Influence of Dam to Rainfall-Runoff Response in a Tropical Climate – A Case Study of Selangor River Basin, Malaysia

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Abstract. This paper discusses the rainfall-runoff response by comparing the runoff coefficient, \( c \), between two catchments of different characteristics within the Selangor River Basin, namely Catchment A (CA) and Catchment B (CB). Catchment B is a sub-catchment of Catchment A, whereby CA is about 6.8 times larger than CB. The landscape of CB is largely covered by forest, has higher river slope and a dam completed in year 2004 at upstream of the basin. Annual mean-areal-rainfall (MAR) and total runoff from 1990 until 2018 was used for the rainfall-runoff coefficient, \( c \) calculations. The rainfall-runoff response was assessed by separating the analysis into 2-time frames; 1990 to 2000 (before dam construction) and 2007 to 2018 (after dam construction). The analysis before dam construction showed that CB has higher runoff response compared to CA. This was due to the difference in land use, catchment slope and lesser water abstractions compared to CA. The runoff coefficient, \( c \) for CA was in the range of 0.19-0.48, while CB was in the range of 0.59-0.79. This means that 19% to 48% of the rainfall was converted into runoff for CA, and 59% to 79% of the precipitation turned into runoff for CB. As suspected, after the dam construction the \( c \) coefficient for CB changed to 0.28-0.89, indicating a higher variability in the catchment response due to dam operations and control at the upstream.

1. Introduction
Flooding is a natural environmental event that occur around the countries in the world. Land use and land cover change (LULC) is the main factor that influences the hydrological cycle and the availability of water resources. The change in LULC alters the interception, infiltration rate and evapotranspiration (EP) [1]. Runoff can be defined as the portion of precipitation that makes its way towards rivers or oceans as surface or subsurface flow. In general, runoff is generated through two different mechanism which are saturation excess and infiltration excess. Saturation excess is generated when the soil become fully saturated with water then additional precipitation cannot infiltrate [3]. Infiltration excess occurs when the rainfall intensity becomes higher than the infiltration rate, and becomes runoff flowing over land to a different location [4].

The runoff coefficient is widely used and is an important parameter describing the basin response either in an annual or event basis. Annual runoff coefficient is the total runoff over total precipitation in a year [5] while event-based runoff coefficient are the ratio of total flow over total rainfall for a specific storm event. The use of event flow instead of total annual flow allows to investigate rainfall-runoff response for a single event. However, by using total flow, the response of single event is combined with pre-event flow condition. Meaning, by event based, high flow in the wet season or low
flow during summer may be observed [5]. According to Thompson (2006), runoff coefficient, c, can be defined as the dimensionless ratio intended to indicate the amount of runoff generated by the watershed to the amount of precipitation received. In general, a larger value of c to the area with low infiltration and high runoff such as pavement, steep gradient while a lower value of c to area with high infiltration and low runoff such as forest and flat land.

Land use changes are mostly induced by human activities, for example, deforestation, afforestation, and farmland reclamation have led to significant agricultural-land-pattern changes and eventually affect the hydrological processes such as evapotranspiration (ET), interception, infiltration. This will finally change the surface and subsurface flows [7]. Land use is the utilization of land resources by humans for various land activities and purposes such as for transport (road and highway), agriculture (farm), residential (housing and settlement), commercial (business and factories) and power (dam and reservoir). Dams and reservoirs impact the environment through their presence in the landscape by altering basin connectivity and modifying thermal, hydrologic and sediment regimes [8]. The water in a river is a complex water system characterized by numerous river reaches and reservoir due to the influences of dams [9]. Meanwhile, another effect of dams regulation is reducing peak flow during the flooding season and releasing during the dry season due to change in the river flow regime [10].

