https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

Natural Hazards and Earth System Sciences
Discussions

Assessment of probability distributions and minimum storage draft-rate analysis in the equatorial region

Hasrul Hazman Hasan[1], Siti Fatin Mohd Razali[1], Nur Shazwani Muhammad[1], Zawawi Samba Mohamed[1], Firdaus Mohamad Hamzah[2]

[1]Department of Civil Engineering, Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, Bangi, 43600, Malaysia
[2]Department of Engineering Education, Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, Bangi, 43600, Malaysia

Correspondence to: Siti Fatin Mohd Razali (fatinrazali@ukm.edu.my)

Abstract. Streamflow information is critical to the management and development of water resources strategies. The reliability of water supply from rivers depends on their low flow characteristics. Low flow frequency analysis was derived using the Weibull plotting position and four specific distributions. Maximum likelihood was used to parameterise, while Kolmogorov-Smirnov tests are used to evaluate their fit to the dataset. The best probability distribution is then selected based on individual probabilistic analysis and the flow duration curve for the study threshold level (Q_{90} percentiles) with the pooling procedure derived to quantify the drought characteristics. The mass curve is used to quantify the minimum storage draft-rate required to maintain the 50% mean annual flow for a recurrence interval of 10 years. The results indicated the hydrological droughts have generally become more frequent and critical in the availability of rivers to sustain water demand during low flows.

1 Introduction

Droughts are long-term natural disaster phenomena resulting from less than average precipitation causing significant damages to a wide variety of sectors and affecting large regions. The rapid development of the world now shows an increase in populations, and climate change lends to increase drought occurrences (Bakanoğullari and Yeşilköy, 2014; Tigkas et al., 2012). Droughts have considerable economic, societal, and environmental impacts. Drought can typically be classified into four types depending on different kinds of drought impacts in different areas: meteorological, hydrological, agricultural and socio-economic (Hasan et al., 2019; Tri et al., 2019). Any types of drought are dynamic and defined by various characteristics such as frequency, severity, duration, and magnitude. The main factor involved in hydrological drought is climate change and anthropogenic activities of surface water resources. The assessment of hydrological drought provides a better representation of the hydrological cycle's water surface. Hydrological drought also allows the incorporation of spatial details that impact internal storage and soil, vegetation and terrain characteristics. This study mainly focuses on hydrological drought. The related

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

hydrological aspects, including low water levels and decreased groundwater recharge, are more directly affected by the hydrological drought impacts.

Low flow frequency analysis is the purpose of assessing the probability of drought occurring (Cancelliere and Salas, 2010). In analysing droughts for water supply management, information on the low flow frequency analysis is crucial (Koteia et al., 2016). In Smakhtin's study, he analysed the existing method of estimating low flow time series, including extreme low flow analysis, baseflow separation, duration curve, and streamflow recessions (Smakhtin, 2001). Prolonged hydrological drought will result in phenomena of low flow events. A hydrological drought of severity – duration – frequency (SDF) curve was developed using a threshold level method developed by Sung and Chung, (2014). Hydrological drought events occur when a water deficit occurs within a specified period when the streamflow is less than threshold levels, and the drought ends when the streamflow is above the threshold level in a series of times (Fleig et al., 2006).

The hydrological drought design system is rather complicated, and susceptible to catchment characteristics or climate, and a combination of the two variables (Loon et al., 2015; Mohammed and Scholz, 2018; Zhai and Tao, 2017). Precipitation and temperature are two main factors among different environmental factors that mainly determine the climate model and antecedent situation for hydrological drought events (Joetzjer et al., 2013). Watershed also performs a significant part in the propagation of drought and affects procedures such as pooling, lagging, and lengthening (Fleig et al., 2006; Sarailidis et al., 2019a). Some research further explored the specific functions of climate control and watershed influence in regulating features of hydrological drought, and the findings are hugely based on spatial scales (Austin and Nelms, 2017; Barker et al., 2016; Liu et al., 2012; Zarafshani et al., 2016; Zhu et al., 2018). Generally, the hydrological drought duration and the quantity of the deficit are more climate-related than watershed control. However, watershed features such as geology, region, slope, and groundwater regime perform a significant part in regulating hydrological drought duration and quantity deficit for the regional scale where the climate is presumed to be relatively constant (Gianfagna et al., 2015; Laaha and Blöschl, 2006, 2007; Liu et al., 2016). The influences on hydrological drought are not restricted to the external variables such as climatic and watershed variables and should not be disregarded for anthropogenic activities in the form of land-use modification, reservoir control, irrigation, and water extraction or withdrawal (Hatzigiannakis et al., 2016; Richter and Thomas, 2007; Sun et al., 2018; Toriman et al., 2013).

High demand for water that can accommodate the daily water consumption of the population, as well as the lack of rain, has caused disruptions of water supply in Selangor (Khalid, 2018; Kwan et al., 2013; Ngang et al., 2017). Water shortages associated with the incident of El Nino / Southern Oscillation (ENSO) impacted parts of Malaysia, including Selangor (Sanusi et al., 2015; Shaaban et al., 2003; Zainal et al., 2017). Consequently, the characteristics of hydrological drought must be identified, and the effects of hydrological drought quantitatively evaluated. Studies conducted by Iqbal et al. (2016), Azadi et al. (2018), and Tigkas et al. (2012) have highlighted the issue of hydrological drought and its impact on agricultural, socio-

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

economic and streamflow in the watershed (Azadi et al., 2018; Iqbal et al., 2016; Tigkas et al., 2012). The hydrological drought was referred to as the most critical aspect of drought with significantly reduced streamflow and lower water storage in the river system (Hasan et al., 2019). Because of this, in order to ensure that water supply requirements are met, the storage rate for each river should be known to ensure that the minimum storage during low flow and drought in the coming years will be able to accommodate consumers' water demand.

This study concentrates on three significant issues. First, to find the best-fit models for determining the frequency analysis of low flow over return periods. Second, to evaluate the threshold level value for drought analysis, and finally, to estimate the storage-draft rate required at the recurrence interval for the streamflow station in Selangor. This study is essential to understand the concept of low flow, drought characteristics, and the predictive significance of river storage-draft rates in managing sustainable water catchment. The results are useful for developing measures to maintain flow variability and can be used to develop policies for risk management.

2 Methodology

Streamflow data were obtained from the Department of Irrigation and Drainage Malaysia, which covers approximately 40 years (1978 to 2017) of records for all streamflow gauging stations. Precautions were taken to ensure reasonable low flow regimes are captured. The daily streamflow had consistent statistical properties and analysis of streamflow for determining the threshold level values to drought analysis. Lastly, the minimum storage draft rate required for Selangor was determined using a mass curve analysis.

2.1 Site description

The scope of this study covers the entire streamflow station in the Selangor state. Selangor covers an area of 8,104 km^2 and is located on Peninsular Malaysia's west coast. Selangor's water supply system not only covers the state of Selangor but also supplies water to the Kuala Lumpur and Putrajaya areas (Sakke et al., 2016). Langat River Basin, Klang River Basin, and Selangor River Basin are the main river basins in Selangor. There are also three other river basins in Selangor, Buloh River Basin, Bernam River Basin, and Tengi River Basin. Table 1 shows the locations and characteristics of all streamflow gauging stations involved in this study.

Figure 1 shows the seven streamflow gauging stations involved in this study with four streamflow gauging stations located at Langat River Basin at Dengkil, Kajang, Semenyih, and Lui. There are also streamflow gauging stations each at Rantau Panjang for the Selangor River Basin, Tanjung Malim, and JAM SKC for the Bernam River Basin, respectively (Department of Irrigation and Drainage Malaysia, 2011). The headwater of the Langat river basin starts from the northeast of the basin, flows to the southwest, and joins with the Semenyih River. Two dams, the Langat and Semenyih dams, are located at the upper

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

reaches of the Langat river (Elfithri et al., 2018). Both dams serve to regulate the raw water flowing to treatment plants downstream. The main tributaries of Selangor Rivers are Sembah, Kanching, Kerling, Rawang, and Tinggi River. There are two dams, namely the Selangor and Tinggi dam, in the Selangor river basin. Lastly, the Bernam river basin is located in the southern part of the Perak state with a total area of 3,364 km^2 with the main tributaries rivers of Slim, Daharoi, Erong and Trolak river (Department of Irrigation and Drainage Malaysia, 2011).

2.2 Climate characteristics

Selangor state is characterised by its geographical position, which lies near the equator climate that is warm and humid over the year with an average annual rainfall of more than 2477 mm (Lassen et al., 2004). The average annual temperature varies between 27-30 °C, and the average annual relative humidity is between 70-90% (Lee et al., 2013). The climatic equatorial regions are influenced by two monsoons, which are the southwest Indian monsoon and the northeast Asian monsoon.

Two rainy seasons due to northeast and southwest monsoons contribute a significant amount of storm events resulting in a mean annual rainfall of about 2500 mm (Mamun et al., 2010). Even though Selangor is located in the humid region, it occasionally encounters drought periods. Dry spells, low rainfall, and increased soil impermeability due to population growth are the leading causes of low flow events. The low flow usually refers to a stream regime that indicates the average annual streamflow variability associated with the regional climate's annual cycle. A stream's regime can display one or more low flow events depending on the climate. Two rainy and two dry seasons represent the equatorial climate, and the two streamflow regimes have two corresponding periods of high flow and low flow.

2.3 Trend analysis

Trend analysis covers both detection and attribution for hydrological drought (Zou et al., 2018). Trends in streamflow have consequences for hydraulic models that are often based on the notion of stationarity that many researchers are now debating because of climate change effects within not only local but also regional climate patterns, or perhaps basin and regional scale (Zeng et al., 2015). Despite significant improvements in statistical hydrology for trend evaluations in recent years, researchers are beginning to pay more attention to trend analysis in order to understand better hydro-climatic variables such as precipitation (Nam et al., 2015), temperature (Marx et al., 2018), and streamflow in the context of prevailing uncertainties and changes in climate (Bormann and Pinter, 2017).

