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# Development of Analytical Probabilistic Model Parameters for Urban Stormwater Management

(Pembangunan Parameter Kebarangkalian Analisis untuk Model Pengurusan Air Ribut di Bandar)

SALISU DAN'AZUMI*, SUPIAH SHAMSUDIN & AZMI ARIS

ABSTRACT

*Analytical probabilistic models (APM) are closed form mathematical expressions for long term system's output performance derived from the probability distribution of the system's input variables. In order to apply the APM for urban stormwater control systems' design, APM parameters have to be made known. These input parameters include APM parameters which are derived from the meteorological rainfall characteristics; storm depth, duration, intensity and inter-event time. This study is aimed to develop meteorological APM parameters that can be used for detention pond design in Peninsular Malaysia. Hourly rainfall data covering 10 to 40 years period were analyzed from 13 different locations spread across the Peninsular. The data were analyzed to obtain the APM parameters at different values of minimum storm separation time (MSST). The APM parameter of rainfall duration ($\lambda$) was found to range from a mean value of 0.260 $h^{-1}$ for 2 h MSST to 0.04 $h^{-1}$ for 24 h MSST. The APM parameter of rainfall volume ($\zeta$) ranges from a mean value of 0.091 $mm^{-1}$ for 2 h MSST to 0.038 $mm^{-1}$ for 24 h MSST. Similarly, the APM parameter of rainfall intensity ($\beta$) ranges from a mean value of 0.355 h/mm for 2 h MSST to 0.504 h/mm for 24 h MSST. Finally, the APM parameter of inter-event time ($\psi$) ranges from a mean value of 0.025 $h^{-1}$ for 2 h MSST to 0.012 $h^{-1}$ for 24 h MSST. Once the APM parameters are determined for a particular area, the long term stormwater control systems' performance can easily be determined.*

*Keywords: Analytical probabilistic models (APM); detention pond; meteorological characteristics; stormwater management*

ABSTRAK

*Model kebarangkalian analisis (APM) adalah ungkapan matematik berbentuk tertutup bagi prestasi keluaran sistem jangka panjang diterbitkan daripada taburan kebarangkalian pemboleh ubah input sistem. Untuk menggunakan aplikasi APM dalam reka bentuk sistem kawalan air-ribut bandar, parameter APM perlu diketahui. Parameter input ini termasuk parameter APM yang diterbitkan daripada ciri hujan meteorologi; kedalaman ribut, tempoh, keamatan dan masa antara-peristiwa. Kajian ini bertujuan untuk menghasilkan parameter APM meteorologi yang boleh digunakan untuk reka bentuk kolam tahanan di Semenanjung Malaysia. Data hujan setiap jam yang merangkumi 10 hingga 40 tahun telah dianalisis dari 13 lokasi berlainan di seluruh Semenanjung. Data dianalisis untuk mendapatkan parameter APM pada nilai masa pengasingan ribut minimum (MSST) yang berbeza. Parameter APM tempoh hujan ($\lambda$) adalah bernilai purata 0.260 $jam^{-1}$ untuk 2 jam MSST ke 0.04 $jam^{-1}$ untuk MSST 24 jam. Parameter APM isi padu hujan ($\zeta$) bernilai purata antara 0.091 $mm^{-1}$ untuk 2 jam MSST ke 0.038 $mm^{-1}$ untuk MSST 24 jam. Begitu juga, parameter APM keamatan hujan ($\beta$) adalah antara nilai purata 0.355 jam/mm untuk 2 jam MSST ke 0.504 jam/mm untuk MSST 24 jam. Akhirnya, parameter APM antara peristiwa masa ($\psi$) bernilai purata 0.025 $jam^{-1}$ untuk 2 jam MSST ke 0.012 $jam^{-1}$ untuk 24 jam MSST. Apabila parameter APM telah ditentukan bagi kawasan tertentu, prestasi sistem kawalan air-ribut jangka panjang dapat ditentukan dengan mudah.*

*Kata kunci: Ciri meteorologi; model kebarangkalian analitis; penahanan kolam; pengurusan air- ribut*

## INTRODUCTION

In order to plan, design and operate cost-effective drainage systems for urban stormwater management, three modeling approaches are being used. The techniques are: design storm approach, continuous simulation and analytical probabilistic models (APM). The design storm is the traditional approach in hydrologic designs and has stood the test of time. However, the approach suffers from severe criticisms for its assumption that relates rainfall to the resulting runoff without given due consideration to the inter-event time between two successive events, which is known to affect runoff (Adams & Papa 2000). An alternative approach that caters for the shortcomings of the design storm is the continuous simulation, which is now widely applied in the design of urban stormwater drainage systems. However, the approach is time consuming and very costly (Chen & Adams 2007b). The APM, as opposed to the previous approaches, are based on derived probability theory and are closed form analytical expressions for system's output performance derived from the probability distribution of the system's input variables. In order to apply the APM to stormwater control systems' design, some input parameters to the detention pond design have to be known. These input parameters include the APM parameters which are derived from the long term meteorological rainfall characteristic of storm depth, duration, intensity and inter-event time as well as the catchment's parameters of area, runoff coefficient, imperviousness and depression storage. The objective of this paper was to develop meteorological APM parameters that can be used for detention pond design in Peninsular Malaysia.

