



Regionalisation of low flow frequency curves for the Peninsular Malaysia

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SUMMARY

Regional maps and equations for the magnitude and frequency of 1, 7 and 30-day low flows were derived and are presented in this paper. The river gauging stations of neighbouring catchments that produced similar low flow frequency curves were grouped together. As such, the Peninsular Malaysia was divided into seven low flow regions. Regional equations were developed using the multivariate regression technique. An empirical relationship was developed for mean annual minimum flow as a function of catchment area, mean annual rainfall and mean annual evaporation. The regional equations exhibited good coefficient of determination ($R^2 > 0.90$). Three low flow frequency curves showing the low, mean and high limits for each region were proposed based on a graphical best-fit technique. Knowing the catchment area, mean annual rainfall and evaporation in the region, design low flows of different durations can be easily estimated for the ungauged catchments. This procedure is expected to overcome the problem of data unavailability in estimating low flows in the Peninsular Malaysia.

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Introduction

Sustainable water resources planning and management requires adequate gauging data to enable quantification of water quality and quantity (Oyebande, 2001). Information is also required on the river flow patterns and availability of water within the catchment. Lack of adequate hydrological data introduces uncertainty and difficulty in the design and management of water resources systems. The most critical challenge in water resources projects (for irrigation, industrial, domestic, hydropower and environmental) is to establish the reliability of water availability at the point of interest. For any unregulated catchment (with no dams, reservoirs, weirs, etc.), reliability of water availability at the intake is determined from the low flow characteristics of the stream. The critical flow features of interest to designers are flow duration (day), magnitude (m^3/s) and frequency (return period in years). The design duration of low flow represents the tolerance of the user to periods of water unavailability. The magnitude for the specified duration dictates the amount of water available for the user(s). Finally the frequency of the occurrence of a particular mag-

nitude of low flow reflects the risk associated with failure to achieve the water supply objective(s), which is determined based on the socio-economic importance of the scheme.

Estimation of flow characteristics of ungauged catchments is usually based on transferring or extrapolating information from gauged to ungauged sites, a process called regionalisation (Galea et al., 2007; Jeville et al., 2002; Smakthin, 2001; Nathan and McMahon, 1990; Bullock and Andrews, 1997; Hall and Minns, 1999). Several regionalisation approaches have been used, the most common method being that which involves the derivation of empirical relationships between the flow and the catchment characteristics (Gan et al., 1990; Riggs, 1990). These relationships are in most cases region specific. Therefore, regions within which they are applicable have to be delimited, for example using hydrometric zones (Mimikou, 1984). Flow characteristics at an ungauged site are estimated by applying the predictive equation developed for its particular hydrometric zone (NERC, 1975; IH, 1980). Regionalisation also can be done by the application of self-organising feature maps (SOFMs) and fuzzy logic, which have been applied by Srinivas et al. (2008) as a clustering technique for the regionalisation of river flows.

Catchments that belong to the same hydrometric zone, however, may not necessarily have similar hydrological responses since

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geographical proximity is not a sufficient condition for hydrological homogeneity (Acreman and Sinclair, 1986). Meijerink (1985) found that morpho-lithological characteristics could be used to identify catchment groups with similar hydrological responses. An alternative approach to the delimitation of regions with similar hydrological responses, i.e. regions that are hydrologically homogeneous, is the use of multivariate techniques such as multiple regression, cluster and discriminant analysis (Tasker, 1982; Nathan and McMahon, 1990; Burn and Boorman, 1993; Zrinji and Burn, 1994). Ideally, only catchment characteristics should be used for cluster analysis. This enables determination of membership of an ungauged catchment on the basis of its catchment characteristics, to a region with a known relationship between flow and catchment characteristics. The selection of these catchment characteristics is problematic since different sets of predictive variables will identify different clusters. Nathan and McMahon (1990) demonstrated that a combination of multiple regression, cluster analysis and multi-dimensional plotting improved the delimitation of these hydrologically homogeneous regions within which predictive equations for flow characteristics can be developed.