The function of trend analysis defines the situation of one variable versus the other and determines if a shift occurs within specified limits. Either positive or negative is displayed in the orientation of the shift. Mann-Kendall and Sen's T-tests are the most commonly used non-parametric trend analysis methods (Hisdal et al., 2001). The consistency of the performance of the analysis has a crucial significance in the trend analysis studies, particularly on the discharges of any stream. For this study, the Mann-Kendall test is chosen due to its capability of identifying any trend in a time series. The Mann-Kendall test is also based

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

Natural Hazards and Earth System Sciences
Discussions

on rank order and straightforward to calculate. On the other hand, most studies are using Sen's slope estimation technique that presents the shift quantity (Assefa and Moges, 2018). Sen's slope is a non-parametric method for determining any trend's slope. It utilises data from a time series that is similarly distributed. The difference in slope is calculated per changed time for each data point.

In the streamflow time series data, the trend was analysed using the Mann-Kendall test to evaluate the significance of monotonic trends. The test is as follows; Assuming $X_1, X_2, ..., X_n$ is a series of data over a time period, the null hypothesis (H_0) is tested, and the data comes from a series with identically distributed and independent variables. Over time, the data of the H_1, the alternative hypothesis, follows a monotonic trend. Under H_0, the Mann-Kendall test statistic is given by Eq. (1):

$$S = \sum_{i=j}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \, , \tag{1}$$

where x_j and x_i are the data values in years j and i, respectively, with $j > i$; n is the total number of years; *sgn()* is the signum function. The alternative hypothesis H_1 of a two-sided test is that the distribution of x_i and x_j are not identical for all $i, j \leq n$ with $i \neq j$. Therefore, the probability associated with S and the sample size, n, is determined to statistically measure of the trend significance. Normalised test statistics Z are expressed as follows by Eq. (2):

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & (S > 0) \\ 0 & (S = 0) \\ \frac{S-1}{\sqrt{VAR(S)}} & (S < 0) \end{cases} \, , \tag{2}$$

The null hypothesis of no trend is rejected at 99% significance if $|Z| > 2.575$; the null hypothesis of no trend is rejected at 95% significance if $|Z| > 1.96$; and the null hypothesis of no trend is rejected at 95% significance if $|Z| > 1.645$. In the test statistic, S calculates the sum of the difference between data points and the associations between samples to show the presence or absence of a trend. When the value of Z is positive, it gives a positive trend and a negative trend when Z gives a negative value. In this study, the level of significance of 0.05 or 95% (P-value = 0.05) was used. If their P-value was equal to or less than 0.05 (P-value $\leq$ 0.05), the trend tests were considered significant, as shown by Eq. (3) (Coch and Mediero, 2016):

$$Trend = \begin{cases} + \, (Z > 0) \\ 0 \, (Z = 0) \\ - \, (Z < 0) \end{cases} \, , \tag{3}$$

The Mann-Kendall test is associated with the calculation of Sen's slope. Some patterns may not be considered as being statistically significant while they may be of practical interest and if there are any shifts in streamflow, statistical tests may not detect them at a sufficient level of significance. Then a linear trend analysis is also conducted and the trend magnitude is determined by the Sen's slope method. If a trend is identified in a time series, the slope can be determined using the slope

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

estimator (β) in Sen's slope test. The estimator β is the median of all slopes between data pairs for the entire data set. A positive β shows an increasing trend, and a negative β a decreasing trend as given by Eq. (4):

$$\beta = \text{Median}\ \frac{y_j - y_i}{x_j - x_i}\,, \tag{4}$$

with *n* the number of data; *i, j* are indices with *i* = 1, 2, …… (*n*-1) and *j* = 2, 3, …., *n*.

2.4 Probability distribution of low flow frequency analysis

There are several types of frequency distribution functions that have been successfully applied to hydrologic data. The probabilistic behaviour was analysed using four probability distribution functions (PDFs), widely used in extreme value analysis (Joshi and St-Hilaire, 2013; Zaidman et al., 2003). Then, probability distribution functions were fitted with their parameters estimated using the method of maximum likelihood estimation (Assefa and Moges, 2018). Goodness-of-fit was judged by the Kolmogorov–Smirnov test. Here, a 95% confidence level was accepted to reject or accept a fit, based on *D*-value.

The graphical illustration of probability plot is described as the i^{th}-order statistic of the sample, *y(i)*, as a function of a plotting position, which is simply a measure of the non-exceedance probability related to the i^{th}-order statistic from the assumed standardised distribution (Sharma and Panu, 2015). The r^{th}-order statistic is acquired by way of rating the observed sample from the smallest (*i* = 1) to the greatest (*i* = *n*) value, then *y(i)* equals the i^{th} largest value. According to Koteia et al. (2016), the plotting position of low flow, *P* can be obtained using the Weibull formula given by Eq. (5) (Koteia et al., 2016):

$$P = \frac{m}{(N+1)}\,, \tag{5}$$

where, *P* = The probability of low flow; *m* = the ranking, from highest to lowest, of mean annual minimum flow; and *N* = the total number of the mean annual minimum flow.

The selection of probability is according to the shape parameter. This is because the shape parameter can be represented as the skewness parameter. Table 2 shows the probability density functions for each distribution. For this study, the method of maximum likelihood is used for parameter estimation. The likelihood function is defined as Eq. (6):

$$l(\theta|\, x_1, x_2, \dots, x_N) = \prod_{i=1}^{n} f(x_i : \theta_1, \theta_2, \dots., \theta_N)\,, \tag{6}$$

Once the parameters are estimated, the selected distributions will be tested for the assumption that the observed data is actually from the fitted distribution of probability. The Kolmogorov-Smirnov (KS) test has been used to determines the largest discrepancy between the theoretical ($F_n(x_i)$) and empirical ($F_0(x_i)$) cumulative distribution functions. The KS test obtains a *D*-statistic; the maximum vertical is given by Eq. (7):

$$D = max|F_n(x_i) - F_0(x_i)|)\,, \tag{7}$$

Where *r* is the rank of the observation *i* in ascending order. The smaller *D*-values imply a better fit of the streamflow series to the selected probability distribution. If *D* was greater than the critical value (α = 0.05), the distribution was rejected.

2.4.1 Estimation of low flow based on the return period

After the probability calculations, *P* and subsequent returns period the low flow, *T*, the low flow rate variation will be plotted against the return period, *T* on the semi-log graph. With this graph, the specific magnitude of a specified period can be determined (Erfen et al., 2015; Gottschalk et al., 2013). The return period describes the probability of occurring extreme events.

2.5 Flow duration curve (FDC)

Flow Duration Curve (FDC) describes the ratio of a specified percentage of time with discharge is equal to or surpassed (Croker et al., 2003; Mohamoud, 2008; Vogel and Fennessey, 1994), which reflects the relationship between streamflow magnitude and length of time that relates to the average percentage of time a specific flow is exceeded (Sung and Chung, 2014). The FDC was developed by arranging streamflow values in decreasing magnitude order and assigning rank numbers to each streamflow value with the largest flow ranked as one and the smallest *n*, where *n* is the complete record quantity and calculating the percentage of time a given flow was equal to or exceeded (probability of excess) using the relationship in Eq. (8) (Awass, 2009; Koteia et al., 2016; Yahiaoui, 2019):

$$P = [r/(n+1)] X 100, \qquad (8)$$

Where, *P* = the percentage of time a given flow is equalled or exceeded; *n* = the total number of records; *r* = the rank of the flow magnitude. Kannan et al. (2018) indicated the flow duration curve could be divided into five zones, representing high flows (0-10%), humid conditions (10-40%), medium-range flows (40-60%), dry conditions (60-90%), and low flows (90-100%).

While FDCs have a long history in hydrology, they are often criticised because their interpretation historically depends on the specific period in records. A period-of-record of FDC (POR FDC) represents the probability of streamflow exceedance over a long period. This definition can be beneficial as long as the period of record was used to create the FDC is long enough to provide a limiting streamflow distribution, or whether the period of record corresponds to particular planning or design life. Nevertheless, in many nations, records are shorter than this prescribed time for a large part of the gauged catchments. Regardless of the following limitations, engineers are still preferring to use FDC compared to POR FDC. For individual years, they considered FDCs and viewed certain annual FDCs like a sequence of maximum or minimum annual flow. Engineers also want to estimate daily streamflow quantiles for hydrological design and planning. FDCs' annual concept requires FDCs to grant confidence intervals and return dates. FDCs can be built to generalise hydrological frequency analysis using average recurrence intervals.

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

2.5.1 Threshold level method

The low flow value was obtained from the flow duration curve at 90^{th} percentiles. The magnitude of drought characteristics was determined by the threshold value and value difference between the time series. As the daily data series are used, the existence of minor drought events and mutually dependable drought events can be detected (Van Loon and Van Lanen, 2013). According to the study by Sakke et al. (2017), to eliminate the minor drought events, the events that occur for less than 15 days will be excluded while the mutually dependable events were also eliminated by the pooling procedure (Sakke et al., 2017). In this paper, the 7-day moving average was applied as a pooling procedure to obtain smooth data. Through these methods, the mutually dependent drought events will combine into individual and independent drought events (Fleig et al., 2006). The minor drought events will be eliminated or combined with individual drought events automatically (Yahiaoui et al., 2009).

2.6 Minimum storage-draft rate method

The minimum storage draft rate was determined by using the mass curve of low flow at a monthly interval (Bharali, 2015). Although specific evaluation of storage requirements is essential for design, reconnaissance planning can frequently be facilitated by using draft-storage curves based on low-flow frequency analysis. Alrayess et al. (2017) determined the capacity of river storage by the mass curve method. The mass curve has many useful applications in the design of storage capacities, such as to determine the reservoir storage capacity and flood routing (Gao et al., 2017). The procedure for the mass curve method has the following steps; first, construct a mass curve of the historical streamflow (monthly streamflow); determine the slope of the cumulative draft line for the graphical scales; next, superimpose the cumulative draft line on the mass curve; lastly, measure the largest intercept between the cumulative draft line and the mass curve.