APM has been used to assess long term performance of runoff quantity control and runoff quality control facilities in urban catchments. In predicting the response of a catchment to rainfall: rainfall-runoff transformation, meteorological APM parameters and catchment's parameters were used to derive closed-form analytical expression for average annual runoff event volume, runoff event volume return period and peak discharge rate exceedence probability from a catchment (Guo & Adams 1998a, 1998b). Behera et al. (2006) used simplifying assumptions to derive the APM expressions for the probability distribution for event washup load, expected value of pollutant event washoff load, average annual washoff load and long term average pollutant EMC. Chen and Adams (2006a) derived APM expressions for stormwater quality control based on buildup and washoff functions. The expressions derived include the average pollutant EMC and long-term pollutant loads to receiving water. Chen and Adams (2007a) used a different form of rainfall-runoff transformations, pollutants build-up and washoff functions to derive APM expressions for CDF of pollutants load and the expected value of pollutant EMC and average annual pollutant EMC. The analytical models were evaluated with observed values and good agreements were obtained.

APM parameters are also being used to determine the long-term performance of stormwater control facilities. Li and Adams (2000) used APM to derive analytical expressions for fraction of runoff overflow and total pollution mass discharge load from a stormwater storage/ treatment system. Guo and Adams (1999a, 1999b) derived APM expressions for peak outflow rate, flow capture efficiency and volume-weighted average detention time of a stormwater detention basin taking into account the variable inflow and outflow rates and the inter-runoff event time. In each case, the APM were compared with similar results obtained from a continuous simulation model and results were found to be in close agreement. Chen and Adams (2005b, 2007b) modified the rainfall-runoff transformation to consider infiltration rather than a common runoff coefficient in order to develop closed form APM expressions for runoff control performances which include average annual runoff volume, exceedence probability of a spill volume, expected value of a spill volume, average annual volume and number of spills and runoff capture efficiency. Similarly, Chen and Adams (2005a, 2006b) derived APM expressions for stormwater quantity and quality control measures using TSS control as a surrogate measure of other pollutants removal. Closed-form APM expressions for average annual volume of runoff, average annual number of spills, average annual runoff control and pollutant removal efficiency were derived.

## METHODS

### RAINFALL DATA ANALYSIS

Continuous hourly rainfall data covering a period of 10 to 40 years were obtained from the Department of Irrigation and Drainage (DID 2000) Malaysia. Table 1 lists the raingauge stations while Figure 1 shows the map of the stations for the data collection. The continuous rainfall data was divided into discrete events using minimum storm separation times (MSST) of 2 h, 6 h, 12 h and 24 h as there is no universally agreed standard criterion used to separate rainfall data and different researchers reported the use of different MIETD (Burgueno et al. 1994; Dunkerley 2008; Restro-Posada & Eagleson 1982). Rainfall characteristics of depth, duration, intensity and inter-event time were obtained. A computer programme was written in Microsoft Visual Basic to do this task.

### GOODNESS-OF-FIT TESTS

For application of APM approach, the data must fit the exponential distribution (Adams & Papa 2000) and as such, based on the MSST, the data was tested with exponential distribution (using EasyFit software), Kolmogorov-Smirnov and Anderson-Darling tests were performed and a good fit was obtained (Figure 2(a) to 2(d)).

The Kolmogorov-Smirnov test is used to decide if a sample comes from a hypothesized continuous probability density function (PDF). It is based on the largest vertical difference between the theoretical and empirical cumulative distribution function (CDF). For a random variable $X$ and sample ($x_1, x_2, \ldots \ldots . x_n$), the empirical CDF of $X$ ($F_x(x)$) is given by:

$$F_x(x) = \frac{1}{n}\sum_{i=1}^{n} I\left(x_i \leq x\right), \quad (1)$$

where $I$ (condition) = 1 if true and 0 otherwise. Given two cumulative probability functions ($Fx$ and $Fy$), the Kolmogorov-Smirnov test statistics ($D_+$ *and* $D_-$) are given by:

$$D_+ = \max_x \left(F_x(x) - F_y(x)\right) \quad (2)$$

$$D_- = \max_x \left(F_y(x) - F_x(x)\right) \quad (3)$$

The Anderson-Darling test compares the fit of an observed CDF with an expected CDF. It gives more weight to the tail of the distribution and the test statistic ($A^2$) is given by:

$$A^2 = -n - \frac{1}{n}\sum_{i=1}^{n} I\left(2i-1\right)\left[\ln F(X_i) + \ln(1 - F(X_{n-i+1}))\right] \quad (4)$$