The regional approach of low flow analysis for ungauged catchments has been used in many countries including Malaysia (DID, 1985; Drayton et al., 1980; Taylor and Goh, 1976 and IH, 1980). A sufficient amount of good quality hydrometeorological data should be available from a set of neighbouring gauged catchments to estimate the required low flow characteristics of their ungauged counterparts. Industrial, agricultural and urban developments have increased demand on water resources and pressure to provide information on the water availability in rivers that have sparse or no data. In many instances, especially for the small-scale projects, economic and social pressures do not permit delay to allow for acquisition, screening and analysis of stream-flow data. Responding to the urgent need for information on low flows, Hydrological Procedure (HP No.-12) was first prepared by Department of Drainage and Irrigation (DID), Malaysia in 1976 (Taylor and Goh, 1976). However, hydrological procedures are dynamic and such documents need upgrading periodically to account for the changes in landuse, weather and meteorological patterns. As such, the HP No.-12 was updated in 1985, using data up to 1982 (DID, 1985). That existing HP No.-12 has one shortcoming, namely, that the user has to refer to two regionalised maps to estimate the low flows. Moreover, it has not been updated during the last two decades. Thus, there was a need to upgrade the HP No.-12 to estimate low flows in the Peninsular Malaysia. The main objective of this study was to develop a simplified but reliable procedure for estimating low flows in the Peninsular Malaysia.

Methodology

Study area

The study was focussed on the Peninsular Malaysia, which is located in the sub-tropical humid region of the globe. Being located within longitudes 1–5° North and latitudes 100–104° East, the study area is influenced by the equatorial environment and located outside the volcanic, tornado, and severe drought belts. Two rainy seasons (north-east and south-west monsoons) and local convective thunderstorms contribute significant amount of storm events resulting in mean annual rainfall of about 2500 mm (DID, 2000). Although located in the humid region, the peninsula experiences occasional draught spells, the most recent one being in the year 1998. The main causes of low flow are dry spells, low rainfall incidents and increased soil imperviousness due to urbanisation.

Data used

Eighty two (82) stations in the Peninsular Malaysia, with length of records varying from 10 to 37 years (up to 1997) were selected for the analysis. The actual low flow (in m³/s) of 1, 7 and 30 day durations at the selected stations were collected from DID's data archive. Selection of the river gauging stations included the consideration of tidal influence, any major flow control structure and catchment size (larger than 20 km², to be consistent with the conditions selected for the existing HP No.-12). After proper screening of the data, seventy eight (78) stations were accepted for the analysis. Discharge data collected after the construction of any major control structure upstream of the station were not considered. The effect of water abstraction for domestic, industrial and irrigation water supply on the stations was ignored as the data on the abstraction rate was not available. However, the stations were included for the study. It was assumed that $Q_{D,T(\text{Cal})} = \left(\frac{Q_{D,T(\text{Obs})}}{\text{MAM}_{(\text{Obs})}} \right) \times \text{MAM}_{(\text{Cal})}$; where $Q_{D,T}$ is the low flow of D -day duration with a T -year return period. The mean annual minimum (MAM) flow (m³/s) was calculated for each year based on the 1-day low flow data of each station. The subscripts "(cal)" and "(Obs)" indicate calculated and observed (recorded) values. Mean Annual Evaporation (AE, in mm) was extracted from the data archive of the DID, Malaysia. The catchment areas at the river gauging stations were calculated from the digitisation of topographical maps using AutoCAD software.

Statistical analyses

Several distributions were tested (three types of generalised extreme value – GEV, Log-normal and Log-Pearson III) for the frequency analysis of low flows. Generally, the extreme value (EV III) distribution showed good fit with most of the low flow data, which was in agreement with the distribution used in the last upgrading of the HP No.-12 (DID, 1985). The low flows of various return periods were predicted by the method of moments as given by Haan (1977). However, this requires an awkward solution for the shape parameter of the GEV distribution.

$$Q_T = Q_{\text{mean}} + \sigma K \quad (1)$$

in which Q_T = the magnitude of the event for a return period of T years; Q_{mean} = the arithmetic mean value of the annual low flow events; σ = the standard deviation from the mean; K = the chow frequency factor for extreme values, which depends on the type of distribution used.