3 Results

The streamflow data from the seven streamflow gauging stations will be analysed in three aspects, which are mean annual low flow and the probability of occurrence, drought characteristics using the threshold level and the estimation of storage draft rate of the river. Statistical characteristics were calculated from the observed 40 years daily streamflow time series: the mean, minimum, and maximum of 14,610 values data; standard deviation, skewness, and kurtosis for each station (Table 3).

3.1 Trend analysis

Annual series trend analysis presents the overall view of the shift in systems of streamflow (Assefa and Moges, 2018). The Mann-Kendall test and Sen's slope results are displayed in Table 4. The results of this analysis indicated that five selected stations (S01, S02, S04, S05, and S07) are increasing trends of streamflow. Two of the stations, S03 and S06, have indicated a decreasing trend with the negative change of streamflow.

In the S03 and S06 stations there could be several factors for decreasing streamflow. Some of this involves modifications in the catchment of physical characteristics such as changes in land cover in river basins (Hisdal et al., 2001). Another five stations indicated an increase in trends of streamflow due to climate change for the increasing temperature and soil water evaporation (Siwar et al., 2013; Taye et al., 2011). Simple linear regression is often conducted to evaluate the interaction between interest variables and to obtain a change in hydro-climatological variables over time. A positive slope demonstrates an upward trend, while a negative slope indicates a downward trend. Another benefit for this method is that it offers a significance indicator dependent on the slope hypothesis test and also delivers the degree of alteration magnitude. The total difference can be obtained by multiplying the slope by the number of years during the time under observation.

3.2 Low flow frequency analysis

Frequency analysis has focused on fitting a theoretical probability distribution function to the observed data, and providing low flow estimates for any given return period. For each station, annual minimum streamflow was plotted using all the distributions. The goodness of fit was performed using Kolmogorov-Smirnov. All the PDFs were ranked for streamflow at each station. Ranks, according to these three goodness of fit, showed a significant variation. In the case of annual minimum streamflow, various distributions were found the best fit for different stations. Best fit distributions were Gamma, Gumbel, Lognormal 2P and Pearson type-3. Figure 2 shows the example probability of mean annual minimum flow for station 1. The estimated parameters were determined and shown in table 5.

The primary purpose of this study is to determine the best-fitted distribution of probability for each station for low flow frequency analysis. Such projections could provide valuable input for policy and decision-making purposes. The information about the return period of extreme can be used in determining the risk management by extreme events such as hydrological drought, while the geographical station location and the surrounding environmental factors for the variation of streamflow. Table 6 shows the best-fit results of the K-S test and P-value results with their ranking.

The primary aim of the probability distribution fitting is to represent the low flow probability most accurately. Among all the stations, it was found that among all distributions, the Lognormal 2P yielded the most cases of best-fit distributions, while the Gumbel and Gamma yielded the second and third amount of best-fits respectively. Comparatively, it is proposed that 2P Lognormal distributions predict low-flow discharges for all the rivers under analysis, which can be used in water quality and quantity management at gauged and ungauged areas. When the best fit probability distribution of the low flow series of the D-day has been determined, the low flow discharge of the D-day can be estimated according to any given return period. It should be noted that the research is station dependent on this analysis. The low flow-duration-frequency curves were therefore obtained at the base of gauging station. The low flow-duration-frequency curves are powerful tools for many applications, but particularly for engineering practice. An engineer may get any discharge of the low flow-duration-frequency curves from any low flow model. The fraction of non-zero flows in this river basin is always 100 per cent allowing one to measure up to 100-year return cycle D-day low flow discharges. Table 7 shows the return period of low flow at all streamflow stations.

A catchment with a slow or quick response to rainfall intensity that usually has long or rapid recession actions depends entirely on the catchment's physical characteristics. Low flow in catchments that respond quickly is lower than in those that respond slowly. Low flow in catchments that respond slowly is more persistent than in catchments that respond quickly. These differences demonstrate the significant effect on low-flow events of hydrological processes and storages.

Figure 3 displays the low flow relationship with the watershed area represented by the boxplot graph. The boxplot is a standardised way of displaying the distribution of low flow per watershed catchment area based on the five-number summary. The boxplot graph displays the full range of variation, which is from minimum to maximum data set in each station. The largest range for low flow per area is in S06 while the smallest range is in S01. The boxplot graph provides information about the shape of a data set. S01, S02, and S04 are skewed right, S03, S05, and S06 are symmetric shape data, and S07 is skewed left. From the discussions above, it is clear that the natural elements that affect a variety of factors of the river's low flow regime consist of distribution and hydraulic components, climate, and topography.

3.3 Hydrological drought characteristics

The threshold level value per Q percentile obtained from the flow duration curve is shown in Table 8. In this study, only Q_{90} was used as a threshold level in the determination of drought events. Several days and percentage where the streamflow rate was below the average level are recorded to show the severity of droughts events at each station.

3.3.1 Hydrological drought events and deficits

The growing perception of hydrological drought improvement on a global scale has some necessary implications for water management. It is recognised, for example, that the duration and the volume of the deficit of the drought are associated (Fleig et al., 2006). Table 9 shows the summary of the drought series below the threshold level (Q_{90}), without removing minor drought for each station in the Selangor region.

Station S01 has 39 episodes of drought events in 40 years. This station also recorded 1593 days of drought, with a total deficit of 10,299.97 m^3/s. The lowest deficit was recorded in 1994 at 41.53 m^3/s, while the highest deficit was recorded in 1986 at 666.58 m^3/s. The average amount of water deficit is 264.10 m^3/s. This river has been affected by water rationing that happened in Selangor in early 2014 for 3 to 4 months. The most prolonged period of individual drought was recorded in 2014 at 112 days from March 05 to June 24. The shortest period of a single drought was marked three times in 2004 and 2005 by 15 days. Station S02 was part of the Langat river basin and has had 29 episodes of drought events in 40 years. The total duration of the drought events was recorded at 1,261 days from 14,610 days of total observation of only 8.63% of the entire record period and

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

below the threshold level Q90 = 2.99 m^3/s. The overall deficit for this station is 2,340 m^3/s, with an average of 80.70 m^3/s. The lowest deficit was in 1993 at 34.44 m^3/s, while the highest deficit was recorded in 1986 with 179.73 m^3/s. The overall total deficit is 1.57% of the total water flow.

The threshold level of S03 is 1.47 m^3/s at an average level with 12 episodes of drought events. The total number of days of the occurrence of the drought was 1,577 days, which was 10.79% of the overall record of observation. S03 has the record value of the total number and episode of the least drought event among all stations. However, S03 also records a long period of the drought of individual events. The longest single drought took place in 1998, with 241 days commencing on February 24 and ending on October 22. S03 also recorded the lowest deficit amount amongst all stations with 1,660 m^3/s during the period of drought. This total is 2.2% of the total water flow through this station, which is 75,562 m^3/s. The highest deficit was recorded in 1998 with a total of 226 m^3/s over 241 days. The lowest deficit was recorded in the dry season in 1997, with only 21.57 m^3/s within 20 days. Station S04 has 28 episodes of drought occur in 40 years of records. The most prolonged period of individual and annual drought was recorded in 2004 by 306 days. The shortest period was at 15 days in 1999. The number of drought events exceeding the number of years of drought was due to repeated events occurring 18 times with a maximum of four (4) replications in one (1) year. The total number of days of the occurrence of this drought is 1,460 days, which is 9.99% of the total daily flow data. The overall deficit of 28 drought events was 673.54 m^3/s. The lowest total deficit was recorded in 1983 as much as 7 m^3/s, while the highest deficit was recorded in 2004 with 131.27 m^3/s. The average amount of total deficit was 24.06 m^3/s.

Station S05 has been categorised as the most critical station with the highest number of days of droughts events. The longest annual drought event was recorded in 1998 with 217 days, and for individual drought events, this occurred in 1999 with a period of 111 days. Using the threshold level at Q90 = 21.52 m^3/s, 1,236 days (10%) of the total are below the threshold level categorised as drought. Repeat drought events recorded in 1978, 1979, 1986, 1987, 1990, 1998, 2000 and 2002. The drought episode was seen most repetitive in 1998 with four (4) repetitions a year. The total magnitude deficit of the entire river water stream during the occurrence is 18,695.45 m^3/s. The value of the minimum storage rate at 67.36 m^3/s exceeds the amount of low flow rate at 35.61 m^3/s that will occur at the return period of 50-year. Station S06 shows the drought episodes are seen in succession from 2011 to 2017 and 2016 record the highest drought events with four (4) replay events. The year 2014 records the most extended individual drought episode of 177 days, and the longest annual drought comes in 2013 with 372 days. S06 recorded a total deficit of 3,847 m^3/s. The year 2012 recorded the highest deficit of 496.13 m^3/s while 1989 recorded the lowest deficit with only 54.19 m^3/s. The average deficit is 113.16 m^3/s, with 34 episodes of drought event in 40 years.

S07 had the highest drought events with the number of years of drought recorded as 39 years with repeated drought events in 1978, 1983, 1985, 1987, 1990, 1991, 1992, 1998, 1999, 2001, 2002, 2005 and 2016. The most prolonged drought period was recorded in 2005 with a period of only 99 days, while the shortest period was in 1971, 1987, 2000, and 2016 with a period of

15 days. The most prolonged period of individual drought events with 205 days occurred in the same year in 2005. The total drought days at this station was 1,614 days, which was 11.05% of the total days. S07 recorded a deficit of 21,740 m^3/s during the drought episode, and this percentage is the highest percentage recorded compared to other streamflow stations. This stream records a high deficit amount with fewer drought days. The highest deficit reached 1,445 m^3/s recorded in the drought events in 1990, while the lowest deficit was in 1983 with a total of 161.32 m^3/s.