The Selangor River Basin (SRB) (Figure 2), was selected for this study because it is the major source of water supply for Selangor and Federal Territory. It is also prone to rapid land use change and development due to its proximity to Kuala Lumpur and other major townships. As in the parts of Peninsular Malaysia, the climate is characterized by all year round warm and humid with mean daily temperature from 25°C to 32°C [12]. According to Wong et al. (2016) rainfall is characterized by two rainy seasons, which are southwest monsoon (SWM) from May to September and the northeast monsoon (NEM) from November to March. The SRB receives an annual rainfall average of 2154 mm/year. The rainfall during the northeast monsoon is higher (921 mm) than during the southwest monsoon (765 mm). The monthly rainfall shows a bimodal distribution with peak in April and November which coincide with inter-monsoon periods [14].

The objectives for this study are:
1. To calculate the rainfall runoff response and rainfall characteristics on different landscapes, geology and size of catchment.
2. To study the effect of dam on river flow regime of the SRB.

2. Study Area

Figure 1 shows river basins in Selangor and location of dams. The Selangor River Basin (SRB) is located in the state of Selangor and within the district of Hulu Selangor, Gombak and Kuala Selangor. Figure 2 shows the SRB and the locations of rainfall and water level stations. The basin has a total area of 1820km² and has been undergoing rapid land development and land use change since the 1970s [15]. There are two river flow stations in the basin located at Rantau Panjang and Ampang Pecah. Two water supply dams were constructed in the basin as shown in Figure 1. Sungai Selangor Dam was completed and operational in year 2004 and Sungai Tinggi Dam was completed in 1997 (Table 1). The Sungai Selangor Dam has a catchment area of 197 km², located in the upper catchment of SRB with supply capacity of 1,100 MLD or 12.7 m³/s. The Sungai Tinggi Dam is smaller (40 km²), located in the upper reaches of Sungai Buloh, and it was designed to regulate the flow at the existing Batang Berjuntai water supply intake. The Sungai Selangor and Sungai Tinggi Dams were designed to regulate the river flow to give a total net system yield of 3016.5 MLD [16]. The SRB contains eight (8) water treatment plants (water intake), as shown in Table 2 and Figure 3. In this analysis, the SRB is divided into two catchments namely Catchment A (CA) and Catchment B (CB). Catchment A is the whole basin of SRB while CB is the sub-basin of CA and situated at its upstream.
2.1. Catchment A

Catchment A (CA) has an area of 1502 km² and contains seven sub-basins (Figure 4 (a)). About 38% of the catchment is still forested, mostly in the upper catchment. Rubber plantation is the second largest land use (21.6%) followed by residential area which include institution, village, industrial and urban (20.7%), oil palm tree (9.8%), ex-mining land (6.2%) and mangrove (3.7%) as shown in Figure 4 (b). The urban and residential areas are mostly located in the downstream. There are two water supply reservoirs in CA, namely Sungai Selangor Dam in the upstream of Sungai Selangor and Sungai Tinggi Dam in the upper reaches of Sungai Buloh. Figure 4 (d) shows a drainage map where CA have seven (7) number of stream order, $u$ with 275km of perimeter, $P$, stream length, $Lu$ (3875), mean stream length, $Lsm$ (553.51), basin length, $Lb$ (83.61km), drainage density, $Dd$ (2.58km/km²), stream frequency, $Fs$ (7.15), drainage texture, $Rt$ (39.05), form factor, $Rf$ (0.215), circulatory ratio, $Rc$ (0.250), elongation ratio, $Re$ (0.523), compactness constant, $Cc$ (2.00), length of overland flow, $Lg$ (0.78) and shape index, $Sw$ (4.65) as listed in Table 3. Figure 4 (c) shows catchment elevation ranging from 33m to 260m and the steepest slopes are mostly found in the upstream.

2.2. Catchment B

Catchment B (CB) is about 220 km² (Figure 5 (a)), and only about 79.3% of the land use is still forested. Sungai Selangor Dam is located within the catchment. Residential area which included urban and villages comprises about 9.8%, rubber plantation (5.4%), palm oil tree (4.4%) and ex-mining land (1.1%) (Figure 5 (b)). Meanwhile, 84.7% of the catchment area is considered impervious and may be a major source of runoff. Figure 5 (d) shows a drainage map whereby CB has six (6) number of stream order, $u$ with 97km of perimeter, $P$, stream length, $Lu$ (528), mean stream length, $Lsm$ (87.96), basin length, $Lb$ (28.08km), drainage density, $Dd$ (2.40km/km²), stream frequency, $Fs$ (6.79), drainage texture, $Rt$ (15.39), form factor, $Rf$ (0.279), circulatory ratio, $Rc$ (0.294), elongation ratio, $Re$ (0.596), compactness constant, $Cc$ (1.84), length of overland flow, $Lg$ (0.83) and shape index, $Sw$ (3.58) as listed in Table 3. Figure 5 (c) shows the topography of the catchment with elevation ranging from 140m to 260m from sea level.
River flow station (Rantau Panjang)