The D -day low flow values for the return periods of 1.11, 1.25, 2, 5, 10, 20, 25 and 50 years were divided by the station's $\text{MAM}_{(\text{Obs})}$ value to get dimensionless low flow in the form of $Q_{D,T(\text{Obs})}/\text{MAM}_{(\text{Obs})}$. These ratios were, then, plotted against the reduced variate (y) expressed in terms of return period (T) as given in Eq. (2) below (Cunnane, 1978; Victor, 1994). Depending on the number of data, the values of T were calculated either by Eqs. (3) or (4).

$$y = -\ln \left\{ \ln \left(\frac{T}{T-1} \right) \right\} \quad (2)$$

The Kolmogorov-Smirnov test was done (with $\alpha = 0.05$) to check the goodness of fit of the data. Data of the stations that showed goodness of fit statistic falling above its 95% confidence limit (under the null hypothesis) were accepted for the regional grouping. The following plotting position formulas were selected for the study. They were also used in the previous versions of the HP No.-12 (Taylor and Goh, 1976 and DID, 1985):

- (i) The Weibull formula for time series less than 20 years, where data are generally uniform in nature with less dispersed extreme values

$$T = \frac{N + 1}{M} \quad (3)$$

- (ii) The Gringorten formula for time series greater than 20 years, which is better for widely varied dispersed extreme values

$$T = \frac{N + 0.12}{M - 0.44} \quad (4)$$

in which T = the plotting position of an annual low flow in years, N = the length of records in years, M = the rank of data.

Regionalisation process

Two distinct steps were followed for the regionalisation of low flow in the streams. Firstly, a set of regression equations was formulated relating $MAM_{(Cal)}$ to the catchment area (A in km^2), mean annual rainfall (MAR in mm) and mean annual evaporation (AE in mm). Secondly, a set of dimensionless low flow frequency curves was developed relating $Q_{D,T(Obs)}/MAM_{(Obs)}$ to the recurrence interval or return period T .

Stations that exhibited similar dimensionless frequency distributions were identified and grouped into various regions. The grouping of stations into regions was done by superimposing the dimensionless curves and examining similarity of the curves. If a curve from one station was close to a curve from another station nearby, the catchments of these two stations were grouped together into a single region.

Other factors such as rainfall pattern, topography and hydrological characteristics that influence the low flows in a river catchment were also taken into consideration before finalising the regional low flow frequency boundaries. Delineation of the boundaries of the regions was guided by the mean annual rainfall maps (DID, 1991), low flow frequency regions (DID, 1985) and topographical maps published by the Survey Department of Malaysia. After the regional groups had been established, the regional curve for each region was derived by averaging (using arithmetic mean) the dimensionless curves of the stations belonging to that region. Finally, the regional curve was produced (using the third order polynomial curve fitting method) as the representative curve for all rivers in that region.

The coefficients of the multiple regression equation for $MAM_{(Cal)}$ (a , b and c in Eq. (5) below) were determined using SPSS statistical software. The multivariate relationship between catchment characteristics and its MAM (dependent variable) was assumed to be in the form of;

$$MAM_{(Cal)} = a \cdot A^b \cdot (MAR - AE)^c \quad (5)$$

in which $MAM_{(Cal)}$ = the calculated mean annual minimum flow based on the recorded data (m^3/s); A = the catchment area (km^2); MAR = the mean annual rainfall in the catchment (mm); AE = the mean annual evaporation (mm); a = constant coefficient of the equation; b = the exponential coefficient of the area A ; and c = the exponential coefficient of the difference ($MAR - AE$).

Riggs (1973) and Nash and Shaw (1965), among many others, studied the degree of correlation among different catchment properties with stream flows. Gray (1964) observed that A and MAR had the most significant effect on MAM values. Consideration of catchment slope also provides good correlation coefficients for river flow estimation. However, as this parameter is difficult to determine precisely and requires survey or mapping data, catchment

slopes were ignored as a parameter in the regionalised low flow equations. Low flows or droughts occur when there is less rainfall and consequently high evaporation. Thus, during drought periods there are more rainfall losses due to high infiltration and evaporation rates that affect the stream flow (resulting in less flow).

The mean annual rainfall values were abstracted from the isohyetal maps developed for the Peninsular Malaysia. For simplicity, the same group of stations was analysed for regionalisation of the low flow frequency curves and MAM equations. Surprisingly, no further adjustments were required to keep the selected stations within the same region in deriving the MAM equations. Thus the same regions were used for both the frequency curves and the MAM equations. This is an additional improvement or simplification over the existing HP No.-12 prepared by DID, for which two maps are required.