From the results, S01 exhibits the highest number of drought events, which is 39 episodes, with the mean deficit is 264.10 m^3/s. This station is located downstream of the Langat basin. It indicates the downstream watershed catchment has more drought episodes compared to the upstream catchment. Magnitudes differ significantly between catchments since there were also varied specific hydrological characteristics, such as station spatial distribution, precipitation and temperature magnitudes, and frequency of extreme events like drought.

To prevent a future catastrophe in the region, it is crucial to properly understand the temporal characteristics of drought in this transboundary river basin with water deficit. Hydrological drought investigation is provided from streamflow records, and very frequently, the lack of recorded long-term streamflow data hinders a reliable analysis of drought and previous understanding of the phenomenon. Hydrological drought management involves determining a possible level of thresholds. Threshold levels of low exceedance probability are considered to be appropriate for the area of study, unlike the higher exceedance probabilities typically used in a temperate climate.

3.4 Estimation of minimum storage draft-rate

The estimation of the storage draft rate in this study will determine the minimum storage of a river to sustain the water supply during low flows and droughts. The mass curve of the monthly low flow rate is used in this analysis to obtain the minimum storage rate of the river. The mass curve analysis of low flow for the duration of January to December plotted against duration for recurrence interval of 10-year. The cumulative draw off corresponds to a constant draft rate of 50% of the mean annual flow. Figure 4 shows the flow mass curve for the determination of the minimum storage-draft rate of each station. Table 10 shows the monthly minimum storage draft rate value for each station that needs to be maintained at a draft rate of 50% of the mean annual flow during low flows to sustain the water supply.

The minimum storage required for maintaining a draft rate required for S01 is 21.51 m^3/s in October, S02 is 13.37 m^3/s in December, S03 is 4.79 in December. The minimum storage required for S04 is 2.32 m^3/s in October for 40 years' duration period; S05 is 15.00 m^3/s in September. While, the minimum storage required to maintain the draft rate for S06 is 10.90 m^3/s in October, and lastly, for S07 is 6.17 m^3/s in September.

4 Discussion

The results of the analysis demonstrate the spatial and temporal variability of the hydrological drought using streamflow data. This section discusses the advantages and limitations of the implications of these findings.

4.1 Streamflow trend

For the annual average streamflow at the gauging stations, five stations indicated an upward trend, and two stations indicated a downward trend for 40 years' data. The interpretations of trend analysis for relatively partial streamflow records may only reflect a short-term condition and may not be representative of an actual long-term change in the streamflow data. This issue is valid for relatively short-term records that begin or end in a historically low flow condition. One of the influential aims of the time series trend is to define the nature characteristic represented by the sequence of observations and predicted future values of the time series variable. The analysis of observed data for changes and trends of streamflow data can be used to assess the impact of climate change. The streamflow trend can estimate future water availability to maintain and sustain ecosystem functions. Moreover, streamflow trend analysis can also be used to predict any change in river flows for making water withdrawal decisions, which indirectly can improve drought management response.

4.2 Hydrological drought

The hydrological drought effects will happen slowly but last longer. Hydrological drought can lead to consequences for water supply, agriculture, water quality, and electricity production, which leads to both economic and ecological loss. Low flow statistics are often used in characterizing hydrological drought. There are several ways to define low flows. Low flow rates are generally smaller than the median flow of a river. Different low flows can be used to investigate different ecosystem functions of a river and can be used to indicate when a river is in a drought situation.

This study used a hydrological drought index called threshold level methods to identify drought characteristics. This method uses fixed or moving thresholds to identify at what flow a river is considered to be in a drought and easily determine its duration, severity, and frequency. Commonly, the thresholds level is taken from flow duration curves (FDC) of streamflow data. Flow duration curves show the interaction of frequency and magnitude in streamflow using a graphical method. FDC can be developed for different periods such as daily, monthly, and annually based on objectives study. Multiple low flow indices can be obtained from FDC, such as Flows with 70-99% exceedance, Q_{20}/Q_{90}, Q_{50}/Q_{90}, Q_{90}/Q_{50}, 7 days 10-year flow, and 7 days 2-year flow that describe low flow regime of a river (Blum et al., 2016). Calculating frequency and return period of mean annual minimum n-discharge are a standard index. It uses the mean minimum flow of a certain amount of days (n) ranging from 1-30 for every year of record (Sarailidis et al., 2019b). The limitation of FDC is they do not provide any information about the intensity and duration of low flow events in streamflow time series.

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

Natural Hazards and Earth System Sciences
Discussions

When the streamflow falls under a certain threshold level from a streamflow hydrograph, a series of hydrological drought events can be derived. Therefore, it is possible to obtain the drought characteristics, including duration of drought, deficit volume and interval of drought. The value of the threshold level is subjective, but it is necessary as it influences the number of events, the period of drought, and the volume of a deficit. Thresholds may be flow minima that are either ecologically substantiated or are derived from the water resources management requirements, reservoir operation, and navigation (Sarailidis et al., 2019a). Threshold levels between the 70th percentile and 95th percentile flow from the flow duration curve (FDC) are recommended for perennial streams such as the Selangor river catchment (Heudorfer and Stahl, 2017). The 90th percentile flow is used in this study to characterise hydrological droughts from streamflow series.

Several indices could be used to provide a more accurate representation of hydrological drought. Which indices one chooses to use is going to affect the result directly. One of the problems in the use of an annual Q_{90} threshold is the drought events may not be entirely accurate. It is important to note that the Q_{90} threshold merely identifies low flows accounted for catchments regular flow. Therefore, the Q_{90} threshold does not necessarily imply a situation where functions in nature are affected. The threshold level can reflect a specific requirement, such as for water supply or minimum environmental flow, or a normal low flow condition of the river can be represented. For a bigger picture and understanding of the broad spectrum of hydrological drought, more indices need to be put together in an index. Different methods will allow different characteristics of hydrological droughts. The threshold level method should be used for more detailed deficits and in-depth study. Complex indices would be most useful to verify results in regional studies.

5 Conclusion

Low flow analysis is an essential and widely studied design and management of hydrology and water resources. Varying and complex natural processes may produce low flows in a river on a catchment scale. The flow duration curve is one of the primarily used tools for assessing low flow and the river regime. This method was selected because it is one of the most informative ways to display streamflow characteristics throughout the discharge range, regardless of the occurrence sequence. The first aim of this work was to determine the characteristics of low flow by using frequency analysis. Based on the results of the low flow frequency analysis, Gumbel distribution methods were used to predict the magnitude of low flow. Gumbel distribution provides a good fit to annual minimum flow data at each station, and the Kolmogorov-Smirnov test was conducted as an indicator of performance. From the result, the range means the low flow of rivers in Selangor is between 0.75 to 19.47 m^3/s.

Drought is a phenomenon of water shortage when the water supply is below the average level. This study developed a useful principle of using threshold level methods to describe the characteristics of streamflow droughts. From this study, we can make the following conclusions:

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

1) The threshold level using the Q percentile based on the flow duration curve was used as an average level to separate the occurrence of droughts events or otherwise. The number of days and duration of droughts for a station can show the severity of the drought that occurs.
2) The drought characteristics were analysed from time-series below a threshold level (Q90) without removing the minor drought. The magnitude and duration of drought characteristics were determined by the value difference between the time series and the threshold level value.
3) The highest drought events are 39 episodes with a mean volume of the deficit is 557.46 m^3/s while the lowest events of drought are ten (10) episodes with the mean volume of the deficit is 127.71 m^3/s.

The rate of low flow at the recurrence interval of 10-year was used to ensure the minimum storage-draft rate required to sustain the water demand during low flow periods. The restructure of the minimum storage draft rate must be done by hydrologist at a particular return period to ensure the streamflow gauging station has enough water to be supplied to the user during the low flow and drought periods. Based on the analysis of the study, the estimated minimum storage-draft rates for each station cannot meet the water demand during low flow at specific return periods, which is 10-year recurrence interval for this research.

This research is essential to water resources management. Low flow analysis and water availability enable water resource management to make more realistic decisions on water restrictions and provisions for cities and populations. Understanding the concept of low flow and the predictive significance of river storage-rates can also help in managing sustainable water catchment. This study also helps in emphasising the natural flow of water to provide a water supply for continuous use during low flow. Additionally, through this research, the concept of low flow analysis and the predictive significance of minimum storage draft rate can be developed to produce more efficient water resource management systems during the dry season in Selangor, Malaysia.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This research is supported by Universiti Kebangsaan Malaysia research grant GGPI-2016-001 and Ministry of Education Malaysia research grant FRGS/1/2018/TK01/UKM/02/2. Their financial supports are gratefully acknowledged. The authors would also like to acknowledge their gratitude to the Department of Irrigation and Drainage (DID), Malaysia, for providing streamflow data for this study.

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

References

Alrayess, H., Zeybekoglu, U. and Ulke, A.: Different design techniques in determining reservoir capacity, Eur. Water, 60, 107–115, 2017.

Assefa, K. and Moges, M. A.: Low Flow Trends and Frequency Analysis in the Blue Nile Basin, Ethiopia, J. Water Resour. Prot., 10(02), 182–203, doi:10.4236/jwarp.2018.102011, 2018.

Austin, S. H. and Nelms, D. L.: Modeling Summer Month Hydrological Drought Probabilities in the United States Using Antecedent Flow Conditions, J. Am. Water Resour. Assoc., 53(5), 1133–1146, doi:10.1111/1752-1688.12562, 2017.

Awass, A. A.: Hydrological Drought Analysis-occurrence , severity , risks : the case of Wabi Shebele River Basin, , 220, 2009.

