

ENVIRONMENTAL FLOW ANALYSIS FOR WATER RESOURCES MANAGEMENT GUIDELINE IN MALAYSIA



National Water Reserch Institute of Malaysia (NAHRIM)

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EXECUTIVE SUMMARY

Management of environmental flow is useful to sustain the freshwater environment. In Malaysia, study on environmental flow characteristics of rivers is still lacking. In closing the research gap, this study proposes hydrological method for the evaluation of environmental flow characteristics of river basins in Malaysia. It is noted that the estimation of environmental flow in this study is based on hydrological method proposed by World Wide Fund for Nature (WWF), which is lack of biological basis. A total of eight river basins, which are six in Peninsular Malaysia and one each in Sabah and Sarawak were selected as the study sites. Analysis of annual water demand, annual runoff, water exploitation index, maximum (flood) flow, minimum 1-day low flow, minimum 7-day low flow, flow duration curve, intra-inter annual flow, hydrological condition, environmental flow allocation, flood regimes, and environmental water reserve was carried out. Based on the water exploitation indexes, the rivers that fall under severe stress were Sg. Muda, Sg. Johor, and Sg. Selangor; not stress for Sg. Kelantan, Sg. Pahang, Sg. Padas, and Sg. Sadong; low stress for Sg. Linggi. It was also found that the flow values for each flow category (very dry, dry, average and wet) are unique for each catchment and also vary with the month of the year. The study has proposed the range of flow for environmental water allocations under Eflow class A (very good ecological condition), Eflow class B (good ecological condition), Eflow class C (medium ecological condition), and Eflow class D (deficient ecological condition) categories. Moreover, this study also successfully estimated the flood regime and water reserve for all selected river basins.

CHAPTER 1

1. INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Recently, some rivers in the world have been under extreme pressure especially in terms of water resources possibly due to rapid urbanization and over exploitation of the natural resources (Bassi et al., 2014). Increase in impervious surface area because of urbanization significantly affects hydrological cycle. An increased proportion of impervious surface would lead to shorter lag times between onset of precipitation and subsequently higher runoff peaks and total volume of runoff in receiving waters (Shuster et al., 2005). Therefore, changes in river flows can influence chemical, physical, and biological aspects of rivers.

Droughts, floods, storms, and sea level rise have been predicted to increase because of climate change effect. Therefore, changes in magnitude, timing, frequency, duration, and variability of flows in river basins worldwide significantly alter ecosystems. Among these, drought and floods are common water related problems in many countries that lead to massive loss of economy. Hence, there is a need for better understanding and cooperation in the management and sharing of water resources.

Quantity and pattern of flow regimes depend highly on water uses and water resource infrastructure by both consumptive and non-consumptive uses. For consumptive uses particularly for irrigation and urban water supply, the impacts of flow changes may be more than simply a reduction in downstream volume. For non-consumptive uses such as hydropower generation and flood control, they can change the timing of flows, flood pulses, and temperature of the water. Although, these impacts on water regimes from multiple water uses and their interdependencies are complex, they may cause environmental degradation through reduced ecosystem health or changes in ecosystem type.

Environmental flow is a conventional approach to provide nature with an equitable share of water to keep rivers alive and flowing (Vargas et al., 2018, Verma et al., 2015). Flow regimes such as flow magnitude, flood frequency, duration, timing, depth, and velocity are essential to ecosystem health (Arthington et al., 2018). In addition, they are also highly dependent on water quality, including temperature, concentration of nutrients, and other chemical and biological properties. Therefore, management of environmental flow is very crucial to sustain the freshwater environment and to avoid catastrophic effects (Almazán-

Gómez et al., 2018). In Malaysia, study on environmental flow characteristics of rivers is still lacking. In closing the research gap, this study aims to evaluate environmental flow characteristics of eight river basins in Malaysia.

1.2 OBJECTIVES OF THE STUDY

The main aim of this study is to evaluate the environmental flow characteristics of river basins in Malaysia. To achieve the aim of this study, the following objectives were carried out:

- i. To assess the effect of environmental flow on river basins due to anthropogenic causes
- ii. To propose guidelines of water resources management from the environmental flow study at the allocated sites.

1.3 IMPORTANCE OF THE STUDY

Importance of the study is as follows:

- i. There is a need for a comprehensive work to verify and identify the present characteristics of environmental flow of river basins in Malaysia due to anthropogenic causes, which are still not clearly known.
- ii. Findings from this work are useful for better understanding of the impacts of catastrophic and seek to protect and restore natural flow regimes that provide benefits for people and aquatic flora and fauna.

1.4 SCOPE OF THE STUDY

Scope of this study is presented as follows:

- a) To evaluate the environmental flow characteristics of sites by using Hydrological Index Methodology.
- b) To determine water allocations for the environment.
 - i. To collect water demand data for the catchments for the observed streamflow stations in Peninsular Malaysia as listed in Appendix.
 - ii. To calculate water pressure (water demand) in terms of Water Exploitation Index (WEI) by using any suitable methods.
 - iii. To determine thresholds of stress of the catchment.
- c) To analyze flow duration curve characteristics

- i. Data acquisition of 30 years of hydrological data from 1981-2010 for flow components and its attributes
 - ii. To do data screening and processing for more reliable data for analysis.
 - iii. To retrieve and collate existing data for historical observed annual 1-day minimum flow, 7-days minimum flow and average annual flow.
 - iv. To use flow-duration curve (discharge versus percentage of time a discharge is equalled or exceeded) to assess the catchment's surface and groundwater storage and stream flow characteristics.
 - v. To analyze flood flow magnitudes at ARI of 1.0, 1.5, 5.0 and 10 years.
 - vi. To construct 1-day and 7-day minimum low flow duration curves for ARI of 2, 5, 10, 20, 25, 50, and 100 years.
 - vii. To identify annual flow-duration quantiles for the 5th, 10th, 25th, 50th, 75th, 90th and 95th percent exceedances.
 - viii. Use flow duration curve analysis as indicators of hydrologic conditions (i.e. wet versus dry and severe).
- d) To perform range of variability analysis
- i. To set three categories of flow (high flows, low flow and average flow) as benchmark to determine the flow characteristics
 - ii. Analyze inter-annual (very dry, dry, average and wet years) and intra-annual (seasonal flows at monthly scale) variability.
- e) To include considerations of hydrological flow changes and the proposal for environmental water allocations as part of necessary climate change adaptation measures in Malaysia.
- f) To develop environmental flows requirements for water resources management
- i. To review the existing water resources management guideline available for Peninsular Malaysia.
 - ii. To provide guidelines regarding water allocations for environmental requirements based on the study.

CHAPTER 2

2. LITERATURE REVIEW

2.1 INTRODUCTION

An extensive literature review on environmental flow from is presented in this chapter. The contents in this chapter are classified into eight (8) major sections, which are environmental flow, water exploitation index, low flow frequency, flow duration curve, flood flow frequency, intra (seasonal) and inter-annual variability flows, and flood regime.

2.2 ENVIRONMENTAL FLOW

Environmental flow investigation is essential in the current development leading to increasing hydrological alternation through dams and diversions. Increasing water extraction for meeting demands such as for industry, agriculture, recreation, hydropower generation, and domestic water supply modifies the natural conditions of stream flow and ecosystem. Currently, the protection of water resources in river against the impact of dam and water extraction is a challenging particularly in sustainable river basin management field.

In general, environmental flow assessment includes a single hydrologic attribute such as minimum flows and a full range of flows such as floods, average, and low flows varying for seasonal and inter- and intra-annual variation in stream flow variability. In addition, its magnitude, timing, frequency, and rate of change also plays an important role in long-term sustainability of water resources. These parameters affect river ecosystem condition such as fish, wildlife habitat, environmental purposes, and water quality in state of good health. For a comprehensive overview, advantages and disadvantages of existing environmental flow methods are presented in Table 2.1. As additional knowledge, several implemented environmental flow methods and their findings are listed in Table 2.2.

Table 2.1: Advantages and disadvantages of existing environmental flow methods (Liu et al., 2016)

METHOD	ADVANTAGES	DISADVANTAGES	SCOPE OF APPLICATION
HYDROLOGICAL METHOD	Simple; need least data; don not need extensive field-work.	Lack of biological basis; not considering seasonal variation and plentiful and withered circulation of flow; Environmental flow is often expressed in minimum; Historical flow data for years are needed.	River macro strategy management; The areas less controversial and no high priority.
HYDRAULIC METHOD	Data acquisition by Measurements or manning formula; Measurement is relatively simple	Not considering velocity changes; Not considering needs of specific species and life stage; Not considering channel instability with time; Selected section cannot represent the whole channel characteristics	Small and medium-sized rivers (with top width less than 30 m wide) where pollution is not obvious and sediment content is low.
HABITAT METHOD	Considering the change of the habitat by species and its different stages of life	Only consider the individual species, not considering the entire ecosystems; Need more biological data; Take a long time; Capital amount is big; Need a lot of field work.	Small and medium-sized habitat or the region of clear management objectives
ENTIRETY ANALYSIS METHOD	Considering the river ecosystem integrity; Satisfy variety of functions including biological conservation, habitat maintain and pollution control; The most reasonable method at present.	Many subjects involved; Need expertise in ecology, geography, hydrology; Consume a large amount of human resources and time cost.	Widely used in South Africa Currently; need a lot of correction when applied to other areas.

Table 2.2: Several implemented environmental flow methods and their findings.