Results and discussion

Delineation of the whole Peninsular Malaysia into seven (7) low flow regions is shown in Fig. 1. The regionalisation was assisted by the mountain trail along the middle range of the Peninsula. This high ridge also separates Malaysia into two hydrologically symmetric zones, namely, East-coast and West-coast. Multivariate equations, to calculate regional mean annual minimum flows, are given in Table 1. These equations relate $MAM_{(Cal)}$ with catchment area, mean annual rainfall and mean annual evaporation via three coefficients. As given in Table 1, all regions exhibited good coefficient of determination ($R^2 > 0.90$). Normalised low flow ($Q_{D,T(Obs)}/MAM_{(Obs)}$) of D -day duration and required return period are developed and given in Table 2. These equations were expressed in terms of reduced variate (y).

Low flow frequency curves were regionalised without much adjustment. The maximum deviation among the curves of the stations was observed for the low flows with a recurrence interval greater than 20 years. The mean normalised low flow frequency curves for each region are shown in Figs. 2–4. As evident in those figures, frequency curves of the regions comprising hilly areas showed low ratios of normalised flows (e.g. Region LF 3). This indicates that, during drought periods, less water can be expected in the steep terrains. The ratio of annual 1, 3 and 7-day low flows to the $MAM_{(Obs)}$ for all regions varied within 0.04–2.02, 0.02–2.18 and 0.08–3.70, respectively (Table 3). Most of the highest and lowest values of normalised low flow values were observed in the State of Negeri Sembilan (Region LF 5), which is known as the driest state in the Peninsula. Exceptionally high skewness of normalised low flow was not observed for any group. It is quite obvious that a few sub-catchments within the same large region may have different runoff characteristics. Trends of the frequency curves were analysed within the same group and, to guide the user(s), lower and upper boundaries for the normalised low flow frequency equations are given in Table 3. These equations can be used to calculate the normalised low flow of any return period. Low flow frequency values for the most commonly used return periods are shown in Table 3. The upgraded equations reported in this paper were verified comparing the estimated low flow values with the frequency analysis of the recorded data. However, cross-validation of the predicted low flow values for various catchments was essential and is warranted for a future study.

Application procedure

If the catchment area exceeds $20 km^2$, river flow is not significantly regulated by any dam or weirs and the location is not predominantly influenced by tide then the following procedure can