Azadi, H., Keramati, P., Taheri, F., Rafiaani, P., Teklemariam, D., Gebrehiwot, K., Hosseininia, G., Van Passel, S., Lebailly, P. and Witlox, F.: Agricultural land conversion: Reviewing drought impacts and coping strategies, Int. J. Disaster Risk Reduct., 31, 184–195, doi:10.1016/j.ijdrr.2018.05.003, 2018.

Bakanoğullari, F. and Yeşilköy, S.: Determination of Meteorological and Hydrological Drought in Damlıca Creek Watershed in Çatalca-İstanbul, Turkey, Turkish J. Agric. Nat. Sci., 1(1), 1152–1157, 2014.

Barker, L. J., Hannaford, J., Chiverton, A. and Svensson, C.: From meteorological to hydrological drought using standardised indicators, Hydrol. Earth Syst. Sci., 20(6), 2483–2505, doi:10.5194/hess-20-2483-2016, 2016.

Bharali, B.: Estimation of Reservoir Storage Capacity by using Residual Mass Curve, J. Civ. Eng. Environ. Technol., 2(10), 15–18 [online] Available from: http://www.krishisanskriti.org/jceet.html, 2015.

Blum, A. G., Vogel, R. M. and Archfield, S. A.: The probability distribution of daily streamflow in the conterminous United States, Hydrol. Earth Syst. Sci. Discuss., 1–33, doi:10.5194/hess-2016-460, 2016.

Bormann, H. and Pinter, N.: Trends in low flows of German rivers since 1950: Comparability of different low-flow indicators and their spatial patterns, River Res. Appl., 33(7), 1191–1204, doi:10.1002/rra.3152, 2017.

Cancelliere, A. and Salas, J. D.: Drought probabilities and return period for annual streamflows series, J. Hydrol., 391(1–2), 77–89, doi:10.1016/j.jhydrol.2010.07.008, 2010.

Coch, A. and Mediero, L.: Trends in low flows in Spain in the period 1949–2009, Hydrol. Sci. J., 61(3), 568–584, doi:10.1080/02626667.2015.1081202, 2016.

Croker, K. M., Young, A. R., Zaidman, M. D. and Rees, H. G.: Flow duration curve estimation in ephemeral catchments in Portugal, Hydrol. Sci. J., doi:10.1623/hysj.48.3.427.45287, 2003.

Department of Irrigation and Drainage Malaysia: Review of The National Water Resources Study (2000-2050) and Formulation of National Water Resources Policy, Environ. Eval. identified Immed. Work. Proj., 17, 468 [online] Available from: http://www.water.gov.my/jps/resources/PDF/Hydrology Publication/Vol17Johor.pdf, 2011.

Elfithri, R., Mokhtar, M., Pauzi Abdullah, M., Raihan Taha, M., Ekhwan Toriman, M., Mohamad Yasin, R., Yaakub, J., Puteri Khairani Khirotdin, R., Mahathir Amir Sultan, M., S.A, I., N.M, R., Khairul Amri Kamarudin, M., Juahir, H., Ghazali, A., Ismail, A. and Barzani Gasim, M.: Watershed Sustainability Index for Langat UNESCO HELP River Basin, Malaysia, Int. J.

Eng. Technol., 7(3.14), 187, doi:10.14419/ijet.v7i3.14.16882, 2018.

Erfen, Y., Adnan, M. S., Ali, N. C., Amat, N. F. and Zahudi, Z. M.: Comparison of Distribution Methods of Low Flow Analysis for Bandar Segamat, Johor, Appl. Mech. Mater., 773–774(December), 1266–1270, doi:10.4028/www.scientific.net/amm.773-774.1266, 2015.

Fleig, A. K., Tallaksen, L. M., Hisdal, H. and Demuth, S.: A global evaluation of streamflow drought characteristics, Hydrol. Earth Syst. Sci., 10(4), 535–552, doi:10.5194/hess-10-535-2006, 2006.

Gao, P., Li, P., Zhao, B., Xu, R., Zhao, G., Sun, W. and Mu, X.: Use of double mass curves in hydrologic benefit evaluations, Hydrol. Process., 31(26), 4639–4646, doi:10.1002/hyp.11377, 2017.

Gianfagna, C. C., Johnson, C. E., Chandler, D. G. and Hofmann, C.: Watershed area ratio accurately predicts daily streamflow in nested catchments in the Catskills, New York, J. Hydrol. Reg. Stud., 4, 583–594, doi:10.1016/j.ejrh.2015.09.002, 2015.

Gottschalk, L., Yu, K. xia, Leblois, E. and Xiong, L.: Statistics of low flow: Theoretical derivation of the distribution of minimum streamflow series, J. Hydrol., 481, 204–219, doi:10.1016/j.jhydrol.2012.12.047, 2013.

Hasan, H. H., Mohd Razali, S. F., Muhammad, N. S., Ahmad, A., Mohd Razali, S. F., Muhammad, N. S. and Ahmad, A.: Research Trends of Hydrological Drought: A Systematic Review, Water, 11(2252), 1–19, doi:10.3390/w11112252, 2019.

Hatzigiannakis, E., Filintas, A., Ilias, A., Panagopoulos, A., Arampatzis, G. and Hatzispiroglou, I.: Hydrological and rating curve modelling of Pinios River water flows in Central Greece, for environmental and agricultural water resources management, Desalin. Water Treat., 57(25), 11639–11659, doi:10.1080/19443994.2015.1123191, 2016.

Heudorfer, B. and Stahl, K.: Comparison of different threshold level methods for drought propagation analysis in Germany, Hydrol. Res., 48(5), 1311–1326, doi:10.2166/nh.2016.258, 2017.

Hisdal, H., Stahl, K., Tallaksen, L. M. and Demuth, S.: Have streamflow droughts in Europe become more severe or frequent?, Int. J. Climatol., 21(3), 317–333, doi:10.1002/joc.619, 2001.

Iqbal, M. W., Donjedee, S. and Kwanyuen, B.: Farmers ' Perception of Water Management Under Drought Conditions in Badakshan Province , Afghanistan, 2nd World Irrig. Forum, (November), 6–8, 2016.

Joetzjer, E., Douville, H., Delire, C., Ciais, P., Decharme, B. and Tyteca, S.: Hydrologic benchmarking of meteorological drought indices at interannual to climate change timescales: A case study over the Amazon and Mississippi river basins, Hydrol. Earth Syst. Sci., 17(12), 4885–4895, doi:10.5194/hess-17-4885-2013, 2013.

Joshi, D. and St-Hilaire, A.: Low Flow Frequency analysis of three rivers in Eastern Canada, Int. J. Environ. Chem. Ecol. Geol. Geophys. Eng., 8(April), 410–415 [online] Available from: http://waset.org/Publications?p=90, 2013.

Khalid, R. M.: Review of the water supply management and reforms needed to ensure water security in Malaysia, Int. J. Bus. Soc., 19, 472–483, 2018.

Koteia, R., AgyeiAgyareb, W., Kyei-Baffourc, N., Darkwad, T. A.- and TakyiAtakora, E.: Estimation of Flow-Duration and Low-Flow Frequency Parameters for the Sumanpa Stream at Mampong- Ashanti in Ghana for the 1985-2009 Period, Am. Sci. Res. J. Eng. Technol. Sci., 15(1), 62–75, 2016.

Kwan, M. S., Tangang, F. T. and Juneng, L.: Projected changes of future climate extremes in Malaysia, Sains Malaysiana, 42(8), 1051–1058, 2013.

Laaha, G. and Blöschl, G.: A comparison of low flow regionalisation methods-catchment grouping, J. Hydrol., 323(1–4), 193–214, doi:10.1016/j.jhydrol.2005.09.001, 2006.

Laaha, G. and Blöschl, G.: A national low flow estimation procedure for Austria, Hydrol. Sci. J., 52(4), 625–644, doi:10.1623/hysj.52.4.625, 2007.

Lassen, M. F., Bramm, M. E., Richardson, K., Yusoff, F. and Shariff, M.: Phytoplankton community composition and size distribution in the Langat River Estuary, Malaysia, Estuaries, 27(4), 716–727, 2004.

Lee, K. Y., Syakir, M. I., Clark, I. D. and Veizer, J.: Isotope Constraints on the Aquatic Carbon Budget: Langat Watershed, Malaysia, Aquat. Geochemistry, 19(5–6), 443–475, doi:10.1007/s10498-013-9198-3, 2013.

Liu, L., Hong, Y., Bednarczyk, C. N., Yong, B., Shafer, M. A., Riley, R. and Hocker, J. E.: Hydro-Climatological Drought Analyses and Projections Using Meteorological and Hydrological Drought Indices: A Case Study in Blue River Basin, Oklahoma, Water Resour. Manag., 26(10), 2761–2779, doi:10.1007/s11269-012-0044-y, 2012.

Liu, Y., Ren, L., Zhu, Y., Yang, X., Yuan, F., Jiang, S. and Ma, M.: Evolution of Hydrological Drought in Human Disturbed Areas: A Case Study in the Laohahe Catchment, Northern China, Adv. Meteorol., 2016, 1–12, doi:10.1155/2016/5102568, 2016.

Van Loon, A. F. and Van Lanen, H. A. J.: Making the distinction between water scarcity and drought using an observation-modeling framework, Water Resour. Res., 49(3), 1483–1502, doi:10.1002/wrcr.20147, 2013.

Loon, A. F. Van, Laaha, G., Van Loon, A. F. and Laaha, G.: Hydrological drought severity explained by climate and catchment characteristics, J. Hydrol., 526, 3–14, doi:10.1016/j.jhydrol.2014.10.059, 2015.

Mamun, A. A., Hashim, A. and Daoud, J. I.: Regionalisation of low flow frequency curves for the Peninsular Malaysia, J. Hydrol., 381(1–2), 174–180, doi:10.1016/j.jhydrol.2009.11.039, 2010.