PURPOSE	METHODS USED	FINDING	REFERENCE
In-stream flow methods most often used in North America	IFIM, Tennant, Wetted Perimeter, 7Q10 flow, Aquatic Base Flow (ABF).	Comparing results provide useful update and widest application	(Reiser et al., 1989)
In-stream flow methods used in Australia	Tennant, Flow duration (Q95& Q90), Constant yield.	Suggested different methods are suitable according to different conditions or objectives	(Karim et al., 1995)
Comparisons of hydrologically based in-stream flow methods in 70 rivers of Atlantic Canada	Tennant, 25% of the MAF, Monthly (Q50, Q90) flow, Aquatic Base Flow (ABF), 7Q10 flow.	Q90 and 7Q10 methods predict extremely low in-stream flows during winter and summer months; whereas, Q50 flows recommended for gauged and 25% of the MAF & ABF for ungagged basin.	(Caissie and El-Jabi, 1995)
Examine impact of temperature on low stream flow for 77 rivers in the Canadian Prairies and trends analysis	Seasonal 7-day low flow, seasonal 25% of mean flow, Seasonal Q80, Monthly Q50 & Q90.	Decrease in the magnitude and an increase in the frequency of low flow results in poor water quality and negative impact on aquatic life in river, while temperature has an increasing tendency.	(Yulianti and Burn, 1998)
Assessment to fulfilled water requirement for industrial plant located in San and Brah river watershed, India.	50-, 75-, 90-percentile FDC	Only San River met the required water demand	(Pandey and Ramasastri, 2003)
To protect the fish habitat	MAF, Q50, Q90, 7Q2, 7Q10.	Q50 method provide high level and whereas Q90, 7Q2 and 7Q10 methods low level of in-stream flow in small river.	(Caissie et al., 2007)
Assessment of EFRs in major Indian river basin.	Default FDC	Suggested 6 (From A to F) Environmental Management Classes (EMCs).	(Smakhtin, 2006)
Link EFRs with EFs classes	FDC	Developed a software package named Global Environmental Flow Calculator (GEFC) for desktop assessment of EFs.	(Smakhtin and Eriyagama, 2008)

PURPOSE	METHODS USED	FINDING	REFERENCE
Assess and design EFs in the Brahmani-Baitarani river system, Odissa, India.	FDC Tennant	7Q10 FDC and 7Q100 FDC were appropriate methods for designed EFs during drought /low flow periods and normal precipitation years respectively. Required more water improve water quality and livelihood support base of river ecosystem.	(Smakhtin et al., 2004)
Assess optimal EFs in Tungabhadra river, India			(Jha et al., 2008)
Computing the minimum water requirement to save biological activity in Safaood river, Iran.	Tennant, Q95 from FDC, Hydraulic	Q95 from FDC gave compatibility results with the rivers condition whereas; Tennant and Hydraulic methods gave overestimated results.	(Babu and Kumara, 2009)
Comparisons of hydrological based methods for assess EFRs to maintain basic functions in Shahr chai river, Iran.	Tennant, FDC shifting, Low flow index, DRM, GEFC	FDC shifting and DRM methods are more reliable methods in compare to Tennant, 7Q10 and Q90 of AFDC for maintains basic river functions.	(Shokoohi and Hong, 2011)

2.3 WATER EXPLOITATION INDEX

The water exploitation index in a river basin is the mean annual total demand for freshwater divided by the long-term average freshwater resources. It gives an indication of how the total water demand puts pressure on the water resource. In addition, it can be used as an indicator for the area having high demand in relation to their resources.

In general, the following threshold values for the water exploitation index have been used to indicate levels of water stress. It is noted that the non-stress, low stress, stress, and severe water stress are for the water exploitation index values < 10%; 10 to < 20%; 20% to < 40%; and $\geq 40\%$ (Pedro-Monzonis et al., 2015). For example, it can be observed from Figure 2.1 that a total of 20 countries which represent 50% of Europe's population fall under non-stressed. In addition, nine countries including Belgium, Denmark and Romania and southern countries such as Greece, Portugal and Turkey can be considered as having low water stress representing 32% of Europe's population. Moreover, Cyprus, Italy, Malta and Spain are present under water stress category (18% of Europe's population).

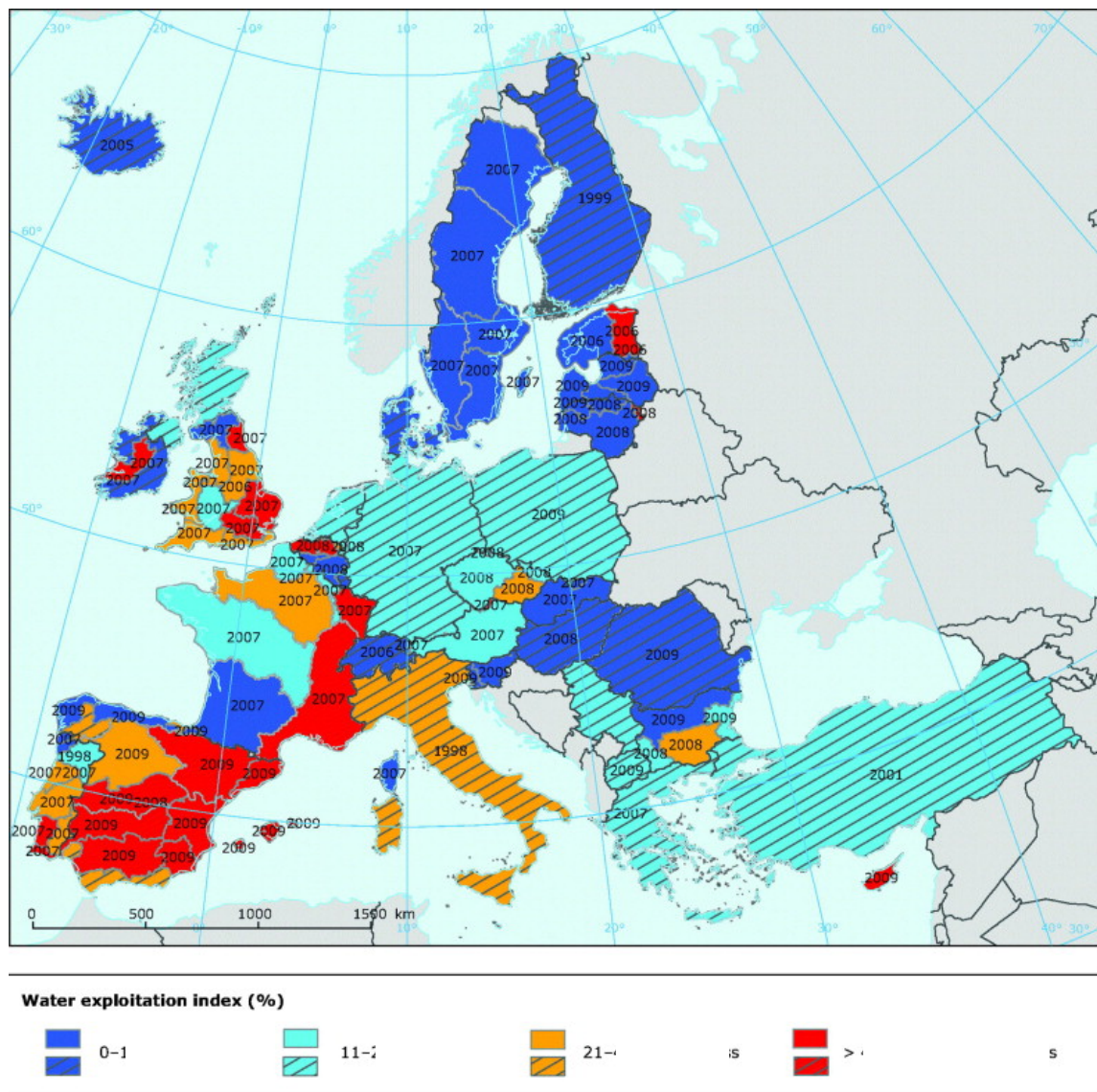


Figure 2.1: Water exploitation index in European Union

2.4 LOW FLOW FREQUENCY

Low flow frequency analysis is a stochastic method used to characterize flow events of rivers. It commonly used a single statistic or index such as Q5, Q50, Q75, or Q95. Customarily, it employed the minimum D-day average discharge per year for the analysis.

Given, a set of observed annual minimum, the purpose is to estimate probability of occurrence of some minimum values. Presuming that the observed values are independent and identically distributed, it can be achieved by estimating the cumulative distribution function, $F(x)$, representing the probability, p , of any previous or future minima.

2.5 FLOW DURATION CURVE

The flow duration curve is a plot representing the percentage of time that flow in a stream that is equal or exceed some specified value of interest. It can also be used as an indicator to show the discharge of the stream that occurs or is exceeded some percent of the time (1 to 1000% of the time). A flow duration curve characterizes the ability of the basin to provide flows of various magnitudes.

The shape of a flow-duration curve in its upper and lower regions is use full to evaluate the stream and basin characteristics. It is established that the shape of the curve in the high-flow region indicates the type of flood regime the basin. Conversely, the shape of the low-flow region characterizes the ability of the basin to sustain low flows during dry seasons.

2.6 FLOOD FLOW FREQUENCY

Flood frequency analysis is a technique that is commonly used to predict design floods for sites along a river. It involves the use of observed annual maximum flow discharge data to calculate statistical characteristics such as mean values, standard deviations, skewness, and recurrence intervals. These statistical parameters are employed to construct frequency distributions such as the employment of a graph representing the likelihood of various discharges as a function of recurrence interval or exceedance probability.

It is well known that flood frequency distributions can be described using many statistical forms. Four of the common forms are Normal Distribution, Log-Normal Distribution, Gumbel Distribution, and Log-Pearson Type III Distribution. There are advantages and disadvantages of each distribution formula.

2.7 INTRA (SEASONAL) AND INTER-ANNUAL VARIABILITY FLOWS

The full range of inter-annual and seasonal variability is defined as the natural, regularly present surface flows in dry and wet seasons at monthly scale (see Figure 2.2). This flow regime component supports several ecological functions such as the maintenance of seasonal habitats' diversity and connectivity, the water chemistry and other hydrodynamic conditions, and in addition to purging invasive and introduced species from the aquatic and riparian communities.

