Malaysian climate. Due to the rainfall simulator's calibration construction, it is based on the tropical rainfall characteristics in terms of intensity, uniformity, and rainfall drop size. Using a rainfall simulator allows controlling the environment to suit the tropical rainfall events. It is useful and much easier to replicate simulated rainfall according to natural rainfall since it is flexible in time and space.

Runoff coefficient is an essential parameter in RM since it was used most frequently in designing water structures in Malaysia. While standard design procedures have been available since the early 1970s, this peak discharge estimation method has been freely used in Malaysia. Regarding the situation, various availability of *C* values such as MSMA and ASCE to be referred and applied in Malaysia has resulted in different peak discharge estimations. Therefore, cost-effective design and construction have seldom been realized. Neither overestimation nor underestimation of runoff events are related to the *C* values applied for design purposes in the RM, which will also cause design inefficiency. The tested *C* values derived from the rainfall simulator experiment will help the designers to estimate the discharge appropriately and suitability with tropical conditions.

Conclusion

A unique design rainfall simulator was developed to investigate runoff coefficients from various surfaces in urban areas. Data obtained from the simulations and the literature were compared to estimate the percentage of differences. It was possible to validate that the rainfall simulator can satisfactorily replicate natural rainfall events due to its advantages in controlling the environment needed. These findings suggest that rainfall simulation in urban runoff research can be a time and cost-efficient approach to developing a unified database. Although it was a small plot scale study using simulated rainfall, the data derived from this experiment was provided satisfactory results. This plot scale study was the first step to understanding more complex rainfall–runoff characteristics in a larger catchment scale.

The result obtained shows that the *C* value was 0.79–0.89 (asphalt), 0.85–0.92 (concrete), 0.77–0.89 (zinc), 0.73–0.85 (brick), 0.85–0.96 (asbestos), 0.8–0.93 (tiled roof), 0.17–0.63 (grass 2°–7°), and 0.35–0.69 (bare soil 2°–7°). The variation of the *C* value was influenced by the total amount of rainfall, surface imperviousness, soil moisture, soil and surface characteristics, slope, and vegetation cover. There was a significant difference in the *C* value obtained in this study compared to the *C* value of MSMA (asphalt

Table 6 Tukey HSD multiple comparison results of peak discharge

	(*I*) *Qp* log	(*J*) *Qp* log	Mean difference (*I-J*)	Standard error	Sig	95% confidence interval	
						Bottom boundary	Upper boundary
Tukey HSD	Cerap	Kajian	−0.54223*	0.12489	0.000	−0.8679	−0.2165
		MSMA	−0.63720*	0.12489	0.000	−0.9629	−0.3115
		ASCE	−0.65796*	0.12489	0.000	−0.9837	−0.3322
	Kajian	Cerap	0.54223*	0.12489	0.000	0.2165	0.8679
		MSMA	−0.09497	0.12489	0.872	−0.4207	0.2307
		ASCE	−0.11573	0.12489	0.791	−0.4414	0.2100
	MSMA	Cerap	0.63720*	0.12489	0.000	0.3115	0.9629
		Kajian	0.09497	0.12489	0.872	−0.2307	0.4207
		ASCE	−0.02076	0.12489	0.998	−0.3465	0.3050
	ASCE	Cerap	0.65796*	0.12489	0.000	0.3322	0.9837
		Kajian	0.11573	0.12489	0.791	−0.2100	0.4414
		MSMA	0.02076	0.12489	0.998	−0.3050	0.3465

*Significance at $p = 0.05$.

and brick) and the *C* value of ASCE (concrete and asbestos, grass, and exposed soil). Four factors that influenced the differences of *C* values in this research were environmental condition, scale, surface physical condition, and soil antecedent moisture. Multiple comparison test shows a significant difference in the peak discharge estimated using RM compared. Nevertheless, peak discharge estimated from various *C* values in the RM did not show any statistical differences. The study also suggests that the experimental *C* values obtained using rainfall simulator provided relevant values and approachable peak discharge estimates similar to C_{MSMA} and C_{ASCE}.

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Declarations

Conflict of interest The authors declare no competing interests.

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