Marx, A., Kumar, R., Thober, S., Rakovec, O., Wanders, N., Zink, M., Wood, E. F., Pan, M., Sheffield, J. and Samaniego, L.: Climate change alters low flows in Europe under global warming of 1.5, 2, and 3°C, Hydrol. Earth Syst. Sci., 22(2), 1017–1032, doi:10.5194/hess-22-1017-2018, 2018.

Mohammed, R. and Scholz, M.: Climate change and anthropogenic intervention impact on the hydrologic anomalies in a semi-arid area: Lower Zab River Basin, Iraq, Environ. Earth Sci., 77(10), 1–19, doi:10.1007/s12665-018-7537-9, 2018.

Mohamoud, Y. M.: Prediction of daily flow duration curves and streamflow for ungauged catchments using regional flow duration curves, Hydrol. Sci. J., doi:10.1623/hysj.53.4.706, 2008.

Nam, W., Shin, H., Jung, Y., Joo, K. and Heo, J. H.: Delineation of the climatic rainfall regions of South Korea based on a multivariate analysis and regional rainfall frequency analyses, Int. J. Climatol., 35(5), 777–793, doi:10.1002/joc.4182, 2015.

Ngang, C. P., Hashim, halimaton S. and Pereira, J. J.: Climate Change Mitigation and Adaptation as a Sustainable Regional Development Strategy : Lessons from the Selangor River Basin , Malaysia, Int. J. Malay World Civilis., 5(Special Issue 1), 43–52, doi:http://dx.doi.org/10.17576/IMAN-2017-05SI1-06, 2017.

Richter, B. D. and Thomas, G. A.: Restoring environmental flows by modifying dam operations, Ecol. Soc., 12(1), doi:10.5751/ES-02014-120112, 2007.

Sakke, N., Ithnin, H., Ibrahim, M. H., Pah, T. and Syed, R.: Hydrological drought and the sustainability of water resources in Malaysia : An analysis of the properties of the Langat Basin , Selangor, Malaysian J. Soc. Sp., 12(7), 133–146, 2016.

Sakke, N., Keselamatan, M., Melalui, S., Bandar, K., Kes, K., Sebatik, P. and Sakke, N.: Severity of Hydrological Drought in the Lui River Basin , Hulu Langat , Selangor, , 2001(February), 2001, 2017.

Sanusi, W., Jemain, A. A., Zin, W. Z. W. and Zahari, M.: The Drought Characteristics Using the First-Order Homogeneous Markov Chain of Monthly Rainfall Data in Peninsular Malaysia, Water Resour. Manag., 29(5), 1523–1539, doi:10.1007/s11269-014-0892-8, 2015.

Sarailidis, G., Vasiliades, L. and Loukas, A.: Analysis of streamflow droughts using fixed and variable thresholds, Hydrol. Process., 33(3), 414–431, doi:10.1002/hyp.13336, 2019a.

Sarailidis, G., Vasiliades, L. and Loukas, A.: Analysis of streamflow droughts using fixed and variable thresholds, Hydrol. Process., 33(3), 414–431, doi:10.1002/hyp.13336, 2019b.

Shaaban, A. J., Low, K. S., Ahmed Jamalluddin Bin Shaaban and Low Koon Sing: Droughts in Malaysia: a Look At Its Characteristics, Impacts, Related Policies and Management Strategies, Water Drain. 2003 Conf., (September 1998), 43–54, 2003.

Sharma, T. C. and Panu, U. S.: Predicting return periods of hydrological droughts using the Pearson 3 distribution: a case from rivers in the Canadian prairies, Hydrol. Sci. J., 60(10), 1783–1796, doi:10.1080/02626667.2014.934824, 2015.

Siwar, C., Ahmed, F. and Begum, R. A.: Climate change, agriculture and food security issues: Malaysian perspective, J. Food, Agric. Environ., 11(2), 1118–1123, 2013.

Smakhtin, V. U.: Low flow hydrology: a review, J. Hydrol., 240, 147–185, doi:10.1016/S0022-1694(00)00340-1, 2001.

Sun, P., Zhang, Q., Yao, R., Singh, V. P. and Song, C.: Low flow regimes of the Tarim River Basin, China: Probabilistic behavior, causes and implications, Water (Switzerland), 10(4), 1–18, doi:10.3390/w10040470, 2018.

Sung, J. H. and Chung, E. S.: Development of streamflow drought severity–duration–frequency curves using the threshold level method, Hydrol. Earth Syst. Sci., 18(9), 3341–3351, doi:10.5194/hess-18-3341-2014, 2014.

Taye, M. T., Ntegeka, V., Ogiramoi, N. P. and Willems, P.: Assessment of climate change impact on hydrological extremes in two source regions of the Nile River Basin, Hydrol. Earth Syst. Sci., 15, 209–222, doi:10.5194/hess-15-209-2011, 2011.

Tigkas, D., Vangelis, H. and Tsakiris, G.: Drought and climatic change impact on streamflow in small watersheds, Sci. Total Environ., 440, 33–41, doi:10.1016/j.scitotenv.2012.08.035, 2012.

Toriman, M. E., Ata, F. M., Kamarudin, M. K. A. and Idris, M.: Bed-load sediment profile and effect of river bank erosion on river cross-section, Am. J. Environ. Sci., 9(4), 292–300, doi:10.3844/ajessp.2013.292.300, 2013.

Tri, D. Q., Dat, T. T. and Truong, D. D.: Application of meteorological and hydrological drought indices to establish drought classification maps of the Ba River basin in Vietnam, Hydrology, 6(49), 1–21, doi:10.3390/hydrology6020049, 2019.

Vogel, R. M. and Fennessey, N. M.: Flow-Duration Curves. I: New Interpretation and Confidence Intervals, J. Water Resour. Plan. Manag., doi:10.1061/(ASCE)0733-9496(1994)120:4(485), 1994.

Natural Hazards and Earth System Sciences
Open Access
Discussions

Yahiaoui, A.: Frequency analysis of the extreme streamflow by the threshold level method in semi-arid region: Case study of Wadi Mekerra catchment in the North-West of Algeria, J. Water L. Dev., 41(1), 139–145, doi:10.2478/jwld-2019-0037, 2019.

Yahiaoui, A., Touaïbia, B. and Bouvier, C.: Frequency analysis of the hydrological drought regime. Case of oued Mina catchment in western of Algeria, Rev. Nat. Technol., 1(1), 3–15, 2009.

Zaidman, M. D., Keller, V., Young, A. R. and Cadman, D.: Flow-duration-frequency behaviour of British rivers based on annual minima data, J. Hydrol., 277(3–4), 195–213, doi:10.1016/S0022-1694(03)00089-1, 2003.

Zainal, M. K., Begum, R. A., Maulud, K. N. A. and Salleh, N. H. M.: Socio-economic impacts of climate change in the coastal areas of Malaysia, in Proceedings of IPI Research Colloquium2, pp. 95–99., 2017.

Zarafshani, K., Sharafi, L., Azadi, H. and Van Passel, S.: Vulnerability assessment models to drought: Toward a conceptual framework, Sustain., 8(6), 1–21, doi:10.3390/su8060588, 2016.

Zeng, X., Wang, D. and Wu, J.: Evaluating the Three Methods of Goodness of Fit Test for Frequency Analysis, J. Risk Anal. Cris. Response, 5(3), 178, doi:10.2991/jrarc.2015.5.3.5, 2015.

Zhai, R. and Tao, F.: Contributions of climate change and human activities to runoff change in seven typical catchments across China, Sci. Total Environ., 605–606, 219–229, doi:10.1016/j.scitotenv.2017.06.210, 2017.

Zhu, N., Xu, J., Li, W., Li, K. and Zhou, C.: A Comprehensive Approach to Assess the Hydrological Drought of Inland River Basin in Northwest China, Atmosphere (Basel)., 9(10), 370, doi:10.3390/atmos9100370, 2018.

Zou, L., Xia, J., Ning, L., She, D. and Zhan, C.: Identification of hydrological drought in Eastern China using a time-dependent drought index, Water (Switzerland), 10(3), 1–20, doi:10.3390/w10030315, 2018.

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

Figure

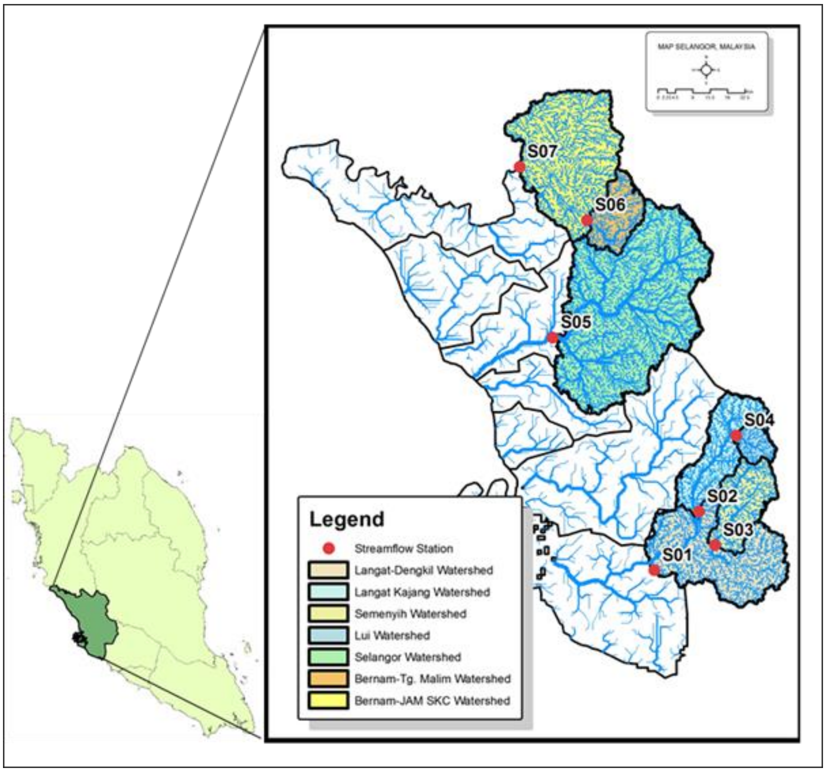

Figure 1: River basin and streamflow station in Selangor.