TABLE 1. Stations used in data collection

| Station location | Station ID | Period of data collection (years) |
|---|---|---|
| Alor Star | 6108001 | 1996-2009 |
| Penang | 5302003 | 1999-2009 |
| Kuala Lumpur | 3116006 | 1996-2009 |
| Melaka | 2224038 | 1988-2009 |
| Segamat | 2528012 | 1999-2009 |
| Kluang | 2033002 | 2000-2009 |
| Ulu Remis | 1834001 | 1996-2009 |
| Kota Bharu | 6122064 | 1988-2009 |
| Kuala Terengganu | 4131001 | 1996-2009 |
| Kuantan | 3833002 | 1988-2009 |
| Mersing | 2237164 | 1988-2009 |
| Kota Tinggi | 1737001 | 1996-2008 |
| Johor Bahru | 1437116 | 1970-2010 |

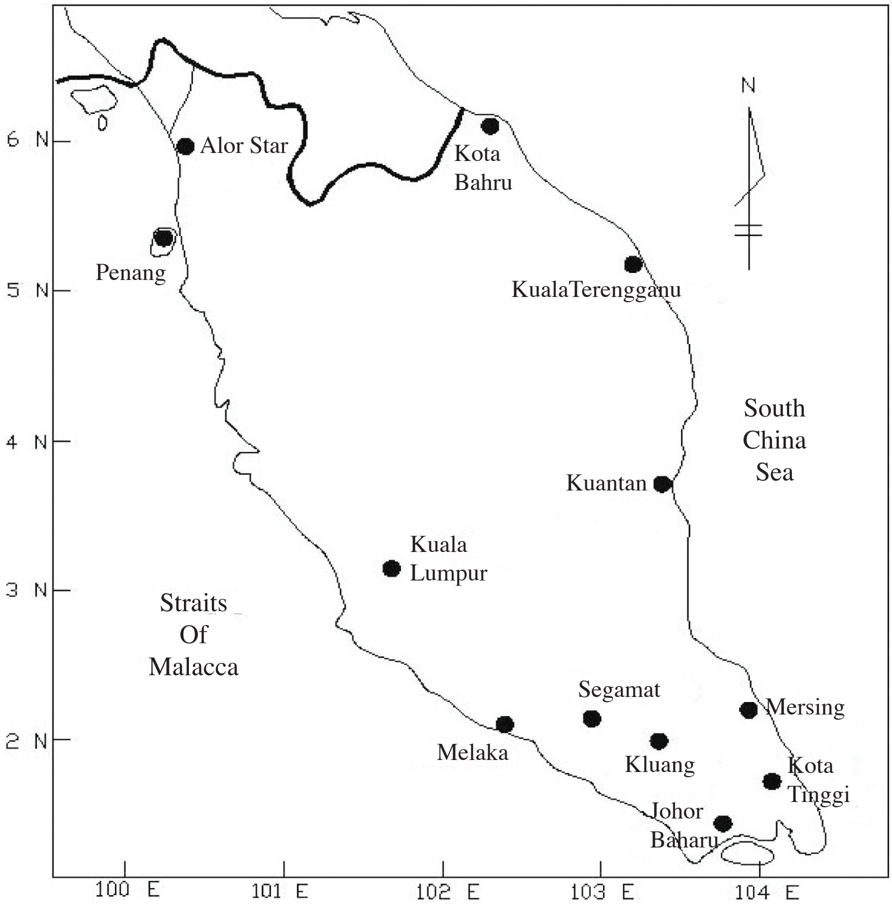


FIGURE 1. Map of Peninsular Malaysia showing the rainfall stations

## DEVELOPMENT OF APM PARAMETERS

The APM parameters of $\lambda$ ($h^{-1}$),$\zeta$ ($mm^{-1}$), $\beta$ (h/mm), $\psi$ ($h^{-1}$) were calculated as the inverse of average duration per rainfall event t (h), inverse of average volume per rainfall event v (mm), inverse of average intensity per rainfall event $i$ (mm/h) and inverse of average inter-event time $b$ (h), respectively, while $\theta$ (#/yr) is the average annual number of events. Figure 3 shows the flowchart for the analysis of rainfall data.