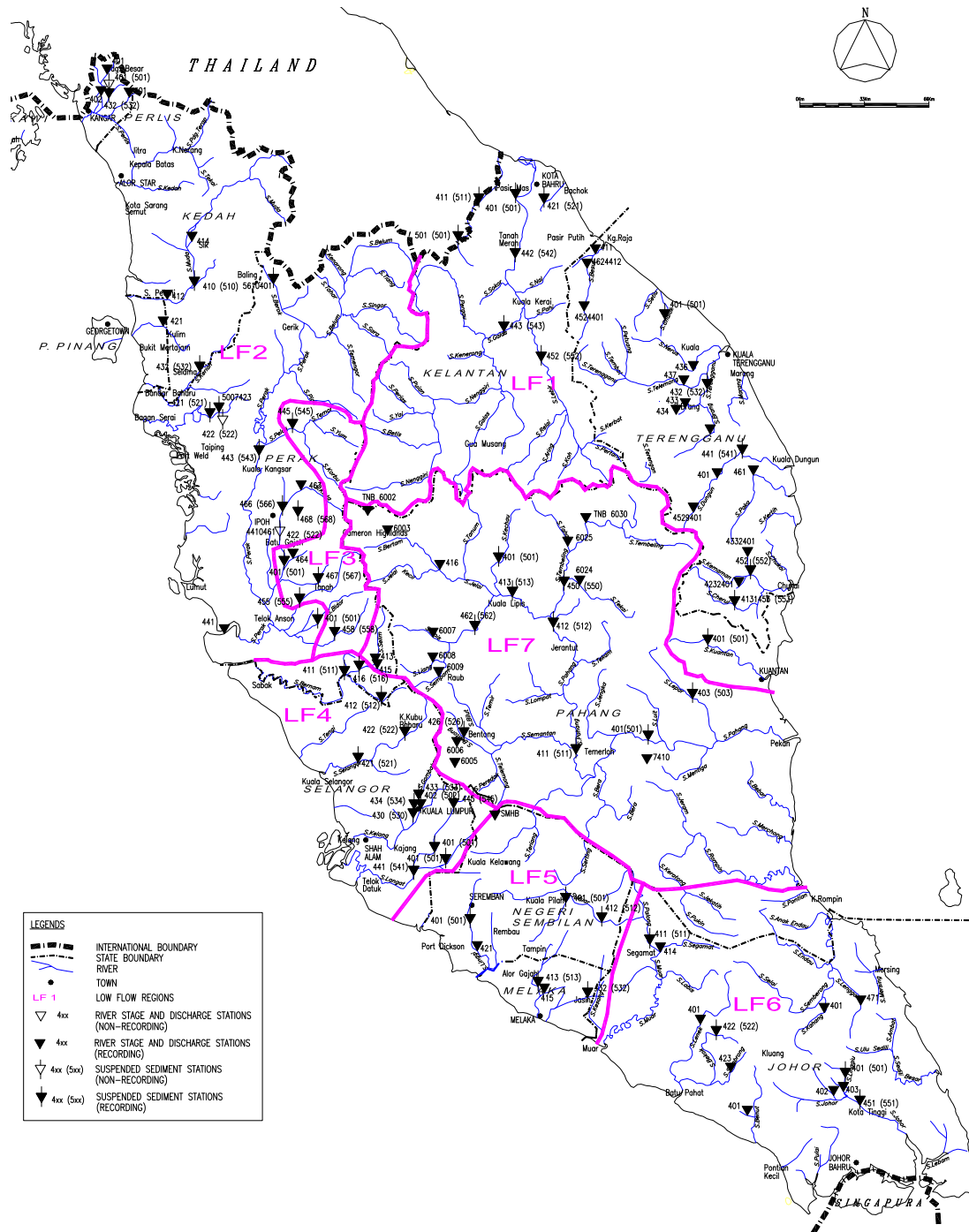


Fig. 1. Low flow regions for the Peninsular Malaysia.

Table 1

Regionalised equations to calculate mean annual minimum (MAM) values for different regions.

Region	Statistical MAM Equations	R^2
LF1	$MAM = \exp(-6.3270A^{1.0190})(MAR-AE)^{0.2690}$	0.963
LF2	$MAM = \exp(-5.2669A^{0.6890})(MAR-AE)^{-1.0870}$	0.916
LF3	$MAM = \exp(-6.5820A^{0.8990})(MAR-AE)^{0.4670}$	0.917
LF4	$MAM = \exp(-15.3000A^{1.0090})(MAR-AE)^{1.5800}$	0.991
LF5	$MAM = \exp(-9.0950A^{1.0380})(MAR-AE)^{0.5840}$	0.982
LF6	$MAM = \exp(-3.3020A^{0.7310})(MAR-AE)^{0.0060}$	0.969
LF7	$MAM = \exp(-2.8840A^{0.8010})(MAR-AE)^{-0.0250}$	0.993

Note: LF1 = low flow region 1, exp = exponential.

be applied to estimate design low flows for an ungauged catchment in the Peninsular Malaysia.

- Determine the catchment area, A (km^2);
- Calculate or estimate the mean annual rainfall, MAR (mm) and AE (mm) for the catchment;
- Identify the mean annual minimum (MAM) flow region from Fig. 1;
- Calculate MAM from the appropriate regional equation using the coefficients given in Table 1;
- Compute the $(Q_{D,T}/MAM)$ value for 1–50 years return period from the regional low flow frequency equations given in Table 2;