**Figure 3.** Water intake and dam location.

**Table 1.** Information of dam.

| Dam          | Catchment Area (km²) | Storage capacity (m³/m) | Year completed |
|--------------|----------------------|-------------------------|----------------|
| Sg Selangor  | 197                  | 230                     | 2004           |
| Sg Tinggi    | 40                   | 115                     | 1997           |

**Table 2.** Design capacity of water intake.

| Water Intake                  | Design Capacity (MLD) |
|-------------------------------|-----------------------|
| 1 Sg Tinggi                   | 1.3                   |
| 2 Kuala Kubu Bharu            | 6.7                   |
| 3 Rantau Panjang              | 31.5                  |
| 4 Sg Selangor (F1)            | 950                   |
| 5 Sg Rasa                     | 250                   |
| 6 Sg Badong                   | 800                   |
| 7 Sg Sireh                    | 27                    |
| 8 Sg Selangor (F2-P1&P2)      | 950                   |
| **Total**                     | **3016.5**            |
Figure 4 (a): CA
Figure 4 (b): Land Use of CA
Figure 4 (c): Elevation CA
Figure 4 (d): Drainage CA

Figure 5 (a): CB
Figure 5 (b): Elevation CB
Figure 5 (c): Land Use of CB
Figure 5 (d): Drainage CB

Figure 5. Catchment information for Catchment A and Catchment B
Table 3. Characteristic of CA and CB.

|                      | CA                  | CB                  |
|----------------------|---------------------|---------------------|
| **Area, A (km²)**    | 1502                | 220                 |
| **Land use**         | Forest (38%), Rubber tree (21.6%), Residential (20.7%), Palm oil tree (9.8%), ex-mining land (6.2%), mangrove tree (3.7%) | Forest (79.3%), Residential (9.8%), Rubber tree (5.4%), Palm oil tree (4.4%), ex-mining land (1.1%) |
| **Elevation**        | 33m – 260m          | 140m – 260m         |
| **Perimeter, P (km)  | 275                 | 97                  |
| **Stream order, u**  | 7                   | 6                   |
| **Total no of stream, Nu** | 10738          | 1493                |
| **Stream length, Lu**| 3875                | 528                 |
| **Mean stream length, Lsm** | 553.51        | 87.96               |
| **Basin length, Lb (km)** | 83.61            | 28.08               |
| **Drainage density, Dd (km/km²)** | 2.58            | 2.40                |
| **Stream Frequency, Fs** | 7.15              | 6.79                |
| **Drainage texture, Rt** | 39.05             | 15.39               |
| **Form factor, Rf**  | 0.215               | 0.279               |
| **Circulatory ratio, Rc** | 0.250             | 0.294               |
| **Elongation ratio, Re** | 0.523             | 0.596               |
| **Compactness constant, Cc** | 2.00             | 1.84                |
| **Length of overland flow, Lg** | 0.78            | 0.83                |
| **Shape index, Sw**  | 4.65                | 3.58                |

3. Methodology
Rainfall and river flow data were obtained from Department of Irrigation and Drainage (DID) at hourly interval from year 1990 to year 2018. Besides that, the Digital Elevation Model (DEM) data were downloaded from Alos Palsar Alaska Satellite Facility (ASF) with 15m resolution. The DEM data were analyzed using GIS pre-processing (version 10.4.1) as shown in Figure 6 to determine the watershed characteristics. The details information on the location of water intake, rainfall station, river flow station and dam were obtained from Lembaga Urus Air Selangor (LUAS). Lastly, for land use, data were obtained from Department of Agriculture (DOA) for year 2015.