## RESULTS

Application of APM requires that the long term rainfall data follows an exponential distribution and as such results of goodness-of-fit tests indicated that the rainfall characteristics (rainfall duration, rainfall volume, rainfall intensity and storm separation time) fit exponential distribution. Figures 2(a) to 2(d) show typical fits of exponential distribution to histograms of rainfall characteristics using 6 h MSST. Exponential fits using 2 h, 12 h and 24 h MSST also showed a similar fit with all the rainfall characteristics thus confirming the validity of modeling Malaysian rainfall with exponential distribution. Tables 2, 3, 4 and 5 present the APM parameters using MSST of 2 h, 6 h, 12 h and 24 h, respectively. The various terms used in the tables are defined, thus: $t$ (h) is the average duration of rainfall event and $\lambda$ ($h^{-1}$) is the parameter for exponential PDF of rainfall duration, $v$ (mm) is the average volume of rainfall event and $\zeta$ ($mm^{-1}$) is the parameter for exponential PDF of rainfall volume, $i$ (mm/h) is the average intensity of rainfall event and $\beta$ (h/mm) is the parameter for exponential PDF of rainfall intensity, $b$ (h) is the average inter-event time and $\psi$ ($h^{-1}$) is the parameter for exponential PDF of inter-event time and $\theta$ (#/yr) is the average annual number of rainfall events.

The parameter for exponential PDF of rainfall duration $(\lambda)$ ranges from 0.116 $h^{-1}$ to 0.369 $h^{-1}$ for 2 h MSST to a range of 0.027 $h^{-1}$ to 0.052 $h^{-1}$ for 24 h MSST. The parameter for exponential PDF of rainfall volume $(\zeta)$ ranges from 0.068 $mm^{-1}$ to 0.111 $mm^{-1}$ for 2 h MSST to 0.028 $mm^{-1}$ to 0.051 $mm^{-1}$ for 24 h MSST. Similarly, the parameter for exponential PDF of rainfall intensity $(\beta)$ ranges from 0.256 h/mm to 0.429 h/mm for 2 h MSST to 0.401 h/mm to 0.670 h/mm for 24 h MSST. Finally, the parameter for exponential PDF of inter-event time $(\psi)$ ranges from 0.019 $h^{-1}$ to 0.033 $h^{-1}$ for 2 h MSST to 0.010 $h^{-1}$ to 0.014 $h^{-1}$ for 24 h MSST.

## DESIGN EXAMPLE

To illustrate the design procedure for the application of APM parameters to detention pond design in Malaysia, we consider an urban catchment in Kuala Lumpur to be serviced with a detention facility. The catchment's area is 61400 $m^2$ and it is required to design a detention