Table 2Regionalised equations to calculate D -day duration low flow of different frequencies for 1–50 years return period.

Region	$Q_{1,T}/MAM$ frequency equations	$Q_{7,T}/MAM$ frequency equations	$Q_{30,T}/MAM$ frequency equations
LF1	$0.0174y^3 + 0.1508y^2 - 0.5326y + 1.0472$	$0.0172y^3 + 0.1492y^2 - 0.5300y + 1.1528$	$0.0229y^3 + 0.1990y^2 - 0.7075y + 1.6336$
LF2	$0.0193y^3 + 0.1818y^2 - 0.6607y + 1.0985$	$0.0212y^3 + 0.1956y^2 - 0.7118y + 1.2633$	$0.0231y^3 + 0.2240y^2 - 0.8883y + 1.8383$
LF3	$0.0081y^3 + 0.0757y^2 - 0.3236y + 0.9158$	$0.0098y^3 + 0.0862y^2 - 0.3398y + 0.9810$	$0.0118y^3 + 0.1072y^2 - 0.4311y + 1.2861$
LF4	$0.0158y^3 + 0.1338y^2 - 0.4548y + 1.0336$	$0.0180y^3 + 0.1519y^2 - 0.5058y + 1.1346$	$0.0183y^3 + 0.1637y^2 - 0.6111y + 1.5932$
LF5	$0.0353y^3 + 0.2802y^2 - 0.7826y + 0.9985$	$0.0367y^3 + 0.2917y^2 - 0.8334y + 1.1251$	$0.0648y^3 + 0.5088y^2 - 1.4307y + 1.8503$
LF6	$0.0269y^3 + 0.2261y^2 - 0.6906y + 1.0558$	$0.0277y^3 + 0.2266y^2 - 0.6891y + 1.1432$	$0.0289y^3 + 0.2460y^2 - 0.8333y + 1.5995$
LF7	$0.0136y^3 + 0.1147y^2 - 0.3935y + 1.0665$	$0.0168y^3 + 0.1390y^2 - 0.4508y + 1.1633$	$0.0168y^3 + 0.1472y^2 - 0.5374y + 1.5390$