Figure 6. GIS Pre-processing ArcGIS.
The method to study the hydrological responses of land use changes include statistical analysis and model simulation. For statistical analysis, the methods include trend analysis of long time series and the paired catchment approach [11]. In this study, Selangor River Basin (SRB) in Selangor Malaysia, was chosen as the case study to understand the catchment response for different landscapes, geology, catchment characteristics and dam effect on total runoff. To achieve objective 1, which is to calculate the rainfall runoff response for different catchment characteristic, a data set of rainfall and runoff values were used. The data were from year 2007 to year 2017 for Catchment A while data from year 2009 to year 2018 (ten years of analysis) were used for Catchment B. Missing and errors in rainfall data were filled by multiple imputation linear regression method using R program (MICE). Then, Thiessen Polygon method was applied to obtain the areal rainfall for each catchment. There are 27 rainfall stations for Catchment A and three rainfall stations for Catchment B. The method is widely used due to its practicability and less time consuming with highly accurate estimates. After that, the total runoff over total annual aerial rainfall for each year were calculated to obtain the runoff coefficient, \( c \). The runoff coefficient, \( c \), is indicated to measure the rainfall runoff response. The study used trend analysis of long time series to describe the rainfall characteristic. The steps are shown in Figure 7.

Beside study the rainfall runoff response within the catchment, the effect of dam on river flow regime at Selangor River Basin were also investigated. Sungai Selangor dam was completed at year 2004 and Sungai Tinggi dam was completed at year 1997 but the size of Sungai Selangor Dam is three times bigger than Sungai Tinggi Dam. Therefore, the study focuses on Sungai Selangor Dam on river flow regime. Another set of rainfall and runoff data starting from year 1990 to year 2000 were used. Then, similar procedures were applied as shown in Figure 7. Finally, the runoff coefficient, \( c \), was calculated for year 1990 to year 2000 and the \( c \) value was compared for both catchments. Graphs showing before and after the construction of dam are plotted as in Figure 11.

4. Result and Discussion

4.1. Rainfall Characteristic

The rainfall analysis for CA used 11 years data 2007 to 2017, whereas for CB data from 2009 to 2018 (10 years) were used. Missing data were filled in using multiple imputation linear regression method using R program (MICE). The multiple imputation technique involved three steps: i) data imputation, ii) data analysis and iii) data pooling. In the first step, several plausible complete versions of the incomplete data sets are created. Next, in the second step, the different complete version of the
incomplete dataset was analyzed using standard statistical procedure which result in multiple different outcomes of the statistical analyses. Finally, these results are combined into the overall statistical analysis where the uncertainty about the missing data is incorporated in the standard errors and significance tests [17].

In CA, 27 rainfall stations were used whereas for CB, only three stations are available. Data from all stations were used to calculate areal rainfall using Thiessen Polygon method in ArcGIS. Thiessen polygon method is widely applied for its accuracy and fast computation. The calculation of Thiessen polygon method is simple because only area of sample data is needed. When dataset is stable, the accuracy of Thiessen polygon method is higher than arithmetic mean [18]. The areal rainfall was calculated for the mean monthly and annual total.

Over 11 years from 2007 to 2018, CA received annual rainfall in a range from 2207mm to 3071mm with mean annual of 2699mm/yr. In CB, the annual rainfall ranges from 1888mm to 3461mm with mean annual of 2507mm/yr. Like CA, the driest and wettest years in CB were in 2016 and 2012, respectively. The driest in 2016 could be due to the El Nino event, where it was found that Malaysia was strongly effected by El Nino in the years from 2014 to 2016 resulting to abnormal amount of rainfall [19]. The trend of rainfall for both catchments shows decreasing trend in the total annual rainfall received. Figure 8 shows a comparison of annual rainfall between the two catchments.