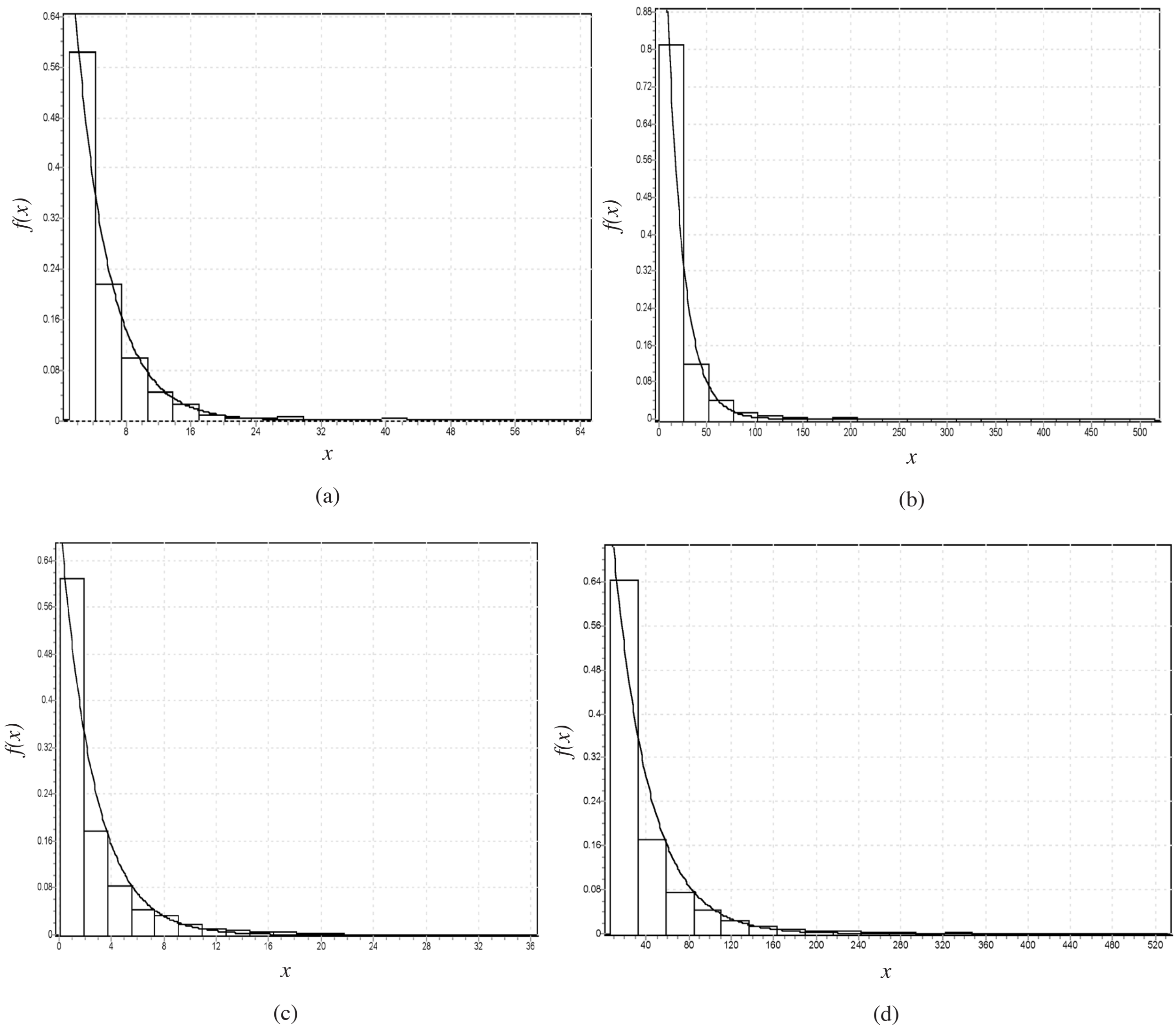


FIGURE 2(a). Exponential PDF fit of rainfall duration for Kedah using 6 h MSST, (b) exponential PDF fit of rainfall volume for Terengganu using 6 h MSST, (c) exponential PDF fit of rainfall intensity for Johor using 6 h MSST and 2(d) exponential PDF fit of inter-event time for Kuala Lumpur using 6 h MSST

TABLE 2. APM parameters with 2 h MSST

| Station locations | Analytical probabilistic model parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $t$ (h) | $\lambda$ ($h^{-1}$) | $v$ (mm) | $\zeta$ ($mm^{-1}$) | $i$ (mm/h) | $\beta$ (h/mm) | $b$ (h) | $\psi$ ($h^{-1}$) | $\theta$ (#/yr) |
| Alor Star | 3.046 | 0.328 | 8.977 | 0.111 | 2.410 | 0.415 | 30.202 | 0.033 | 260 |
| Penang | 2.717 | 0.368 | 10.003 | 0.100 | 3.216 | 0.311 | 33.772 | 0.030 | 240 |
| Kuala Lumpur | 2.710 | 0.369 | 11.532 | 0.087 | 3.912 | 0.256 | 33.052 | 0.030 | 245 |
| Melaka | 3.792 | 0.264 | 9.796 | 0.102 | 2.928 | 0.342 | 46.166 | 0.022 | 174 |
| Segamat | 4.354 | 0.230 | 9.739 | 0.103 | 2.332 | 0.429 | 51.644 | 0.019 | 155 |
| Kluang | 4.248 | 0.235 | 11.219 | 0.089 | 2.648 | 0.378 | 51.683 | 0.019 | 155 |
| Ulu Remis | 3.795 | 0.264 | 9.920 | 0.101 | 2.655 | 0.377 | 39.866 | 0.025 | 199 |
| Kota Bharu | 8.642 | 0.116 | 14.611 | 0.068 | 2.490 | 0.402 | 53.736 | 0.019 | 133 |
| Kuala Terengganu | 4.721 | 0.212 | 13.371 | 0.075 | 3.178 | 0.315 | 35.236 | 0.028 | 219 |
| Kuantan | 3.988 | 0.251 | 11.968 | 0.084 | 2.648 | 0.378 | 37.432 | 0.027 | 211 |
| Mersing | 3.440 | 0.291 | 10.874 | 0.092 | 3.060 | 0.327 | 33.436 | 0.030 | 237 |
| Kota Tinggi | 3.802 | 0.263 | 10.377 | 0.096 | 2.795 | 0.358 | 42.184 | 0.024 | 190 |
| Johor Bahru | 5.097 | 0.196 | 12.384 | 0.081 | 2.984 | 0.335 | 40.175 | 0.025 | 195 |