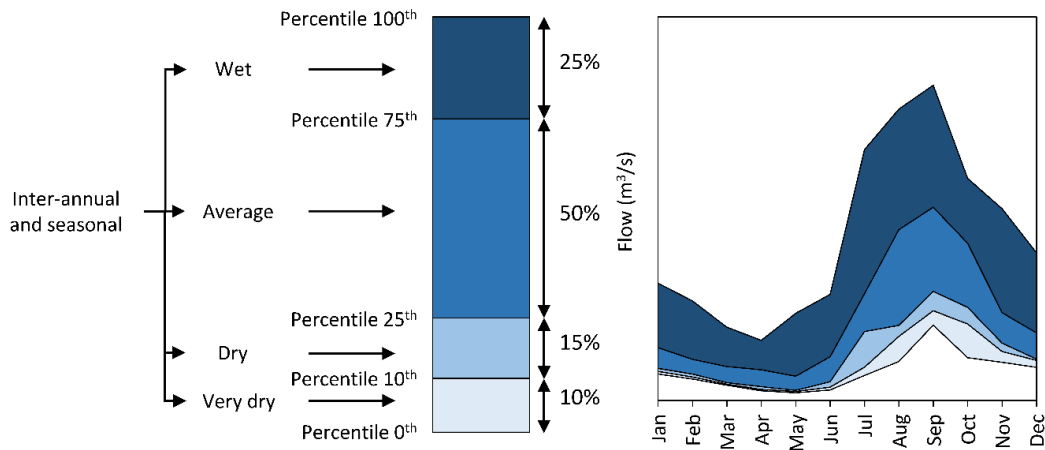


Figure 2.2: Conceptual setting for the inter-annual and seasonal variability limits of the hydrological conditions of low flows based on frequencies of occurrence

Based on a frequency of occurrence approach, it considers four hydrological conditions: wet, average, dry, and very dry low flows. They are computed in cubic meters per second (m^3/s), according to the flows characteristic of percentiles 75th, 25th, 10th, and 0th of the full set of natural or unregulated inter-annual mean monthly observed records. These percentiles set the threshold of each hydrological condition, and thus the flows' variability by their frequency of occurrence. The characteristic flows of wet conditions are those that exceed only 25% of the time from the full set of records. Similarly, the threshold of flows for the average condition is $\pm 25\%$ of percentile 50th (median). The flows characteristic of percentile 25th set the lower limit of this condition while the ones of percentile 75th set the upper limit. The flows characteristic of dry and very dry conditions are below the average threshold. For these conditions, the 10th and 0th percentiles set the limits, respectively. With this characterization, flows are expected to happen within the thresholds with the following natural frequency of occurrence: wet 25%, average 50%, dry 15%, and very dry 10% of the time.

2.8 FLOOD REGIME

The flood regime is defined as a set of peak flow episodic events. They are identified based on the maximum daily natural (m^3/s) per year of the full set of records, with their corresponding attributes of magnitude, frequency, duration, time of occurrence (timing) and rate of change (rise and fall). The set of flow events are typified for at least three categories of peaks (I, II and III) according to their historical and modeled frequencies of occurrence at 1, 1.5 and 5 years return period. The recurrence intervals of these events represent the magnitudes of the natural range of (I) intra-annual or high flow pulses, (II) the inter-annual

characteristic of bankfulls, and (III) moderate inter-annual peak events. Altogether, these events play an important role in connecting the river laterally with its floodplain and sustaining the related ecological and biological processes, among other functions.

CHAPTER 3

3. METHODOLOGY

3.1 INTRODUCTION

This chapter presents methodologies used to achieve the study objectives. A total of eight river basins; six in Peninsular Malaysia and one each in Sabah and Sarawak were selected as the study sites.

3.2 PROJECT OUTLINE

Figure 3.1 shows the flowchart summary of the present study.

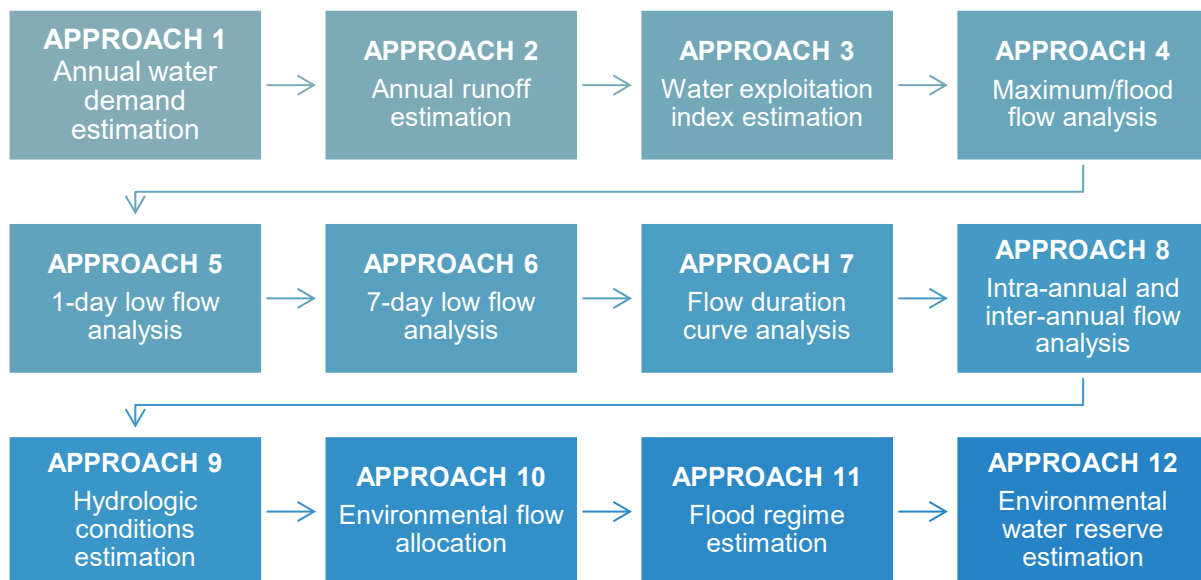


Figure 3.1 Flow chart summary of research activities

3.3 STUDY AREA

This study focuses on the environmental flow characteristics for river basins in Malaysia. The selected river basins are Sg. Muda, Sg. Kelantan, Sg. Pahang, Sg. Johor, Sg. Linggi, Sg. Selangor, Sg. Padas, and Sg. Sadong located in Kedah, Kelantan, Pahang, Johor, Negeri Sembilan, Selangor, Sabah, and Sarawak, respectively. The river basins and related information are listed in Table 3.1.

Table 3.1: Selected River basins for this study

River	State	Area of River Basin (km ²)	Area of State (km ²)	Duration of Flow Data	Complete Data Series (Years)
Sg. Muda at Jambatan Syed Omar	Kedah	4,210.0	9,500	1975-2016	17
Sg. Kelantan at Jambatan Guillemard	Kelantan	13,100.0	15,099	1961-2017	22
Sg. Pahang at Temerloh	Pahang	29,300.0	36,137	1963-2017	18
Sg. Johor at Rantau Panjang	Johor	2,285.6	18,985	1971-2017	23
Sg. Linggi at Sua Betong	Negeri Sembilan	1,297.7	6,686	1961-2017	20
Sg. Selangor at Rantau Panjang	Selangor	1,936.9	7,956	1961-2017	23
Sg. Padas at Beaufort JPS	Sabah	9,180.0	7,3613	1982-2015	14
Sg. Sadong at Serian	Sarawak	3,526.6	12,4450	1962-2017	34

3.4 DATA COLLECTION AND SCREENING

Historical long-term data such as river flow, rainfall, rating curve, and water level were obtained from Department of Irrigation and Drainage (DID) Malaysia. Water demand were derived from the report by DID (2011). For screening, only complete data within a year without missing was selected for the analysis and the data with missing was excluded. The number of years which complete data for the selected river basins range from 14 to 34 years as presented in Table 3.1.

3.5 ANNUAL WATER DEMAND ESTIMATION

Several water demands, which are the river abstraction for water supply, irrigation, non-paddy cultivation, and animal husbandry - total livestock water requirement derived from the report by DID (2011) were estimated for each river basin.

3.6 ANNUAL RUNOFF ESTIMATION

In this work, mean annual runoff was estimated using the following equation:

$$A_n R = \frac{D}{A} t \quad (3.1)$$

where $A_n R$ is the annual runoff (m), D is the annual water discharge (m^3/s), A is the area of river basin (m^2), and t is the total time a year (s).

3.7 WATER EXPLOITATION INDEX ESTIMATION

The water exploitation index (WEI) in a river basin is the mean annual total demand for freshwater divided by the long-term average freshwater resources at the river basin. It is mathematically expressed as:

$$WEI = \frac{WD}{WR} \times 100\% \quad (3.2)$$

where WEI is the water exploitation index (%), WD is the annual water demand (m^3), and WR is the water resource availability (m^3). It is well established that the water exploitation index have been used as an indicator to classify water stress levels into four categories as presented in Table 3.2.

Table 3.2: Water exploitation index category

WEI	Levels of Water Stress
< 10%	Not-stress
10 to <20	Low stress
20 to < 40	Stress
$\geq 40\%$	Severe stress

3.8 FLOOD FLOW ANALYSIS

This analysis involves the use of observed annual maximum flow discharge data to estimate various discharges as a function of recurrence interval or exceedance probability. Three of the common forms are, Gumbel, Weibull, and Fréchet distributions with advantages and disadvantages of each distribution formula. To simplify the use of the distribution,

generalized extreme value (GEV) distribution was developed. Basically, it is a family of continuous probability distributions developed within extreme value theory to combine the Gumbel, Fréchet, and Weibull families also known as type I, II and III extreme value distributions. The cumulative distribution function (CDF) of the GEV distribution is expressed mathematically as:

$$F(x) = \exp \left[- \left\{ 1 + \xi \left(\frac{x - \mu}{\sigma} \right) \right\}^{-1/\xi} \right] \quad (3.3)$$

where x is the observed discharge data, μ is the location parameter, σ is the scale parameter, and ξ is the shape parameter.

The shape parameter ξ governs the tail behaviors of the distribution. The sub-families defined by $\xi = 0$, $\xi > 0$, and $\xi < 0$ correspond to the Gumbel, Fréchet, and Weibull families, respectively. In practically, the parameters of GEV must be solved numerically using numerical simulation optimization. For instance, MATLAB Optimization Toolbox fitting function called “gevfit” provided the related numerical analysis.

In order to calculate the estimates of exceedance probabilities associated with historical observation flow data, Gringorten's plotting position formula is suggested.

$$q_i = \frac{i - a}{N + 1 - 2a} \quad (3.4)$$

where q_i is the exceedance probability associated with a specific observation, N is the number of annual flow observations, i is the rank of specific observation with i equal 1 being the largest to i equal N being the smallest, and a is the constant for estimation, which is 0.44 using Gringorten's method.