Both catchments show that November received higher rainfall (333 mm/month) while February was the driest with 122 mm/month. The variation of rainfall per month at CA and CB is generally characterized by bimodal variations with two peaks as shown in Figure 9 which are primary peak occurring during November and secondary peak during April or May due to inter-monsoon periods. During the monsoon transitions (inter-monsoon) periods, the west coast of Peninsular Malaysia receives more rainfall compared to other seasons [14]. This is because the weather in CA and CB are influenced by two monsoon regimes, which are northeast monsoon (NEM) (known as wet season) that brings heavy rainfall in Malaysia particularly to the east coast states of Peninsular and southwest monsoon (SWM) (known as dry season) normally with relatively drier weather. Record shows that widespread floods have occurred especially during the NEM season [12].

The rainfall usually pours at the evening from 3pm to 10pm (Figure 10) for all months for both catchments. The rainfall is a convective rain that occurs when the energy of the sun at the noon heats the surface of the earth causing water to evaporate to form water vapor. Convective rainfall is widespread in areas where the ground is heated by the hot sun such as the tropics [20]. Therefore, Malaysia’s rainforests experience heavy rainfall mostly at the afternoons.

4.2. Rainfall Runoff Response
The rainfall-runoff analysis at Rantau Panjang was conducted to assess the dam influence on the streamflow regime. Figure 11 shows the rainfall-runoff relationship for CA and CB. Prior to dam construction, the annual runoff generally increases as rainfall increases for both catchments. However, after the dam construction, the runoff in CB decreases when rainfall increases. This pattern is not expected under normal condition. The dam was constructed to store as much water as possible during rainy season and to be used during dry periods, hence the rainfall-runoff relationship for CB is highly dependent on the dam operations and is not influenced by natural catchment response.

The effect of dam however was not significant for CA other than a slight change in the slope of the rainfall-runoff relationship and the runoff means. Before the dam construction, the total average runoff for CA was lower (896 mm) compared to after construction (1129 mm). This is because most of the area at Selangor River Basin (SRB) were still pervious in year 1990 to year 2000. Therefore, the infiltration rate is higher. Expended impervious surfaces such as parking lots, roofs, driveways and sidewalks will block the precipitation infiltrate into the groundwater thus increase the total volume and peak discharge of the streamflow [21]. Rainfall falling on impervious areas is presumed to produce surface runoff. Increasing the percentage of impervious area would result to increase of the runoff volume, reduced flow time and lag time, increased in peak discharges with resulting shift in the flood frequency curve [22].
Figure 8. Annual rainfall CA and CB.

Figure 9. Monthly rainfall CB and CB.

Figure 10. Heat map for CA and CB.
Before dam construction, the rainfall runoff response for CB was higher compared to CA (Figure 11). The volume of runoff from CB is higher than CA for any rainfall events. This may be due to larger water catchment storage in CA and the amount of water intakes’ facilities within the catchment. Catchment A has eight water intake stations in total within the catchment compared to CB which has only one. Therefore, the runoff water in CA was extracted thus reducing the amount of runoff volume extracted from the observed hydrographs. Besides that, morphometric perimeter for both catchments is also different. Circulatory ratio, Rc, and elongation ratio, Re for CB is higher than CA meaning CA indicates low relief and impermeable surface thus lower lag time compared to CB. Catchment B also have strong relief and steep slopes, meaning shorter time to peak. The form factor, Rf, for CB is larger than CA, thus CB has high peak flow of short duration compared to CA.

After the construction of dam, the rainfall-runoff model was not significant for Catchment B which has a p value of 0.439 (p-value > 0.05) as shown in Table 4. This is due to the regulated water from Sungai Selangor dam consequence to insignificant relationship between the observed rainfall and runoff. According to Adam et al. (2007), the construction and operation of large reservoir results in shift in streamflow seasonality that reduces peak flows and increases low flows. Another effect of dams regulation is reducing peak flow during the flooding season and releasing during the dry season due to change in the river flow regime [10]. Figure 13 shows the flow duration curve for CA and CB before and after dam construction. Slight changes of the high and low flows are seen for CA, however for CB some significant changes for the high flows can be seen. The high flows for CB were reduced after the dam construction. This correlates with the dam operation of reducing the runoff volumes particularly during high flows.