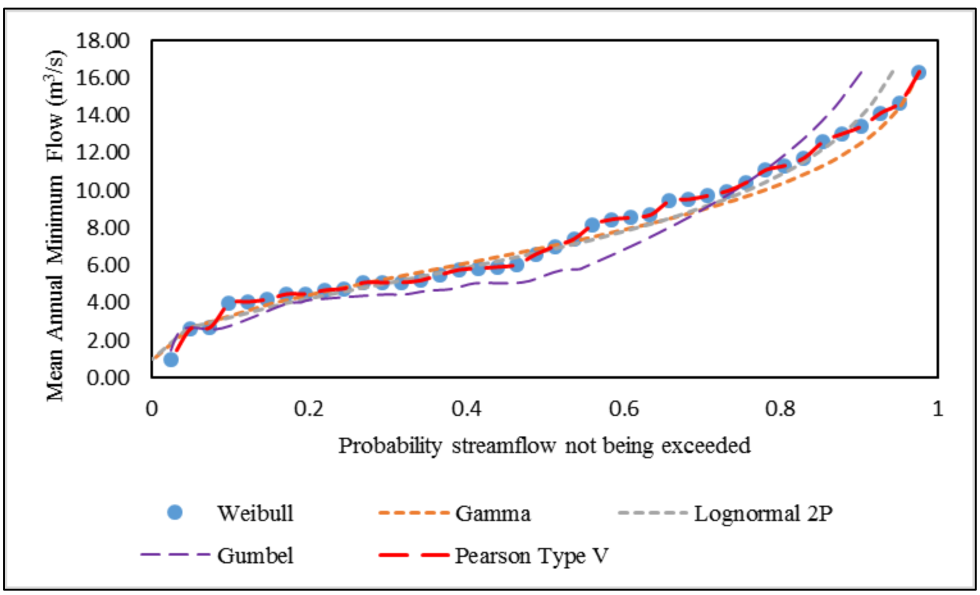

Figure 2: Probability of mean annual minimum flow for station 1.

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

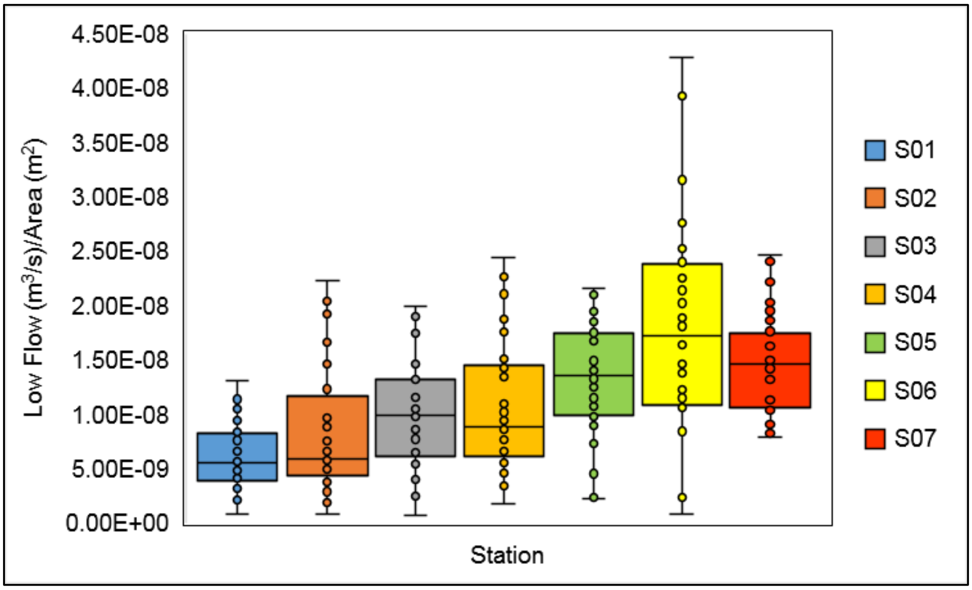

Figure 3: The boxplot low flow per watershed catchment area.

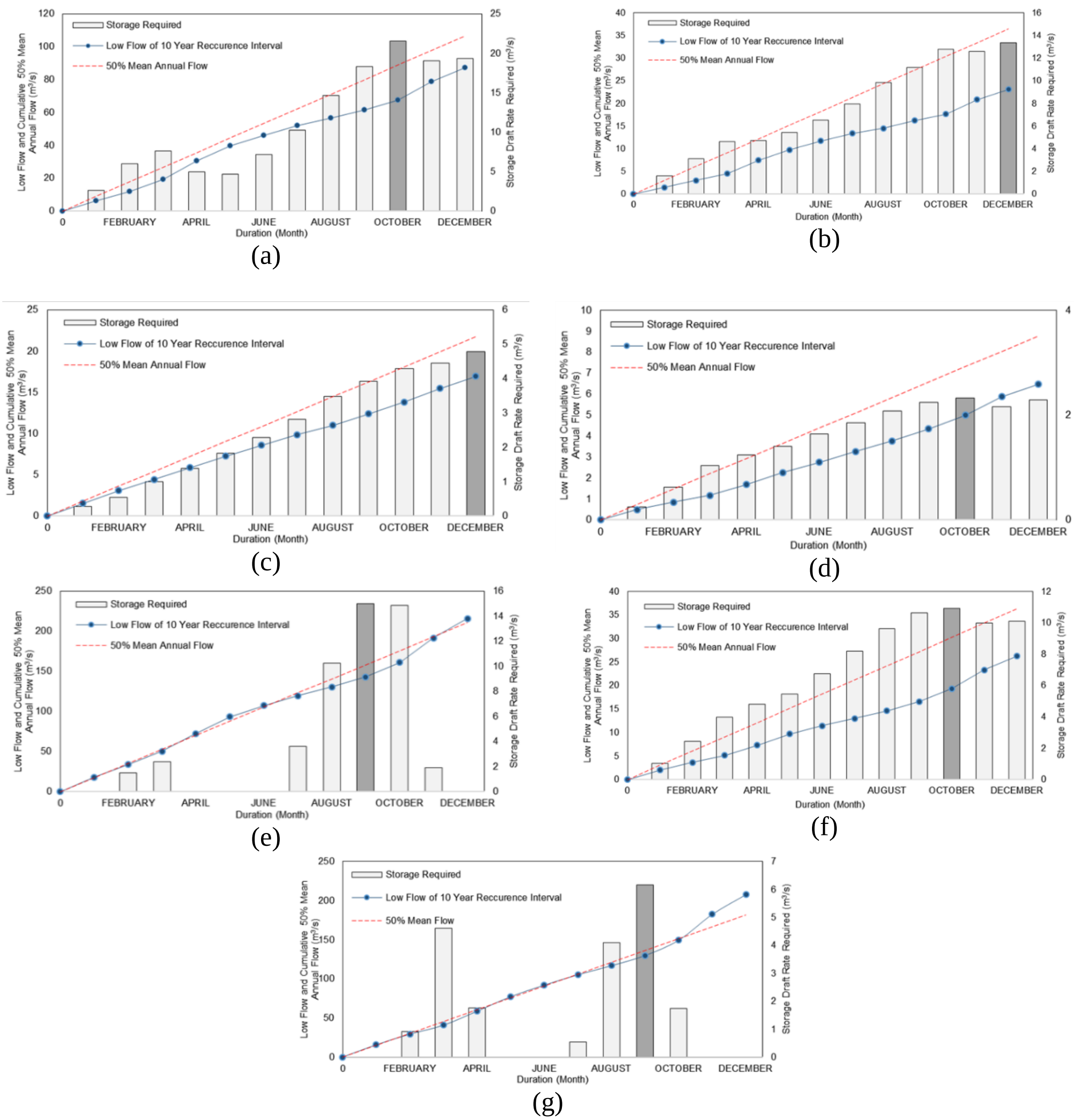

Figure 4: Minimum storage draft rate with cumulative 50% mean flow (a) S01 (b) S02 (c) S03 (d) S04 (e) S05 (f) S06 (g) S07.

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

Table 1 The characteristics of streamflow gauging stations in Selangor.

Station No.	River Name	River Basin	Location Coordinate (WGS)		Area (km^2)
S01	Langat-Dengkil	Langat	02°51'20" N	101°40'55" E	1240
S02	Langat-Kajang	Langat	02°59'40" N	101°47'10" E	380
S03	Semenyih	Langat	02°54'55" N	101°49'25" E	225
S04	Lui	Langat	03°10'25" N	101°52'20" E	68
S05	Selangor	Selangor	03°24'10" N	101°26'35" E	1450
S06	Bernam- Tg. Malim	Bernam	03°40'45" N	101°31'20" E	186
S07	Bernam-JAM SKC	Bernam	03°48'15" N	101°21'50" E	1090

Table 2 Probability density function for Gamma, Gumbel, Lognormal 2P and Pearson type-3 distributions

No.	Distribution	Probability Density Function
1	Gamma	$f(x) = \frac{\beta^{-\alpha} x^{\alpha-1}}{\Gamma(\alpha)} exp(\frac{-x}{\beta})$ $\alpha > 0$, $\beta > 0$, $x > 0$, where α is the location parameter, and β is the scale parameter
2	Gumbel	$Fx(x) = exp\left[exp\left(\frac{x-\beta}{\alpha}\right)\right]$ $-\infty < x < \infty$; $-\infty < \beta < \infty$; $\alpha > 0$. The α and β parameters are parameters of scale and location.
3	Lognormal 2P	$fx(x) = \frac{1}{\sqrt[x]{2\pi\beta^2}} e^{-\frac{(\ln x - \alpha)^2}{2\beta^2}}$ $x > 0$, $\alpha > 0$, $\beta > 0$.
4	Pearson type-3 (PE3)	$fx(x) = \frac{\lambda^{\beta}(x-\varepsilon)^{\beta-1} e^{-\lambda(x-\varepsilon)}}{\Gamma(\beta)}$ $x \geq \varepsilon$.