TABLE 3. APM Parameters with 6 h MSST

| Station locations | Analytical probabilistic model parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $t$ (h) | $\lambda$ ($h^{-1}$) | $v$ (mm) | $\zeta$ ($mm^{-1}$) | $i$ (mm/h) | $\beta$ (h/mm) | $b$ (h) | $\psi$ ($h^{-1}$) | $\theta$ (#/yr) |
| Alor Star | 5.155 | 0.194 | 11.982 | 0.083 | 2.395 | 0.418 | 39.252 | 0.025 | 194 |
| Penang | 4.502 | 0.222 | 13.082 | 0.076 | 3.134 | 0.319 | 43.217 | 0.023 | 184 |
| Kuala Lumpur | 4.085 | 0.245 | 14.293 | 0.070 | 3.879 | 0.258 | 40.131 | 0.025 | 198 |
| Melaka | 4.910 | 0.204 | 11.383 | 0.088 | 2.818 | 0.355 | 53.137 | 0.019 | 150 |
| Segamat | 5.558 | 0.180 | 11.279 | 0.089 | 2.318 | 0.431 | 59.293 | 0.017 | 134 |
| Kluang | 5.226 | 0.191 | 12.710 | 0.079 | 2.679 | 0.373 | 58.136 | 0.017 | 137 |
| Ulu Remis | 4.739 | 0.211 | 11.309 | 0.088 | 2.657 | 0.376 | 44.963 | 0.022 | 175 |
| Kota Bharu | 10.475 | 0.095 | 16.866 | 0.059 | 2.459 | 0.407 | 61.530 | 0.016 | 115 |
| Kuala Terengganu | 6.827 | 0.146 | 16.969 | 0.059 | 3.078 | 0.325 | 43.833 | 0.023 | 173 |
| Kuantan | 6.767 | 0.148 | 16.688 | 0.060 | 2.600 | 0.385 | 50.990 | 0.020 | 152 |
| Mersing | 5.410 | 0.185 | 14.137 | 0.071 | 3.041 | 0.329 | 42.530 | 0.024 | 183 |
| Kota Tinggi | 4.925 | 0.203 | 12.073 | 0.083 | 2.822 | 0.354 | 48.576 | 0.021 | 164 |
| Johor Bahru | 6.394 | 0.156 | 14.329 | 0.070 | 3.004 | 0.333 | 45.990 | 0.022 | 169 |

pond for the catchment. If the runoff coefficient (φ) and depression storage ($S_d$) of the catchment are 0.6 and 0.5 mm, respectively, estimate (a) the average annual volume of runoff from the catchment (b) the required size of a detention pond at the site, if the maximum allowable discharge from the pond *(Ω)* is 0.1 $m^3$/s and spill from the pond is to be allowed only once in every ten years.

The APM parameters for the catchment can be obtained using the Kuala Lumpur raingauge parameters in Table 3 i.e. $\lambda$ = 0.245 $h^{-1}$, $\zeta$ = 0.07 $mm^{-1}$, $\beta$ = 0.258 h/mm, $\psi$ = 0.025 $h^{-1}$, $\theta$ =198 events/year for MSST = 6 h.

The average annual volume of runoff *(R)* is given by (5):

$$R = \theta \frac{\varphi}{\zeta} e^{-\zeta S_d} = 198 \frac{0.5}{0.07} e^{-0.07*0.5} = 1365.54 \text{ mm.} \quad (5)$$

The spill-recurrence interval calculation is given by (6):

$$T_R = \frac{1}{\theta G_p(0)}, \quad (6)$$

where $T_R$ = 10 years is the recurrence interval and average annual number of events $\theta$ = 198, so the probability of spill per rainfall event $G_P(0)$ = 0.000505.

The analytical expression of probability of spill per rainfall event is given by (7) (Adams & Papa 2000).

TABLE 4. APM parameters with 12 h MSST

| Station locations | Analytical probabilistic model parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $t$ (h) | $\lambda$ (h$^{-1}$) | $v$ (mm) | $\zeta$ (mm$^{-1}$) | $i$ (mm/h) | $\beta$ (h/mm) | $b$ (h) | $\psi$ (h$^{-1}$) | $\theta$ (#/yr) |
| Alor Star | 9.298 | 0.108 | 14.983 | 0.067 | 2.343 | 0.427 | 48.698 | 0.021 | 149 |
| Penang | 7.715 | 0.130 | 16.367 | 0.061 | 2.961 | 0.338 | 51.986 | 0.019 | 147 |
| Kuala Lumpur | 6.670 | 0.150 | 17.257 | 0.058 | 3.800 | 0.263 | 46.713 | 0.021 | 164 |
| Melaka | 6.758 | 0.148 | 12.950 | 0.077 | 2.699 | 0.370 | 59.283 | 0.017 | 132 |
| Segamat | 7.735 | 0.129 | 13.041 | 0.077 | 2.283 | 0.438 | 67.241 | 0.015 | 116 |
| Kluang | 6.985 | 0.143 | 14.372 | 0.070 | 2.570 | 0.389 | 64.660 | 0.015 | 121 |
| Ulu Remis | 6.269 | 0.160 | 12.688 | 0.079 | 2.643 | 0.378 | 49.220 | 0.020 | 157 |
| Kota Bharu | 13.589 | 0.074 | 19.609 | 0.051 | 2.392 | 0.418 | 70.127 | 0.014 | 99 |
| Kuala Terengganu | 10.762 | 0.093 | 21.386 | 0.047 | 2.972 | 0.336 | 53.088 | 0.019 | 137 |
| Kuantan | 10.725 | 0.093 | 21.109 | 0.047 | 2.513 | 0.398 | 62.331 | 0.016 | 120 |
| Mersing | 8.458 | 0.118 | 17.312 | 0.058 | 2.965 | 0.337 | 50.249 | 0.020 | 149 |
| Kota Tinggi | 6.869 | 0.146 | 13.828 | 0.072 | 2.820 | 0.355 | 54.410 | 0.018 | 143 |
| Johor Bahru | 8.606 | 0.116 | 16.444 | 0.061 | 2.912 | 0.343 | 51.510 | 0.019 | 147 |