Non-exceedance probabilities associated with historical observation flow data was estimated using the following equation:

$$p_i = 1 - q_i \quad (3.5)$$

Next, the return period corresponding to the non-exceedance probability was estimated using the following equation:

$$T = \frac{1}{1 - p_i} \quad (3.6)$$

To conduct flood flow analysis, annual maximum flow was used. The data were then listed from smallest to highest value. It was then followed by starting to rank the data in decreasing order (from N to 1). It is then followed by the estimation of non-exceedance probabilities and return period associated with historical observation flow data. It is necessary to apply numerical simulation (gevfit) to obtain GEV parameters (μ , σ , and ξ). The non-exceedance probabilities of the GEV distribution can be then estimated. Next, maximum flows at different return period can be estimated. Finally, plotting return period vs flows obtained from observation data analysis using Gringorten's with GEV distribution can be carried out.

3.9 LOW FLOW ANALYSIS (1-DAY AND 7-DAY LOW FLOWS)

Low flow analysis is used to characterize low flow events of rivers. Assuming that the observed values are independent and identically distributed, it can be achieved by estimating the cumulative distribution function, $F(x)$, representing the probability, p , of any previous or future minimum values. The relationship between $F(x)$ and p is as follows:

$$p = F(x) \quad (3.7)$$

To conduct low flow analysis, annual minimum low flow was used. The only difference between fitting the GEV to a minima series by fitting the GEV to a flood series is that the minima series is negatively transformed prior to fitting the distribution. When the minima series is negatively transformed, the smallest value of the observed minima series becomes the largest value of the transformed series and vice versa. Consequently, the negatively transformed minima series behaves like a flood series with the smallest being the largest in the series. The minima series is ranked in descending order, with q_n the smallest value and q_1 the largest value in the series.

Then, it is necessary to transform the values into negative values by $x_i = -y_i$. Estimate non-exceedance probabilities and return period associated with historical observation flow data before applying the numerical simulation to obtain GEV parameters (μ , σ , and ξ). Estimation of the non-exceedance probabilities of the GEV distribution can be next carried out. Minimum low flows at different return period can be estimated. Next, plotting return period vs flows obtained from observation data analysis using Gringorten's with GEV distribution becomes the final step.

3.10 FLOW DURATION CURVE ANALYSIS

To construct a flow duration curve, daily flow data are used. The procedure employed in this work is presented as follows. Daily discharges were sorted (ranked) for period of record from the largest value to the smallest value. It is then followed by assigning each discharge value with a rank (M), starting with 1 for the largest daily discharge value. Next, the percentage exceedance can be estimated for each daily discharge value. The percentage exceedance scale is presented from 0% to 100%, so each percentage exceedance increment is 100% divided by the number of data points.

3.11 INTRA-ANNUAL AND INTER-ANNUAL FLOW ANALYSIS

Intra-annual flow variability was analyzed based on ordinary seasonal flows at monthly scale. It shows the seasonal pattern of the flow regime within a year according to the whole series of flows record available. Inter-annual flow variability was analyzed at percentiles 0 (P0), 10 (P10), 25 (P25), and 75 (P75). The flow values at P0, P10, P25, and P75 varied with the month as presented in Figure 3.2. For instance, flow value at P0 for January (M1) is derived from all monthly flow data ($a_1..a_n$) only in January for all year as illustrated in Figure 3.2. Similarly, flow value at P0 for December (M12) is derived from all monthly flow data ($l_1..l_n$) only in December for all year. The same procedure was carried out for the analysis of flow values at P10, P25, and P75.

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
Y_1	a_1											l_1
Y_2	a_2											l_2
Y_n	a_n											l_n
P0	$a_1..a_n$											$l_1..l_n$
P10	$a_1..a_n$											$l_1..l_n$
P25	$a_1..a_n$											$l_1..l_n$
P75	$a_1..a_n$											$l_1..l_n$

Figure 3.2: Illustration of the data structure for the analysis of Intra-annual and inter-annual. It is noted that M1-M12 are months, Y_1 - Y_n are year, and a-l are monthly average flows.

3.12 HYDROLOGIC CONDITIONS

Hydrological conditions of very dry, dry, average, and wet years were estimated. Range of flows at percentiles 0, 10, 25, and 75 was defined as very dry, dry, average, and wet conditions, respectively, as presented in Table 3.3.

Table 3.3: Range of flows at each percentile for very dry, dry, average, and wet conditions

Percentile	Condition
0	Very dry
10	Dry
25	Average
75	Wet

3.13 ENVIRONMENTAL FLOW (ORDINARY FLOW) ALLOCATION ESTIMATION

A river is considered in a very good ecological condition (Eflow class A), if it can maintain 20% of its wet year flows, 50% of its average year flows, 20% of its dry year flows, and 10% of its very dry year flows as presented in Table 3.4. In addition, a river can be categorized in a good ecological condition (Eflow class B) when it is able to maintain 10% of its wet year flows, 40% of its average year flows, 30% of its dry year flows, and 20% of its very dry year flows. A river is in a medium ecological condition (Eflow class C) when it falls under 0% of its wet year flows, 20% of its average year flows, 40% of its dry year flows, and 40% of its very dry year flows. On other hand, a river is categorized under a deficient ecological condition (Eflow class D) when it recorded 0% of its wet year flows, 0% of its average year flows, 40% of its dry year flows, and 60% of its very dry year flows.

Table 3.4: Calculation of environmental water allocation according to the frequency of occurrence of seasonal flows

Environmental Management Class	Ecological Desired State	Frequency of Occurrence of Seasonal Flows			
		Wet	Average	Dry	Very dry
A	Very good	0.2	0.5	0.2	0.1
B	Good	0.1	0.4	0.3	0.2
C	Medium	0.0	0.2	0.4	0.3
D	Deficient	0.0	0.0	0.4	0.6

Therefore, environmental water allocation according to the frequency of occurrence of seasonal flows at each ecological desired state can be estimated using the following equation:

$$Tv = f_W \times v_W + f_A \times v_A + f_D \times v_D + f_{VD} \times v_{VD} \quad (3.8)$$

where Tv is the total volume of ordinary seasonal flows, f is the occurrence frequency of a regime i , and v is the volume of the ordinary flow regime i . W , A , D , and VD refer to wet, average, dry, and very dry, respectively. Figure 3.3 shows illustration of the data structure for the analysis of environmental flow allocation estimation.

	M1	...	M12
P0	a_1	...	l_1
P10	a_2	...	l_2
P25	a_3	...	l_3
P75	a_4	...	l_4
EF A	$0.2a_4 + 0.5a_3 + 0.2a_2 + 0.1a_1$	...	$0.2l_4 + 0.5l_3 + 0.2l_2 + 0.1l_1$
EF B	...	...	...
EF C	...	...	...
EF D	$0.0a_4 + 0.0a_3 + 0.4a_2 + 0.6a_1$	...	$0.0l_4 + 0.0l_3 + 0.4l_2 + 0.6l_1$

Figure 3.3: Illustration of the data structure for the environmental flow allocation estimation. It is noted that a_1 - a_4 are monthly average flows at different percentiles and EF A, EF B, EF C, and EF D are Eflow class A, Eflow class B, Eflow class C, and Eflow class D, respectively.

3.14 FLOOD REGIME ESTIMATION

Flood regime for all selected river basins was estimated based on four categories of flood magnitude, which are 1.0, 1.5, 5.0, and 10 years period of return obtained from GEV analysis as presented in Table 3.5. The attributes of the flood regime in terms of its duration, timing, and rate of change patterns for each flood category were characterized from historical events as illustrated in Figure 3.4. The duration of each episodic event was determined according to the cumulative relative frequency in which said events have occurred historically in the complete natural flow data (a value between 75 – 85% is adequate) as shown in figure 3.5.

The timing was determined based on the months of the natural occurrence of these same events by using a relative frequency of approximately 80 – 90% because it captures the typical peak flow's seasonality (Salinas-Rodríguez et al., 2018). Rate of change for raises was estimated using means of all positive differences between consecutive daily changes values while for falls was estimated using means of all negative differences between consecutive daily changes values (Richter et al., 1997).

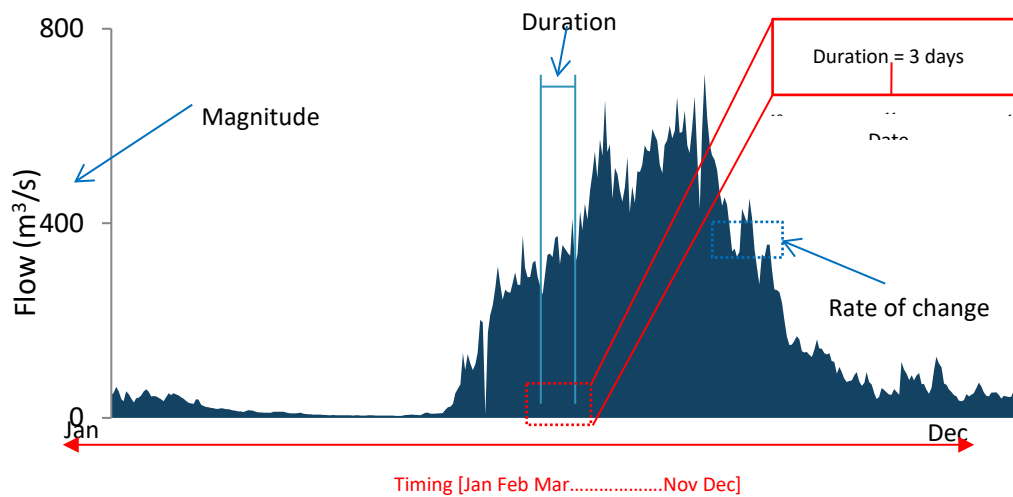


Figure 3.4: Illustration of the data extraction of flow magnitude, duration, and rate of change from daily flow.

d	Frequency	Relative frequency	Cumulative relative frequency
D ₁	F ₁	$RF_1 = F_1/N$	$CRF_1 = RF_1$
D ₂	F ₂	$RF_2 = F_2/N$	$CRF_2 = RF_1 + RF_2$
...	...	...	...
...	...	...	...
D _n	F _n	$RF_n = F_n/N$	$CRF_n = RF_{n-1} + RF_n$

Figure 3.5: Illustration of the data structure for the analysis of relative frequency and cumulative relative frequency of the flood duration. Similar procedure was applied for the analysis of timing. It is noted that D₁-D_n is the duration (d) of flood, F₁-F_n is the frequency of flood duration, RF₁-RF_n is the relative frequency of flood duration, and CRF₁-CRF_n is the cumulative relative frequency of flood duration.