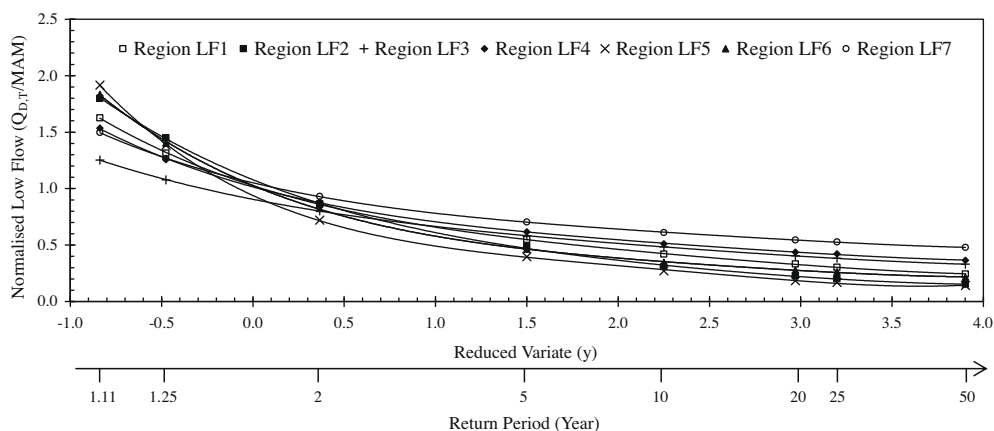
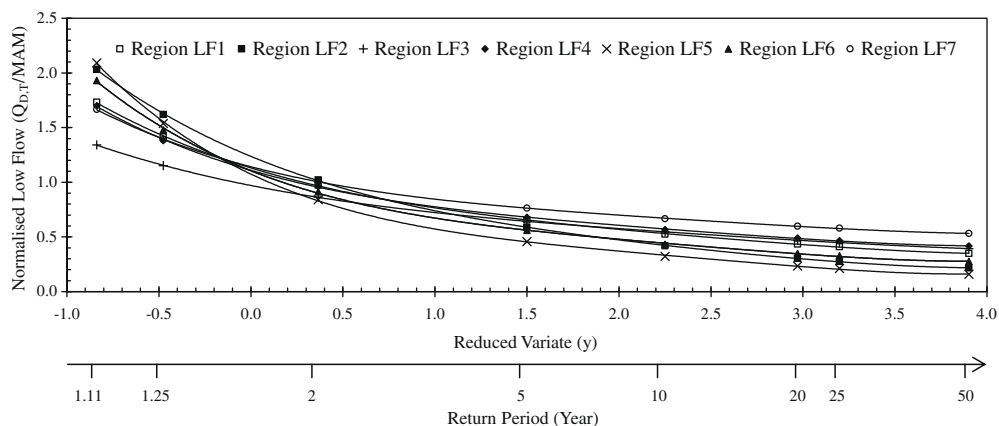
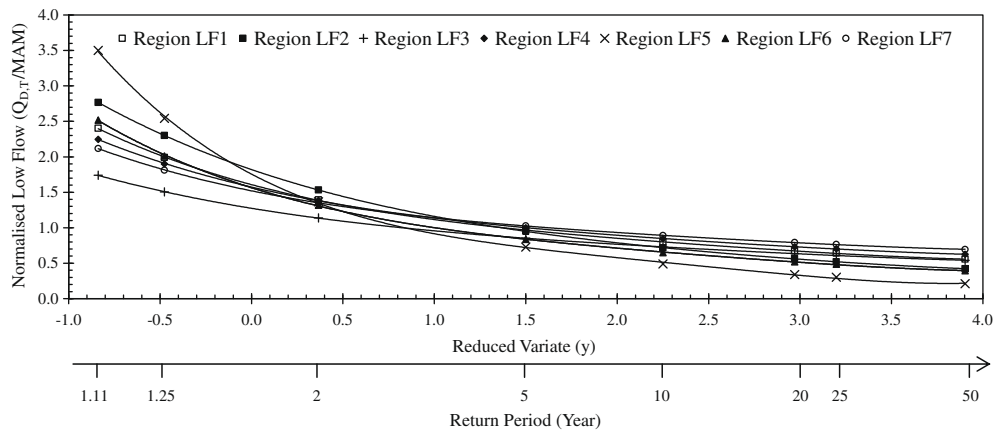
Note: y = reduced variate = $-\ln\{\ln[T/(T-1)]\}$ and T = return period (year).**Fig. 2.** Regionalised 1-day low flow curves for the Peninsular Malaysia.**Fig. 3.** Regionalised 7-day low flow curves for the Peninsular Malaysia.**Fig. 4.** Regionalised 30-day low flow curves for the Peninsular Malaysia.