### Table 4. Model Performance and Evaluation.

|                | CA before dam construction | CB before dam construction | CA after dam construction | CB after dam construction |
|----------------|----------------------------|----------------------------|---------------------------|---------------------------|
| R²             | 0.88                       | 0.83                       | 0.75                      | 0.08                      |
| p-value        | 0.0018                     | 0.004                      | 0.00058                   | 0.439                     |

Assessment on the runoff coefficient, $c$, is shown in Figure 12. For CA, before dam construction the $c$ values are between 0.19 to 0.48 indicating that only 19% to 48% of rainfall turned into runoff but after the existence of dam, the $c$ value changed within the range of 0.35 to 0.49, Table 5. This shows an increase of the lower range of the runoff coefficients.

For CB, before construction of dam, the $c$ values were between the range of 0.59 to 0.79, but then changes to the range of 0.28 to 0.89 after dam construction. However, as from CA, the lower range of $c$ values reduce to 0.28 from 0.59 and larger values of $c$ increase from 0.79 to 0.89. This indicates the variability of the rainfall-runoff response becomes larger for CB. This is due to the regulated water from the dam, where during dry season, the dam releases water into the river and vice versa during wet season. Then, runoff coefficient, $c$, for CB is as shown in Figure 12.
Table 5. Runoff Coefficient, $c$.

|        | CA prior to dam construction | CA after dam construction | CA before dam construction | CA after dam construction | CB prior to dam construction | CB after dam construction |
|--------|-----------------------------|--------------------------|---------------------------|--------------------------|-----------------------------|---------------------------|
| min    | 0.19                        | 0.35                     | 0.59                      | 0.28                     |                             |                           |
| Q1     | 0.29                        | 0.40                     | 0.67                      | 0.37                     |                             |                           |
| median | 0.43                        | 0.45                     | 0.69                      | 0.53                     |                             |                           |
| Q3     | 0.44                        | 0.47                     | 0.73                      | 0.67                     |                             |                           |
| max    | 0.48                        | 0.49                     | 0.79                      | 0.89                     |                             |                           |
| mean   | 0.37                        | 0.44                     | 0.70                      | 0.53                     |                             |                           |
| range  | 0.29                        | 0.15                     | 0.20                      | 0.61                     |                             |                           |

Figure 11. Rainfall-Runoff Relationship.

Figure 12. Boxplot of Runoff Coefficient, $c$ for CA and CB.
Figure 13: Flow Duration Curve

(a) Catchment A, CA prior to dam construction
(b) Catchment B, CB prior to dam construction

Flow Duration Curve

Discharge (m³/s)

% of time

Discharge (m³/s)
5. Conclusion
The paper assessed the rainfall-runoff response of two catchments with different characteristics. One is the Sungai Selangor River Basin as Catchment A (CA) and another, a sub-catchment of CA located at the upstream, as Catchment B (CB). Both catchments have similar exposure of rainfall. The total rainfall has a decreasing trend for the past 10 years, and the monthly rainfall was characterized by bimodal variation: first peak in November and second peak in April or May due to effect of inter-monsoon. Both catchments were also affected by Sungai Selangor Dam operation with CB having the most significant changes. Catchment B runoff coefficient, $c$ and runoff were higher before and after the dam construction compared to CA. The variation of $c$ for CB becomes higher after the dam construction, while the $c$ values for CA only changes slightly for the lower range of $c$ values. This is because the dam regulates water during wet and dry season. As the dam is in CB, CB flow and runoff changed significantly. By understanding the runoff coefficient, we can learn how the catchment characteristics can transform rainfall into runoff and provide a basis for information about the catchment response. The result also shows that, Sungai Selangor Dam regulates the water flow regime by reducing the peak flow during flooding season and releasing during the dry season, hence changing the high and low flows at the catchment outlet.

Acknowledgement
The authors would like to state their appreciation to the funding from the Malaysia Research University Network (MRUN), vot number R.J130000.7851.4L897. The authors also thank the Department of Irrigation and Drainage Malaysia (DID), and the Selangor Water Management Board (LUAS) for providing data and information for the research.

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