Table 3.5: Calculation of environmental water allocation according to the frequency of occurrence of flood categories

Environmental Management Class	Ecological Desired State	Flood Categories			
		1.0	1.5	5.0	10.0
A	Very good	10.0	6.0	2.0	1.0
B	Good	5.0	3.0	2.0	1.0
C	Medium	3.0	2.0	1.0	1.0
D	Deficient	2.0	1.0	1.0	1.0

Next, calculation of environmental water allocation according to the frequency of occurrence of flood categories can be carried using the following equation:

$$Tv_{fr} = [f_{1.0} \times D_{1.0} \times v_{1.0} + f_{1.5} \times D_{1.5} \times v_{1.5} + f_{5.0} \times D_{5.0} \times v_{5.0} + f_{10.0} \times D_{10.0} \times v_{10.0}] / 10 \quad (3.9)$$

where Tv_{fr} is the total volume of ordinary seasonal flows, f is the occurrence frequency of flood i , D is the duration of flood i , and v is the volume of the flood i . Figure 3.6 shows illustration of the data structure for the analysis of flood regime estimation.

RP	1.0 year	..	10.0 years
Flow	a_1	..	a_4
d	b_1	..	b_4
EF A	$[10a_1b_1+6a_1b_1+2a_1b_1+1a_1b_1]/10$	..	$[10a_4b_4+6a_4b_4+2a_4b_4+1a_4b_4]/10$
EF B	...	..	...
EF C	...	..	...
EF D	$[2a_1b_1+1a_1b_1+1a_1b_1+1a_1b_1]/10$	..	$[2a_4b_4+1a_4b_4+2a_4b_4+1a_4b_4]/10$

Figure 3.6: Illustration of the data structure for the analysis of flood regime estimation. It is noted that RP is the return period, a_1 - a_4 are maximum flow values at different return periods obtained from the GEV analysis, and b_1 - b_4 is the duration (d) of the maximum flow.

3.15 ENVIRONMENTAL WATER RESERVE ESTIMATION

In this study, environmental water reserve (total) was estimated from annual ordinary seasonal flows (Mm^3 /year) and flood regimes (Mm^3 /year) at different environmental classes as shown in Figure 3.7 and Figure 3.8, respectively. Percentage of mean annual runoff ($Pmar$) was estimated by dividing the environmental water reserve with annual water availability (Mm^3 /year). The aforementioned equations are given as follows:

$$FEWR = Tosf + Tfr \quad (3.10)$$

with $FEWR$ is the environmental water reserve ($Mm^3/year$), $Tosf$ is the total ordinary seasonal flows in annual basis ($Mm^3/year$), and Tfr is the total flood regimes in annual basis ($Mm^3/year$).

$$Pmar = \frac{FEWR}{AWA} \times 100\% \quad (3.11)$$

with $FEWR$ is the environmental water reserve ($Mm^3/year$) and AWA is the annual water availability ($Mm^3/year$).

	M1	...	M12	Average flow (m^3/s)	$Tosf$ ($m^3/year$)
EF A	a_1	...	l_1	$av_1 = (a_1 + \dots + l_1)/12$	av_1 in yearly basis
EF B	...	...	...	...	...
EF C	...	...	...	...	...
EF D	a_4	...	l_4	$av_4 = (a_4 + \dots + l_4)/12$	av_4 in yearly basis

Figure 3.7: Illustration of the data structure for the analysis of the total ordinary seasonal flows in annual basis. It is noted that a_1 - l_4 are the flows at different Eflow classes. Obviously, $Tosf$ is obtained by converting the monthly average flow (m^3/s) at each Eflow class into yearly basis ($m^3/year$).

RP	1.0	1.5	5.0	10.0	Tfr ($m^3/year$)
EF A	a_1	b_1	c_1	d_1	$Tfr_A = (a_1 + \dots + d_4)$
EF B	...	...	...	...	...
EF C	...	...	...	...	...
EF D	a_4	b_4	c_4	d_4	$Tfr_D = (a_1 + \dots + d_4)$

Figure 3.8: Illustration of the data structure for the analysis of the total flood regimes in annual basis. It is noted that a_1 - d_4 are flood regimes at different return periods for each Eflow class.

For a comprehensive overview, Figure 3.9 illustrates the data structure for the analysis of the environmental water reserve ($FEWR$). In addition, Figure 3.10 Illustrates the data structure for the analysis of percentage of mean annual runoff ($Pmar$). It is noted that AWA is the annual water availability of a river.

	Tosf (m ³ /year)	Tfr (m ³ /year)	FEWR (m ³ /year)
EF A	Tosf _A	Tfr _A	FEWR _A = Tosf _A + Tfr _A
EF B	...	...	...
EF C	...	...	...
EF D	Tosf _D	Tfr _D	FEWR _D = Tosf _D + Tfr _D

Figure 3.9: Illustration of the data structure for the analysis of the environmental water reserve (*FEWR*).

	FEWR (m ³ /year)	AWA (m ³ /year)	Pmar (%)
EF A	FEWR _A	AWA	Pmar _A = [FEWR _A /AWA]×100%
EF B	...	...	...
EF C	...	...	...
EF D	FEWR _D	AWA	Pmar _A = [FEWR _D /AWA]×100%

Figure 3.10: Illustration of the data structure for the analysis of percentage of mean annual runoff (*Pmar*). It is noted that AWA is the annual water availability of a river.

CHAPTER 4

4. RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter provides findings of this work. Results for water demand, runoff, water resource availability, water exploitation index, low flow analysis, flow duration curve, flood flow, inter and intra annual flow, indicators of hydrologic condition, range or variability analysis, flood regime, and water reserve for all selected river basins are presented.

4.2 RATING CURVE ANALYSIS

Overall, the consistency of rating curves was observed for Sg. Kelantan, Sg. Pahang, Sg. Johor, Sg. Linggi, Sg. Selangor, Sg. Padas, and Sg. Sadong. Sg. Muda shows moderately consistent rating curve as listed in Table 4.1 and shown in Figure 4.1(a). For Sg. Sadong, rating curves and their formula at different water levels are also given in Figure 4.1. It is noted that the rating curves for Sg. Sadong are $Q = 6.37 \cdot (h - 0.00)^{1.86}$ [$h = 1.22 - 7.49$ m] and $Q = 0.85 \cdot (h - 2.49)^{3.73}$ [$h = 7.49 - 8.32$ m]. It is noted from the figure that the verification was carried out by analysis of gauging data vs data obtained using the model. By providing R^2 above 0.9, the model was capable for the description of the river flow data. The provided rating curves for all river basins are acceptable and can be used for the estimation of flows for each river basin.

Table 4.1: Water exploitation index for the selected river basins

River	Category
Sg. Muda at Jambatan Syed Omar	Moderately consistent
Sg. Kelantan at Jambatan Guillemard	Consistent
Sg. Pahang at Temerloh	Consistent
Sg. Johor at Rantau Panjang	Consistent
Sg. Linggi at Sua Betong	Moderately consistent
Sg. Selangor at Rantau Panjang	Consistent
Sg. Padas at Beaufort JPS	Moderately consistent
Sg. Sadong at Serian	Moderately consistent

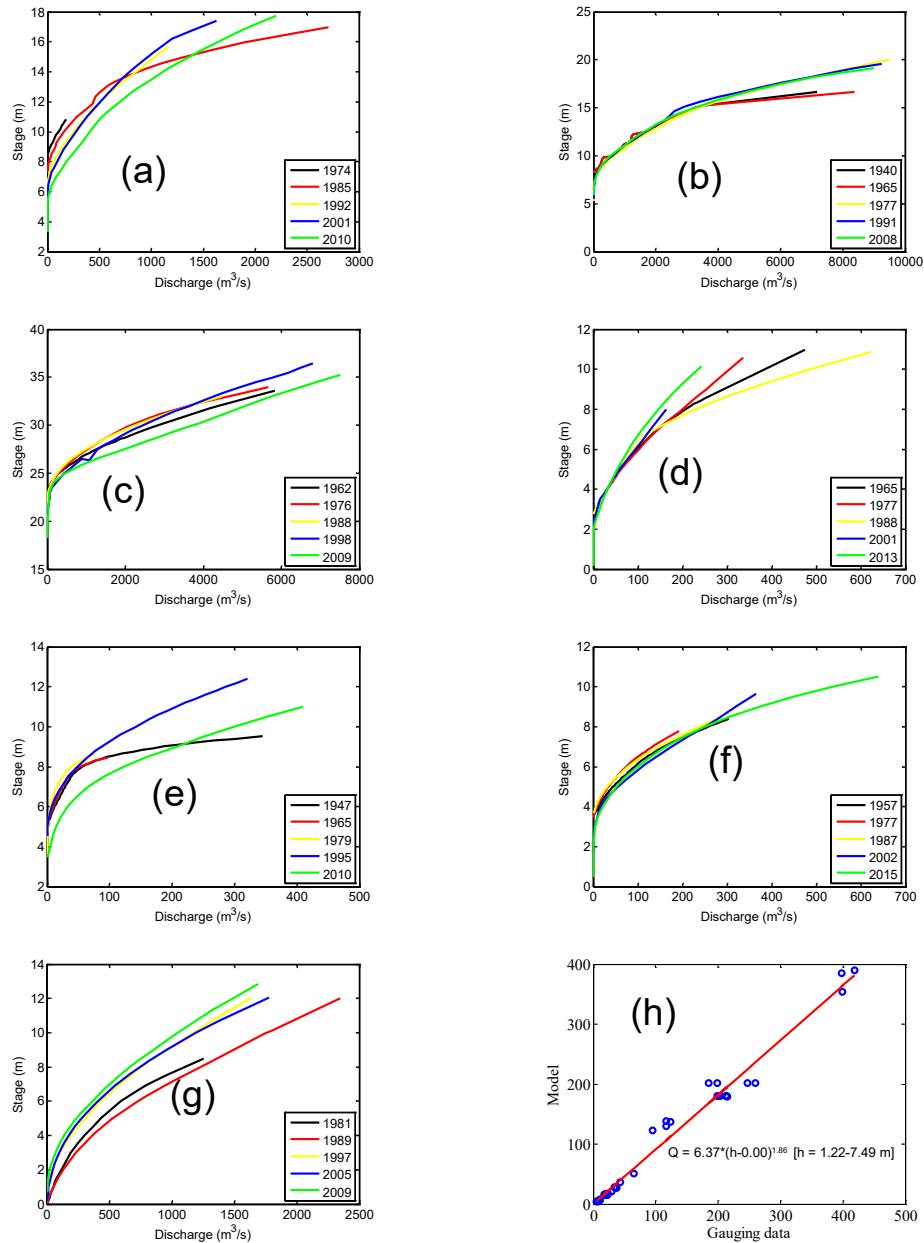


Figure 4.1: Rating curve for (a) Sg. Muda, (b) Sg. Kelantan, (c) Sg. Pahang, (d) Sg. Johor, (e) Sg. Linggi, (f) Sg. Selangor, and (g) Sg. Padas while rating curves and their formula for Sg. Sadong at different levels are presented in (h)

4.3 ANNUAL WATER DEMAND

Table 4.2 presents the daily water demand for different uses at the selected river basins. The highest daily water demand for water supply at all selected river basins was at Sg. Selangor. In addition, the highest daily water demand for the irrigation was at Sg. Kelantan. The highest daily water demand for the non-paddy cultivation category was at Sg. Kelantan. The highest demand for animal husbandry - total livestock water requirement was at Sg. Pahang.