TABLE 5. APM parameters with 24 h MSST

| Station locations | Analytical probabilistic model parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $t$ (h) | $\lambda$ (h$^{-1}$) | $v$ (mm) | $\zeta$ (mm$^{-1}$) | $i$ (mm/h) | $\beta$ (h/mm) | $b$ (h) | $\psi$ (h$^{-1}$) | $\theta$ (#/yr) |
| Alor Star | 36.689 | 0.027 | 30.918 | 0.032 | 1.494 | 0.670 | 80.619 | 0.012 | 74 |
| Penang | 25.770 | 0.039 | 28.125 | 0.036 | 2.320 | 0.431 | 76.821 | 0.013 | 85 |
| Kuala Lumpur | 26.442 | 0.038 | 30.939 | 0.032 | 2.496 | 0.401 | 69.620 | 0.014 | 91 |
| Melaka | 19.362 | 0.052 | 19.598 | 0.051 | 2.073 | 0.482 | 80.580 | 0.012 | 87 |
| Segamat | 20.547 | 0.049 | 19.668 | 0.051 | 1.665 | 0.601 | 92.532 | 0.011 | 77 |
| Kluang | 19.981 | 0.050 | 21.889 | 0.046 | 1.965 | 0.509 | 89.138 | 0.011 | 79 |
| Ulu Remis | 24.604 | 0.041 | 22.232 | 0.045 | 1.719 | 0.582 | 72.623 | 0.014 | 89 |
| Kota Bharu | 28.449 | 0.035 | 29.063 | 0.034 | 1.986 | 0.504 | 95.627 | 0.010 | 67 |
| Kuala Terengganu | 30.118 | 0.033 | 36.205 | 0.028 | 2.290 | 0.437 | 78.077 | 0.013 | 81 |
| Kuantan | 25.401 | 0.039 | 32.224 | 0.031 | 1.998 | 0.501 | 86.124 | 0.012 | 79 |
| Mersing | 28.075 | 0.036 | 30.270 | 0.033 | 2.071 | 0.483 | 74.574 | 0.013 | 85 |
| Kota Tinggi | 24.176 | 0.041 | 23.541 | 0.042 | 2.070 | 0.483 | 80.145 | 0.012 | 84 |
| Johor Bahru | 26.971 | 0.037 | 27.910 | 0.036 | 2.144 | 0.466 | 75.054 | 0.013 | 87 |

$$G_P(0) = \left[\frac{1/\Omega}{\lambda/\Omega + \zeta/\vartheta}\right]\left[\frac{\left(\psi/\Omega\right) + \left(\zeta/\vartheta\right) e^{-\left(\psi/\Omega + \zeta/\vartheta\right)S_A}}{\psi/\Omega + \zeta/\vartheta}\right] e^{-\zeta S_d}. \quad (7)$$

All the terms in (7) have been defined previously. Rearranging to solve for $S_A$ gives:

$$S_A = -\frac{1}{\psi/\Omega + \zeta/\varphi} \ln\left\{\frac{\varphi}{\zeta}\left[\frac{\lambda/\Omega + \zeta/\varphi}{\lambda/\Omega}\left(\frac{\psi}{\Omega} + \frac{\zeta}{\vartheta}\right) G_P(0) e^{\zeta S_d} - \frac{\psi}{\Omega}\right]\right\}, \quad (8)$$

where all the terms have been defined previously. Note that the unit of $\Omega$ was converted to its equivalent in mm depth over the catchment area per hour (i.e. 0.1 $m^3/s$ = 5.863 mm/h)) which gives $S_A$ = 39.615 mm. Converting back the unit of $S_A$ (from depth uniformly distributed over the catchment to $m^3$) gives $S_A$ = 2432.36 $m^3$.

## DISCUSSION

Urbanization brings about the creation of impervious areas and the buildup of pollutants due to the urban activities. These resulted in increased volume of runoff and the