Table 3Regionalised $Q_{D,T}/MAM$ values (based on the observed data) to calculate 1, 7 and 30 day low flows for the most commonly used return periods.

RP (Year)	RV (y)	Region LF1			Region LF2			Region LF3			Region LF4			Region LF5			Region LF6			Region LF7		
		LL	Mean	UL	LL	Mean	UL	LL	Mean	UL	LL	Mean	UL	LL	Mean	UL	LL	Mean	UL	LL	Mean	UL
1-day low flow																						
1.11	−0.84	1.50	1.63	1.74	1.64	1.80	1.94	0.97	1.25	1.38	1.40	1.51	1.62	1.85	1.93	2.02	1.69	1.84	1.99	1.43	1.51	1.64
1.25	−0.48	1.22	1.32	1.44	1.33	1.45	1.60	0.82	1.08	1.21	1.16	1.26	1.37	1.30	1.38	1.47	1.25	1.40	1.55	1.17	1.26	1.42
2	0.37	0.77	0.86	0.98	0.77	0.86	1.01	0.54	0.80	0.93	0.78	0.90	0.97	0.64	0.72	0.81	0.68	0.83	0.98	0.83	0.93	1.06
5	1.50	0.46	0.55	0.66	0.37	0.48	0.61	0.34	0.58	0.71	0.52	0.62	0.72	0.31	0.39	0.48	0.31	0.46	0.61	0.62	0.70	0.83
10	2.25	0.32	0.42	0.53	0.21	0.31	0.46	0.26	0.48	0.61	0.41	0.51	0.61	0.17	0.27	0.34	0.20	0.35	0.50	0.53	0.61	0.74
20	2.97	0.23	0.33	0.44	0.13	0.23	0.37	0.18	0.40	0.52	0.34	0.44	0.54	0.08	0.18	0.24	0.13	0.28	0.43	0.47	0.55	0.68
25	3.22	0.21	0.31	0.41	0.10	0.20	0.35	0.18	0.38	0.49	0.32	0.42	0.52	0.06	0.16	0.23	0.11	0.26	0.41	0.45	0.53	0.66
50	3.90	0.14	0.24	0.34	0.05	0.15	0.34	0.17	0.33	0.44	0.29	0.37	0.48	0.04	0.14	0.21	0.07	0.22	0.35	0.43	0.48	0.64
7-day low flow																						
1.11	−0.84	1.52	1.74	1.85	1.82	2.01	2.08	1.05	1.34	1.47	1.55	1.69	1.85	1.95	2.09	2.18	1.78	1.92	2.03	1.51	1.67	1.86
1.25	−0.48	1.18	1.41	1.53	1.42	1.62	1.69	0.88	1.15	1.28	1.26	1.38	1.55	1.41	1.54	1.63	1.35	1.48	1.60	1.24	1.39	1.58
2	0.37	0.74	0.97	1.08	0.82	1.02	1.09	0.62	0.86	0.99	0.84	0.96	1.13	0.71	0.84	0.93	0.78	0.91	1.03	0.86	1.01	1.20
5	1.50	0.43	0.66	0.76	0.39	0.59	0.66	0.42	0.64	0.77	0.56	0.68	0.85	0.33	0.46	0.55	0.43	0.56	0.68	0.61	0.76	0.95
10	2.25	0.30	0.53	0.62	0.22	0.42	0.49	0.32	0.54	0.67	0.45	0.57	0.72	0.19	0.32	0.41	0.30	0.43	0.55	0.52	0.67	0.86
20	2.97	0.20	0.43	0.54	0.11	0.30	0.37	0.25	0.47	0.60	0.36	0.49	0.62	0.10	0.23	0.32	0.22	0.35	0.47	0.45	0.60	0.79
25	3.20	0.17	0.41	0.52	0.08	0.28	0.35	0.24	0.45	0.58	0.34	0.46	0.59	0.07	0.21	0.30	0.19	0.33	0.45	0.43	0.58	0.77
50	3.90	0.16	0.35	0.46	0.02	0.22	0.33	0.20	0.39	0.53	0.31	0.42	0.53	0.05	0.16	0.26	0.15	0.28	0.40	0.38	0.53	0.70
30-day low flow																						
1.11	−0.84	2.18	2.39	2.52	2.54	2.77	3.20	1.55	1.74	1.97	1.98	2.24	2.40	3.00	3.48	3.70	2.35	2.52	2.91	1.78	2.11	2.48
1.25	−0.48	1.79	1.99	2.12	2.12	2.30	2.74	1.34	1.50	1.76	1.65	1.90	2.06	2.35	2.54	2.75	1.86	2.01	2.40	1.48	1.81	2.19
2	0.37	1.19	1.39	1.52	1.31	1.53	1.97	0.98	1.14	1.40	1.14	1.39	1.55	1.18	1.36	1.57	1.17	1.32	1.71	1.02	1.35	1.73
5	1.50	0.77	0.97	1.10	0.81	0.95	1.30	0.69	0.85	1.11	0.75	1.00	1.16	0.56	0.73	0.91	0.69	0.84	1.23	0.70	1.03	1.41
10	2.25	0.60	0.80	0.93	0.59	0.72	0.99	0.57	0.73	0.99	0.60	0.85	1.01	0.34	0.49	0.64	0.50	0.65	1.04	0.56	0.89	1.24
20	2.97	0.47	0.67	0.80	0.46	0.56	0.78	0.48	0.64	0.87	0.50	0.74	0.89	0.17	0.34	0.50	0.37	0.52	0.87	0.46	0.79	1.11
25	3.20	0.43	0.63	0.76	0.40	0.52	0.69	0.46	0.60	0.82	0.48	0.69	0.84	0.14	0.30	0.44	0.32	0.48	0.82	0.44	0.77	1.05
50	3.90	0.38	0.56	0.66	0.33	0.42	0.57	0.41	0.54	0.71	0.46	0.62	0.76	0.08	0.21	0.35	0.24	0.39	0.68	0.38	0.69	0.97

Note: LL = lower limit, UL = upper limit, RP = return period and RV = reduced variate.

- Select the lower and upper limits of ($Q_{D,T}/MAM$) values from Table 3 to study different scenario for the most commonly used return periods;
- Calculate the magnitude of design low flow, $Q_{D,T}$ for various return periods by multiplying the ($Q_{D,T}/MAM$) factor by the calculated MAM value.

Conclusions

Regionalisation of empirical or statistical hydrological equations is one of the widely used techniques not only for the ungauged catchments but also to facilitate the study of alternative scenarios and take prompt decisions for planning purposes. Like any statistical regional hydrological equation, multivariate low

flow equations also need upgrading and updating to take account of changes in the hydrological or climatic characteristics of the catchments. Regional low flow equations for the Peninsular Malaysia were revised and upgraded incorporating new data (1983 and onwards). Normalised low flow frequency curves and multivariate regression equations were developed for seven regions covering the Peninsula. The equations developed here display very good coefficient of determination which reflects the correlation coefficient and are verified by observed low flow values. The updated regional low flow equations presented in this paper are expected to provide good estimation of low flow under the recent landuse and hydro meteorological conditions. It is expected that, using the regionalised method presented in this paper, low flows of different durations and frequencies can be obtained with relatively little effort. However, it is realised that cross-validation of the predicted

low flow values (which is not done in the study) could have strengthened the reliability of the proposed equations.

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