Moreover, Table 4.3 lists the annual water demand for the selected river basins. Annual water demand abstracted from Sg. Muda, Sg. Kelantan, Sg. Pahang, Sg. Johor, Sg. Linggi, Sg. Selangor, Sg. Padas, and Sg. Sadong were 1,962, 1,411, 894, 848, 228, 1,135, 249, and 128.81 Mm³, respectively. The highest and the lowest annual water demand abstracted from the river basins are at Sg. Muda and Sg. Sadong, respectively.

Table 4.2: Daily water demand for different uses for the selected river basins.

River	Water Demand (MLD)				
	RA	I	NP	AH	Total
Sg. Muda at Jambatan Syed Omar	1,160	3,840	175.9	200.3	5,376.2
Sg. Kelantan at Jambatan Guillemard	364.9	2,691.4	687.57	121.9	3,865.8
Sg. Pahang at Temerloh	716.8	1,111.8	71.4	549.0	2,449.0
Sg. Johor at Rantau Panjang	2,200	0.0	33.2	89.76	2,322.9
Sg. Linggi at Sua Betong	440	21.3	124.8	37.5	623.7
Sg. Selangor at Rantau Panjang	2,950	0.0	24.3	134.7	3,109.0
Sg. Padas at Beaufort JPS	47.2	501	24.0	111.0	683.3
Sg. Sadong at Serian	26.0	323	0.2	3.8	352.9

It is noted that RA, I, NP, AH refer to the river abstraction for water supply, irrigation, non-paddy cultivation, and animal husbandry - total livestock water requirement, respectively.

Table 4.3: Annual water demand for the selected river basins

River	Annual Water Demand (Mm ³)
Sg. Muda at Jambatan Syed Omar	1,962.31
Sg. Kelantan at Jambatan Guillemard	1,411.02
Sg. Pahang at Temerloh	893.89
Sg. Johor at Rantau Panjang	847.86
Sg. Linggi at Sua Betong	227.65
Sg. Selangor at Rantau Panjang	1,134.79
Sg. Padas at Beaufort JPS	249.40
Sg. Sadong at Serian	128.81

4.4 ANNUAL RUNOFF

Table 4.4 presents area of the river basins at the related JPS stations and the whole river basin. At JPS stations, Sg. Muda, Sg. Kelantan, Sg. Pahang, Sg. Johor, Sg. Linggi, Sg. Selangor, Sg. Padas, and Sg. Sadong 4,150.4, 11,900.0, 28,682.2, 1291.0, 527.0, 1405.0, 8,822.2, and 953.0 km², respectively.

Table 4.4: Area of the selected river basins

River	Area at JPS Station (km ²)	Area the Whole River (km ²)
Sg. Muda at Jambatan Syed Omar	4,150.4	4,210.0
Sg. Kelantan at Jambatan Guillemard	11,900.0	13,100.0
Sg. Pahang at Temerloh	28,682.2	29,300.0
Sg. Johor at Rantau Panjang	1,291.0	2,285.6
Sg. Linggi at Sua Betong	527.0	1,297.7
Sg. Selangor at Rantau Panjang	1,405.0	1,936.9
Sg. Padas at Beaufort JPS	8,822.2	9,180.0
Sg. Sadong at Serian	953.0	3,526.6

In addition, Table 4.5 lists the annual runoff of the selected river basins. Sg. Muda, Sg. Kelantan, Sg. Pahang, Sg. Johor, Sg. Linggi, Sg. Selangor, Sg. Padas, and Sg. Sadong revealed the annual runoff of 619.2, 1,255.8, 646.4, 896.7, 951.1, 1,277.3, 827.2, and 1,607.1 mm, respectively. The runoff represents between 26 to 51% of the rainfall with an average of 36%.

Table 4.5: Annual runoff for the selected river basins

River	Rainfall (mm)	Annual Runoff (mm)	Volume at Station (Mm ³)	Volume the Whole River (Mm ³)
Sg. Muda at Jambatan Syed Omar	2,377	619.2	2,569.9	2,606.8
Sg. Kelantan at Jambatan Guillemard	2,472	1,255.8	14,944.0	16,451.0
Sg. Pahang at Temerloh	2,033	646.4	18,540.2	18,939.5
Sg. Johor at Rantau Panjang	2,239	896.7	1,157.6	2,049.5
Sg. Linggi at Sua Betong	2,046	951.1	501.2	1,234.2
Sg. Selangor at Rantau Panjang	2,659	1,277.3	1,794.6	2,474.0
Sg. Padas at Beaufort JPS	2,259	827.2	7,297.4	7,593.4
Sg. Sadong at Serian	3,266	1,607.1	1,531.6	5,667.7

Table 4.6 lists the annual water resource availability of the selected river basins. Sg. Muda, Sg. Kelantan, Sg. Pahang, Sg. Johor, Sg. Linggi, Sg. Selangor, Sg. Padas, and Sg. Sadong showed the annual water resources of 2,606.8, 16,451.0, 18,939.5, 2,049.5, 1,234.2, 2,474.0, 7,593.4, and 5,667.7 Mm³, respectively. As expected, the highest water resources availability was obtained from the biggest river basin, Sg. Pahang and the smallest basins, Sg. Linggi, produced the least runoff volume.

Table 4.6: Annual water availability for the selected river basins

River	Annual Water Availability or Volume the Whole River (Mm ³)
Sg. Muda at Jambatan Syed Omar	2,606.8
Sg. Kelantan at Jambatan Guillemard	16,451.0
Sg. Pahang at Temerloh	18,939.5
Sg. Johor at Rantau Panjang	2,049.5
Sg. Linggi at Sua Betong	1,234.2
Sg. Selangor at Rantau Panjang	2,474.0
Sg. Padas at Beaufort JPS	7,593.4
Sg. Sadong at Serian	5,667.7

4.5 WATER EXPLOITATION INDEX

The water exploitation index has been used as an indicator to classify water stress levels into four categories as presented in Table 4.7. For the selected river basins, WEI indexes for Sg. Muda, Sg. Kelantan, Sg. Pahang, Sg. Johor, Sg. Linggi, Sg. Selangor, Sg. Padas, and Sg. Sadong were 75.3, 8.6, 4.7, 41.4, 18.4, 45.9, 3.3, and 2.3%, respectively. By their WEI indicators, Sg. Muda, Sg. Johor, and Sg. Selangor fall under severe water stress category as presented in Table 4.8. Sg. Linggi was under low stress because of its WEI index of 18.4%. In addition, Sg. Kelantan, Sg. Pahang, Sg. Padas, and Sg. Sadong are under not-stress categories, respectively.

Table 4.7: Water exploitation index category

WEI	Levels of Water Stress
< 10%	Not-stress
10 to <20	Low stress
20 to < 40	Stress
≥ 40%	Severe stress

Table 4.8: Water exploitation index for the selected river basins

River	Water exploitation index (%)	Levels of water stress
Sg. Muda at Jambatan Syed Omar	75.3	Severe stress
Sg. Kelantan at Jambatan Guillemard	8.6	Not-stress
Sg. Pahang at Temerloh	4.7	Not-stress
Sg. Johor at Rantau Panjang	41.4	Severe stress
Sg. Linggi at Sua Betong	18.4	Low stress
Sg. Selangor at Rantau Panjang	45.9	Severe stress
Sg. Padas at Beaufort JPS	3.3	Not-stress
Sg. Sadong at Serian	2.3	Not-stress

Since water exploitation index for Sg. Muda is 75%, which is under severe stress category, it is crucial to re-evaluate the current rate of water abstraction. At the moment, the river water is mainly used for water supply and irrigation, which made up to 21% and 71% of the total demand, respectively. The use of alternative water resources such as groundwater and rainwater harvesting can be implemented to reduce the dependency of water supply from the river. In addition, it is necessary to improve the irrigation efficiency, which is at the moment only about 40%. The implementation of aforementioned strategies could improve water exploitation index. For instance, in order to improve the water exploitation index status from severe stress to stress category, it is necessary to reduce water abstraction by providing alternative resources for supply and irrigation by 35% and 56%, respectively.

Water exploitation index for Sg. Kelantan revealed under not stress category (8.6% WEI). This is possibly due to low water abstraction for water supply, which is only 9% of the total demand. The state of Kelantan explored groundwater by approximately 40% of the total supply. This strategy should be maintained although providing other alternative water resources is recommended. Water exploitation index for Sg. Pahang revealed under not stress category (4.7% WEI). This is possibly due to higher runoff volume of water provided by the river basin with the whole area of 29,300.0 km². This strategy should be maintained although providing other alternative water resources is remarkable.

Water exploitation index for Sg. Johor revealed under severe stress category. Although there is no water abstraction for irrigation, the abstraction for water supply consumes up to 94%. The use of groundwater and rainwater harvesting must be encouraged to reduce the dependency of water supply from the river. For instance, the reduction of 4%

and 55% abstraction for water supply can improve the water exploitation index to be stress and low stress category, respectively.