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

Table 3 The statistical analysis for time series of streamflow (1978 - 2017).

Station No.	Mean Flow (m^3/s)	Minimum Flow (m^3/s)	Maximum Flow (m^3/s)	Standard Deviation	Skewness	Kurtosis
S01	34.32	1.00	552.62	31.326	4.027	35.819
S02	10.23	0.30	153.87	9.595	4.197	32.222
S03	5.17	0.15	32.41	3.730	2.296	8.996
S04	2.07	0.12	11.93	1.426	1.967	5.726
S05	55.12	3.17	272.59	35.083	1.558	3.163
S06	8.86	0.14	52.51	5.851	1.491	3.716
S07	47.57	8.57	244.75	28.845	1.427	2.744

Table 4 Trend analysis for time series period ('+': Positive trend, '- ': Negative trend, and '0': No trend).

Station	Statistics	1978-1985	1986-1993	1994-2001	2002-2009	2010-2017	Whole Period
S01	Mean	30.05	30.97	36.01	35.40	39.15	34.32
	Minimum	3.96	2.68	1.00	4.46	8.54	1.00
	Maximum	411.73	275.17	165.62	552.62	269.78	552.62
	Mann-Kendall	+	+	0	+	-	+
	Sen's Slope	+	+	+	+	-	+
S02	Mean	8.05	7.58	8.15	15.00	12.35	10.23
	Minimum	1.10	1.27	0.30	0.70	2.31	0.30
	Maximum	153.87	77.86	35.50	133.14	63.09	153.87
	Mann-Kendall	+	+	+	+	+	+
	Sen's Slope	+	+	+	+	+	+
S03	Mean	5.86	6.05	2.67	5.05	6.23	5.17
	Minimum	1.59	1.90	0.15	0.45	2.36	0.15
	Maximum	25.42	30.18	9.24	32.41	30.78	32.41
	Mann-Kendall	+	+	0	+	-	-
	Sen's Slope	+	+	+	+	-	-
S04	Mean	1.65	1.71	2.62	1.71	2.65	2.07
	Minimum	0.24	0.39	0.25	0.12	0.59	0.12
	Maximum	5.96	5.68	11.53	8.41	11.94	11.94
	Mann-Kendall	+	-	-	+	-	+
	Sen's Slope	+	-	-	+	-	+

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

Station	Statistics	1978-1985	1986-1993	1994-2001	2002-2009	2010-2017	Whole Period
S05	Mean	53.74	56.26	52.3	57.69	55.61	55.12
	Minimum	13.61	13.04	3.17	10.56	17.23	3.17
	Maximum	185.29	205.99	263.84	272.76	208.41	272.76
	Mann-Kendall	+	+	-	+	-	+
	Sen's Slope	+	+	-	+	-	+
S06	Mean	7.76	8.36	13.86	10.1	4.22	8.86
	Minimum	2.09	1.57	2.4	1.97	0.14	0.14
	Maximum	30.4	30.49	44.39	52.51	19.42	52.51
	Mann-Kendall	+	+	-	+	-	-
	Sen's Slope	+	+	-	+	-	-
S07	Mean	48.66	41.6	48.05	48.09	51.42	47.57
	Minimum	9.72	10	10.2	8.57	15.5	8.57
	Maximum	244.75	150.59	149.26	190.16	199.82	244.75
	Mann-Kendall	-	+	-	+	-	+
	Sen's Slope	-	+	-	+	-	+

645

Table 5 Estimated parameters for the Gamma, Gumbel, Lognormal 2P and Pearson type 3 distributions.

Distribution	Parameters						
	S01	S02	S03	S04	S05	S06	S07
Gamma	α = 4.24	α = 1.92	α = 4.08	α =3.20	α = 8.13	α = 1.83	α =9.69
	β = 1.78	β = 1.53	β = 0.55	β =0.24	β =2.52	β =2.10	β =1.60
Gumbel	σ = 5.92	σ = 1.92	σ = 1.78	σ = 0.57	σ =17.17	σ = 2.55	σ =13.42
	μ = 2.89	μ = 1.64	μ = 0.87	μ = 0.33	μ = 5.94	μ = 1.68	μ =5.47
Lognormal 2P	σ = 8.09	σ = 3.10	σ = 2.45	σ = 0.75	σ =20.65	σ = 3.70	σ =16.46
	μ =4.81	μ = 2.21	μ = 1.63	μ = 0.42	μ = 7.49	μ =2.79	μ =6.92
Pearson type-3	α = 1.07	α = 2.46	α = 2.87	α = 7.78	α =0.60	α = 2.00	α =0.63
	β = 5.00	β = 5.00	β = 5.00	β = 5.00	β =5.00	β =5.00	β =5.00

Table 6 The values of the Kolmogorov-Smirnov (KS) test

Station	Distribution	KS test statistics	*P*-Value (%)	Rank
S01	Gamma	0.09	91.10	2
	Gumbel	0.09	85.81	3
	Lognormal 2P	0.08	96.26	1
	Pearson type 3	0.23	2.04	4
S02	Gamma	0.09	90.74	2
	Gumbel	0.10	82.41	4
	Lognormal 2P	0.09	88.23	3
	Pearson type 3	0.07	97.96	1
S03	Gamma	0.09	88.10	2
	Gumbel	0.09	89.84	1
	Lognormal 2P	0.10	82.75	3
	Pearson type 3	0.12	58.66	4
S04	Gamma	0.10	81.81	2
	Gumbel	0.11	74.30	3
	Lognormal 2P	0.09	90.04	1
	Pearson type 3	0.19	9.89	4
S05	Gamma	0.08	94.01	1
	Gumbel	0.09	89.56	3
	Lognormal 2P	0.09	90.62	2
	Pearson type 3	0.35	0.01	4
S06	Gamma	0.12	63.54	4
	Gumbel	0.07	99.05	1
	Lognormal 2P	0.10	82.96	2
	Pearson type 3	0.11	74.18	3
S07	Gamma	0.10	84.06	3
	Gumbel	0.09	89.90	2
	Lognormal 2P	0.08	96.08	1
	Pearson type 3	0.36	0.01	4

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

Table 7 The return period of low flow at all streamflow stations.

Station No.	Low Flow at Return Period (m^3/s)						
	1-year	2.3-year	5-year	10-year	25-year	50-year	100-year
S01	21.42	18.19	15.27	12.63	9.13	6.49	3.85
S02	10.60	8.83	7.24	5.80	3.89	2.44	1.00
S03	6.44	5.45	4.55	3.73	2.66	1.84	1.02
S04	2.25	1.90	1.58	1.29	0.91	0.62	0.34
S05	48.40	41.54	35.35	29.72	22.29	16.67	11.05
S06	13.09	10.91	8.93	7.14	4.78	2.98	1.19
S07	34.56	30.14	26.15	22.53	17.74	14.12	10.49

Table 8 The threshold level values for Q70, Q80, Q90, and Q95.

Station No.	Q_{70} (m^3/s)	Q_{80} (m^3/s)	Q_{90} (m^3/s)	Q_{95} (m^3/s)
S01	17.36	13.29	**9.80**	7.21
S02	5.14	4.04	**2.99**	2.34
S03	3.10	2.44	**1.47**	1.05
S04	1.26	1.01	**0.69**	0.54
S05	32.56	27.26	**21.52**	17.72
S06	5.19	4.14	**2.91**	2.14
S07	28.94	23.69	**18.78**	15.83

Table 9 Summary of drought series below the threshold level (Q90) without removing minor drought.

Station No.	No. of multiyear drought events	Drought event (No. of Episode)	Mean deficit (m^3/s)	Minimum deficit (m^3/s)	Maximum deficit (m^3/s)	Mean duration (day)	Maximum duration (day)
S01	13	39	264.10	41.53	666.58	40.8	112
S02	7	29	80.70	34.44	179.73	43.5	104
S03	5	10	127.71	21.57	226.03	121.3	241
S04	8	28	24.06	7.00	131.27	52.1	306
S05	7	27	692.42	201.54	2018.06	45.8	111
S06	10	34	113.16	27.32	308.47	59.9	184
S07	13	39	557.46	161.32	1445.92	41.4	99

https://doi.org/10.5194/nhess-2020-105
Preprint. Discussion started: 22 April 2020

Table 10 The storage-draft rate required for maintaining a draft rate of 50% of the mean annual flow.

	Minimum Storage Draft Rate (m^3/s)						
	S01	**S02**	**S03**	**S04**	**S05**	**S06**	**S07**
January	2.60	1.60	0.27	0.24	-0.56	1.01	-0.66
February	5.95	3.11	0.53	0.62	1.51	2.42	0.91
March	7.59	4.64	1.00	1.03	2.41	3.96	4.60
April	4.94	4.72	1.38	1.23	-2.25	4.80	1.75
May	4.67	5.44	1.82	1.40	-5.34	5.44	-1.66
June	7.14	6.52	2.28	1.64	-1.97	6.74	-1.26
July	10.22	7.93	2.81	1.85	3.61	8.18	0.54
August	14.62	9.84	3.47	2.08	10.23	9.60	4.10
September	18.32	11.17	3.92	2.24	**15.00**	10.64	**6.17**
October	**21.51**	12.78	4.29	**2.32**	14.85	**10.90**	1.74
November	19.06	12.61	4.45	2.16	1.94	9.98	-16.22
December	19.35	**13.37**	**4.79**	2.29	-5.09	10.07	-26.24