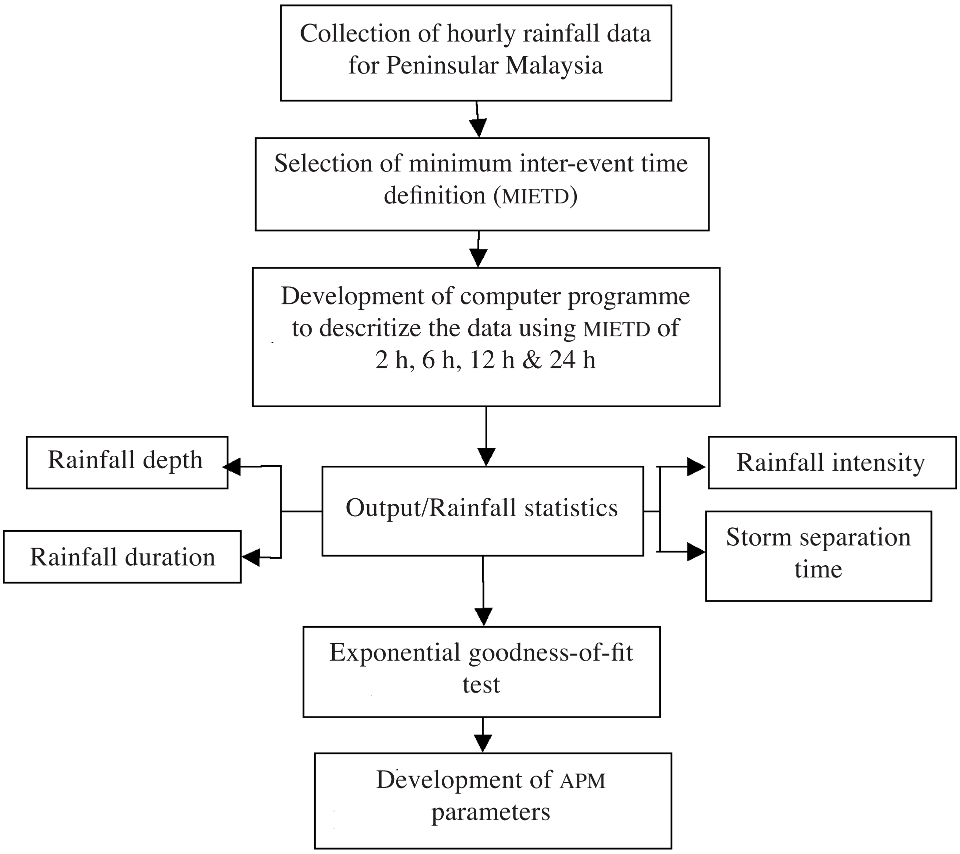


FIGURE 3. Rainfall data analysis

pollutants wash off during stormwater runoff events. The consequences cause flood and non-point source pollution problems at the downstream of urban catchments. In order to effectively manage these problems, detention ponds are stormwater management practices used for the control and treatment of the urban stormwater. Over the last two decades, there have been an increase in the number of stormwater detention ponds designed and constructed for the treatment and control of stormwater in Malaysia (DID 2000). Most of these ponds are designed based on design storm concept, in which the flood control aspect is given attention during design and the pollution control aspect is relegated to the background. Also the design storm assumes that the recurrence interval of runoff is the same as that of rainfall producing it, thus neglecting the storm separation time between two consecutive events. There is the need to better explore the benefits of these systems in such a way that they can serve the dual purposes as flood and pollution control. This can be achieved by extending the detention time long enough for the suspended particles and other pollutants carried by the stormwater to settle (Shammaa et al. 2002). However, if the detention time is too long, there will be little storage for subsequent storms to fill in, which means there is the tendency that the pond may be overwhelmed by subsequent storms (Guo 2002). This call for design approach that is amenable to optimization, such as the APM described earlier. This paper has proposed APM parameters that can serve as inputs to the APM for urban stormwater management in Malaysia.

As the APM parameters are calculated as the inverse of rainfall characteristics, it is observed that the parameters are higher in stations that recorded lower values of the rainfall characteristics (*t, v, i, b*) and vice-varsa. Therefore, stations with longer rainfall duration have lower $\lambda$ parameter compared with stations with shorter duration. The same applies to other APM parameters of rainfall volume, intensity and inter-event time. It is also observed that as more rainfall series are merged into individual events with increasing MSST, their corresponding APM becomes smaller. The effect of MSST on rainfall characteristics has already been discussed elsewhere (Supiah et al. 2010). It is also observed that the MSST affects the ranking of stations as stations with the highest values of parameters at lower MSST may not be on the same rank when the MSST changes to a higher value. This is evident in stations like Kota-Bharu (with lowest $\lambda$ parameter) for 2 h MSST which is replaced by Kedah when the MSST changes to 24 h. Unfortunately, there is no clearly set rule for the selection of MSST and values are more or less chosen arbitrarily depending on the phenomenon of interest (Dunkerly 2008). Finally, to apply the APM technique to detention pond design in any part of the Peninsular, data from the closest raingauge stations may be used or interpolated to obtain values for the particular area.

## Conclusions

In this research, the APM parameters, applicable to Malaysian conditions, have been presented. They are closed form analytical expressions for long term system performances such as the exceedence probability of runoff, average annual number and volume of runoff capture, average annual number and volume of spill volume, average annual pollution control and its EMC. Once the parameters were obtained for a particular area, the performance measures can easily be determined. The approach is quick and less costly making it suitable in system analysis such as optimization and MCDM particularly at the preliminary stage of a project in order to screen the most feasible and economic design alternatives.

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