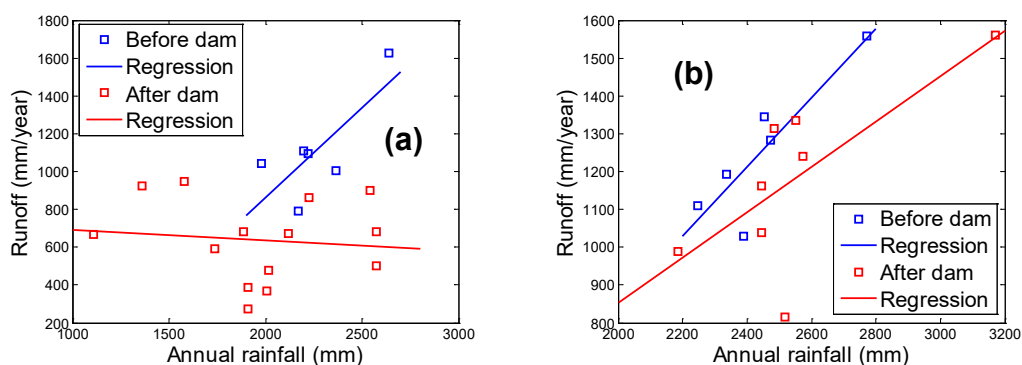
Water exploitation index for Sg. Linggi revealed under low stress category. A strategy can be carried out to move down the water exploitation index category into not stress by reducing abstraction for supply up to 65%. Water exploitation index for Sg. Selangor revealed under severe stress category. The abstraction for water supply consumes up to 94%. The use of groundwater and rainwater harvesting must be encouraged to reduce the dependency of water supply from the river. For instance, the reduction of 14% and 60% abstraction for water supply improve the water exploitation index to be stress and low stress category, respectively.

Although water exploitation index for Sg. Padas revealed under not stress category, future water demand is expected to increase due to uncertainty of climate. It is necessary to provide alternative water resources such as groundwater and rainwater harvesting. Water exploitation index for Sg. Sadong revealed under not stress category. This strategy should be maintained although providing other alternative water resources is recommended.

4.6 MAXIMUM FLOW ANALYSIS

4.6.1 MAXIMUM FLOW ANALYSIS: CASE I (RIVER WITH A DAM)

Figure 4.2(a) shows rainfall-runoff relationship for Sg. Johor before and after the presence of the dam (Linggiu dam in 1993). Rainfall-runoff relationship for Sg. Selangor before and after the presence of the dam (Selangor dam, 2001) and for Sg. Muda before and after the presence of the dam (Beris dam, 2004) is presented in Figures 4.2(b)-(c), respectively.



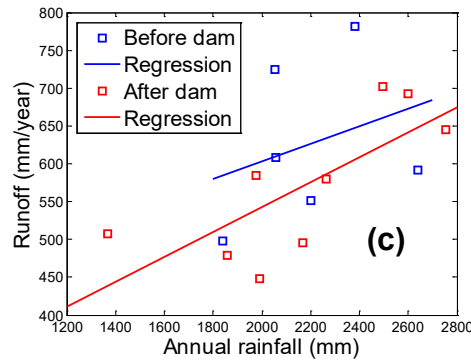


Figure 4.2: Rainfall-runoff relationship for (a) Sg. Johor, (b) Sg. Selangor, and (c) Sg. Muda before and after the dam construction

Maximum flows at different return periods for selected river basins before and after the dam construction are presented in Table 4.9. Annual maximum flow for Sg. Johor at return periods of 2, 5, 10, 20, 25, 50, and 100 years prior to the dam construction were 216.16, 345.15, 444.64, 552.23, 589.08, 711.63, and 847.99 m³/s, respectively. After the completion of the dam, the corresponding values were 139.01, 243.67, 351.61, 498.66, 556.91, 782.03, and 1,094.35 m³/s. In general, higher annual maximum flows after dam construction are probably due the water release from the dam. During an extreme rainfall, the capacity of the dam may not be able to store all runoff coming into the dam. Consequently, the dam must release the excess water to the river to avoid the dam failure because of overcapacity.

Sg. Selangor exhibited the annual maximum flow at return periods of 2, 5, 10, 20, 25, 50, and 100 of 204.77, 255.98, 288.64, 319.07, 328.54, 357.18, and 384.84 m³/s, respectively. After the dam construction, the corresponding values were 256.74, 321.38, 372.81, 429.79, 449.62, 516.59, and 592.86 m³/s. It is found that increase in maximum flows after dam construction for Sg. Selangor are possibly due to the release from the dam. As previously mentioned, this was carried out to avoid the dam failure because of overcapacity.

Sg. Muda exhibited the annual maximum flow at return periods of 2, 5, 10, 20, 25, 50, and 100 of 530.90, 795.15, 974.15, 1,148.94, 1,205.03, 1,379.78, and 1,556.22 m³/s, respectively. After the dam construction, the corresponding values were 431.55, 566.80, 664.55, 764.98, 798.27, 905.39, and 1,018.91 m³/s. Maximum flows for Sg. Muda were observed to decrease after dam construction, which is possibly due to diversion. It is noted that the Muda dam has diverted most of the upper catchment runoff to the Muda Agricultural Development Agency (MADA) in the

neighboring Kedah River basin for irrigation (mainly paddy), via the Saiong tunnel. The Sg. Muda supplies about 32% of the MADA area's irrigation needs.

Table 4.9: Maximum flows at different return periods for selected river basins before and after the dam construction

T (year)	Sg. Johor		Sg. Selangor		Sg. Muda	
	Maximum flow before dam (m ³ /s)	Maximum flow after dam (m ³ /s)	Maximum flow before dam (m ³ /s)	Maximum flow after dam (m ³ /s)	Maximum flow before dam (m ³ /s)	Maximum flow after dam (m ³ /s)
2	216.16	139.01	204.77	256.74	530.90	431.55
5	345.15	243.67	255.98	321.38	795.15	566.80
10	444.64	351.61	288.64	372.81	974.15	664.55
20	552.23	498.66	319.07	429.79	1,148.94	764.98
25	589.08	556.91	328.54	449.62	1,205.03	798.27
50	711.63	782.03	357.18	516.59	1,379.78	905.39
100	847.99	1,094.35	384.84	592.86	1,556.22	1,018.91

Moreover, annual non-exceedance probability and return period of maximum flow for Sg. Muda, Sg. Selangor, and Sg. Muda before and after the dam construction are shown in Figures 4.3-4.5.

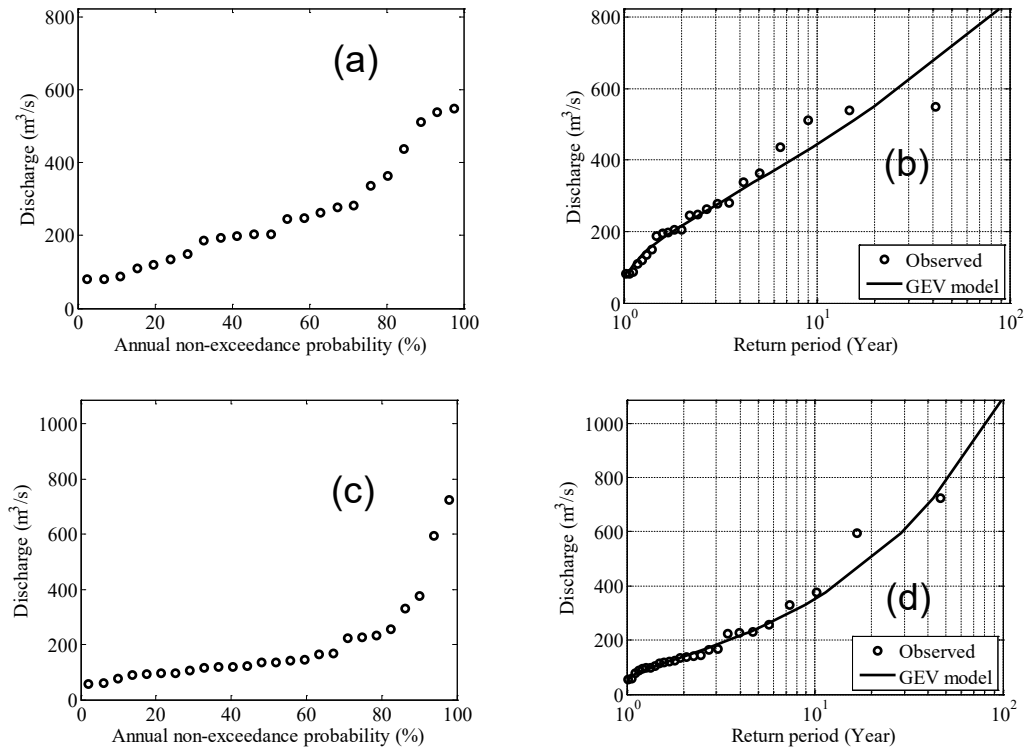


Figure 4.3: Annual non-exceedance probability and return period of annual maximum flow for Sg. Johor (a-b) before and (c-d) after the dam construction

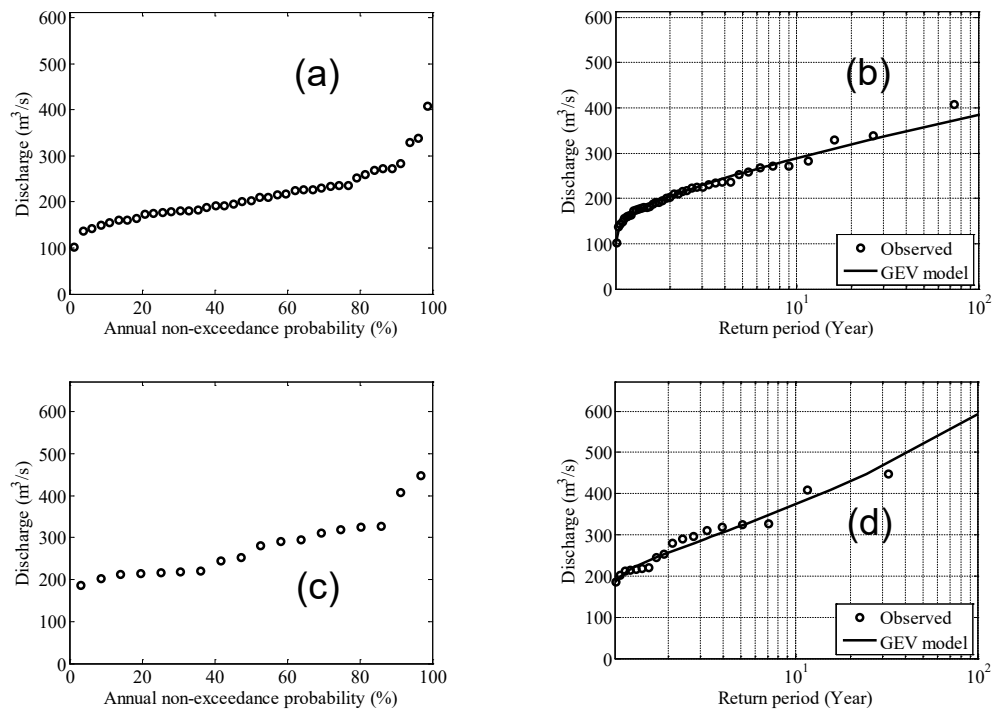


Figure 4.4: Annual non-exceedance probability and return period of annual maximum flow for Sg. Selangor (a-b) before the dam and (c-d) after the dam construction

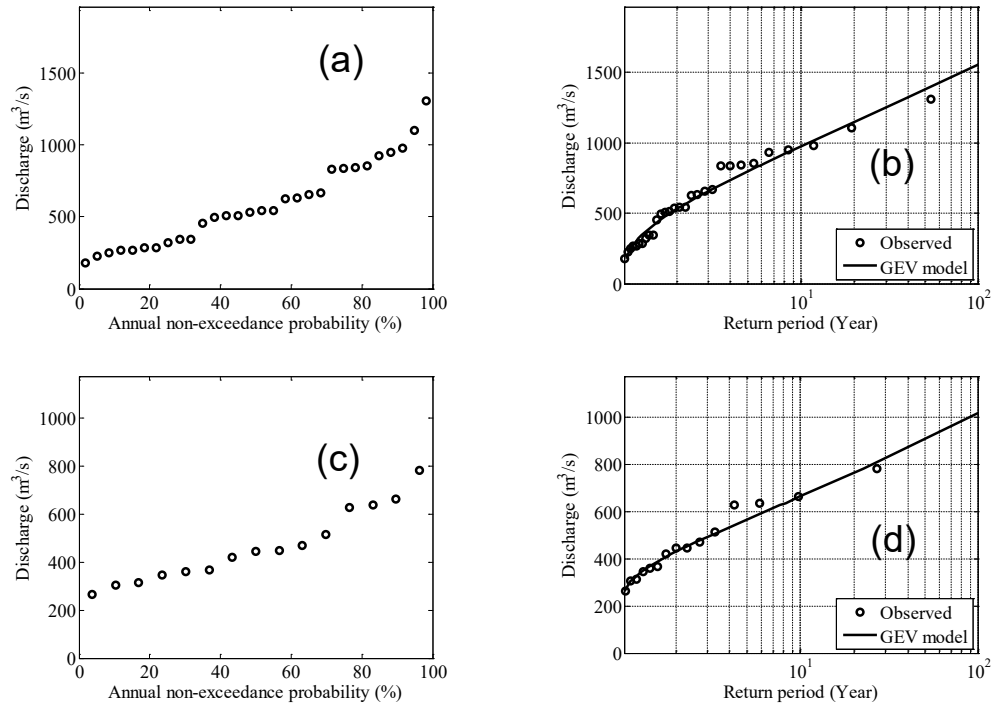


Figure 4.5: Annual non-exceedance probability and return period of annual maximum flow for Sg. Muda (a-b) before the dam and (c-d) after the dam construction

The optimized GEV parameters for the analysis are listed in Table 3.10. The annual maximum flow for Sg. Johor before and after the dam construction exhibited Fréchet distribution. For Sg. Selangor, annual maximum flows before the dam exhibited Fréchet distribution because of the negative value of the optimized ξ parameter. After the dam, discharges of annual maximum flow reflected Fréchet distribution. Annual maximum flow before and after the dam construction for Sg. Muda exhibited Fréchet distribution because of the positive value of the optimized ξ parameters.

Table 4.10: Optimized GEV parameters for selected river basins before and after the dam construction

Parameter	Sg. Johor		Sg. Selangor		Sg. Muda	
	Maximum flow before dam (m³/s)	Maximum flow after dam (m³/s)	Maximum flow before dam (m³/s)	Maximum flow after dam (m³/s)	Maximum flow before dam (m³/s)	Maximum flow after dam (m³/s)
μ	179.30	115.62	187.71	238.74	446.99	390.78
σ	97.60	58.40	46.89	47.38	227.91	109.33
ξ	0.16	0.48	-0.04	0.20	0.02	0.09

4.6.2 MAXIMUM FLOW ANALYSIS: CASE II (RIVER WITHOUT A DAM)

Table 4.11 lists maximum flows at different return periods for the selected rivers. Figure 4.6 shows annual non-exceedance probability and return period of maximum flow for (a-b) Sg. Kelantan, (c-d) Sg. Pahang, (e-f) Sg. Linggi, (g-h) Sg. Padas, and (i-j) Sg. Sadong.

In general, the pattern of maximum flow of the unregulated river basins (without dam) over selected return periods show similar pattern as shown in Figure 4.6. The highest maximum flow was observed for Sg. Kelantan and the lowest for Sg. Linggi. For example, the maximum flow for Sg. Kelantan at 2 and 100 years return periods are 4,292.94 and 9,170.67 m³/s, respectively (see Table 4.11). In addition, the maximum flow for Sg. Linggi at 2 and 100 years return periods are 91.78 and 441.50 m³/s, respectively (see Table 4.11). Moreover, higher maximum flows at Sg. Kelantan compared to Sg. Pahang are probably because annual rainfall in Sg. Kelantan is higher compared to Sg. Pahang. In addition, higher maximum flows at Sg. Sadong compared to Sg. Padas may also be due to higher rainfall in Sg. Sadong compared to Sg. Padas. It is noted that annual rainfall at Sg. Sadong is 3,266 mm, which is much higher than at Sg. Padas, which is only 2,259 mm.

Table 4.11: Discharges at different return periods for maximum flow of the selected rivers

River	Sg. Kelantan (m ³ /s)	Sg. Pahang (m ³ /s)	Sg. Linggi (m ³ /s)	Sg. Padas (m ³ /s)	Sg. Sadong (m ³ /s)
2	4,292.94	3,093.10	91.78	217.60	246.71
5	6,020.64	4,405.68	144.50	290.43	344.95
10	6,968.78	5,200.61	191.72	337.63	412.14
20	7,754.99	5,912.03	249.20	382.16	478.25
25	7,981.87	6,127.79	270.42	396.14	499.57
50	8,619.64	6,763.98	346.60	438.73	566.31
100	9,170.67	7,355.07	441.50	480.35	634.17

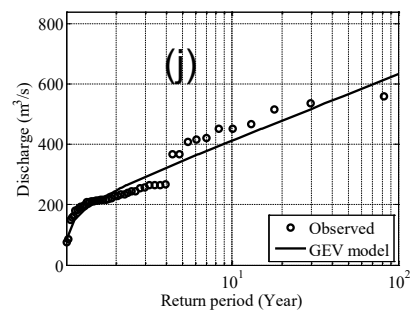
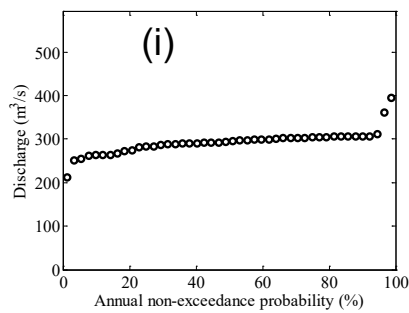
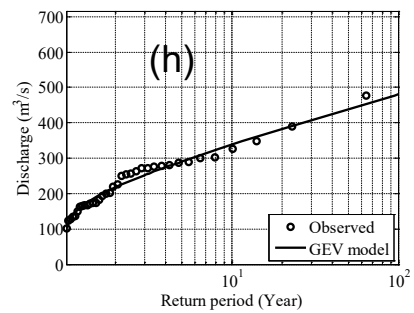
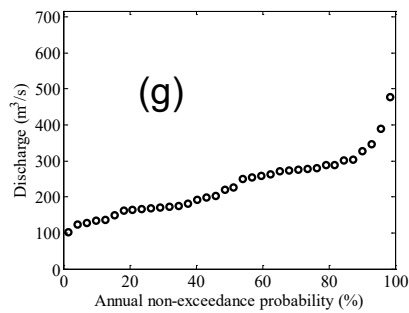
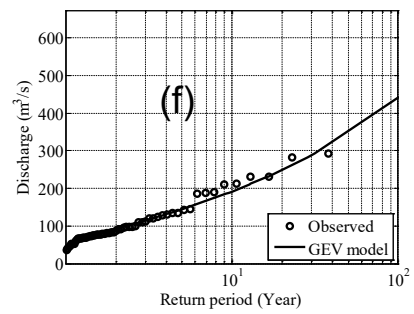
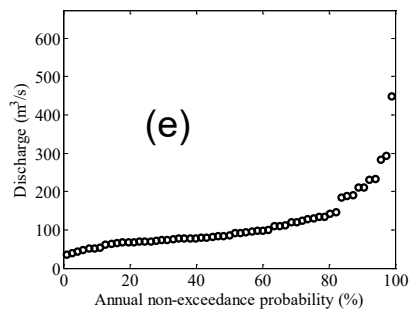
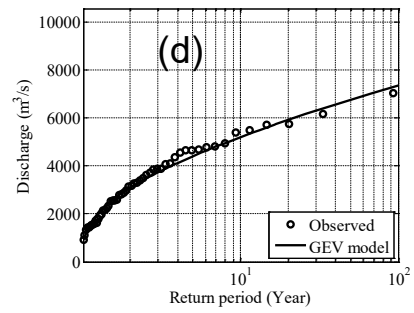
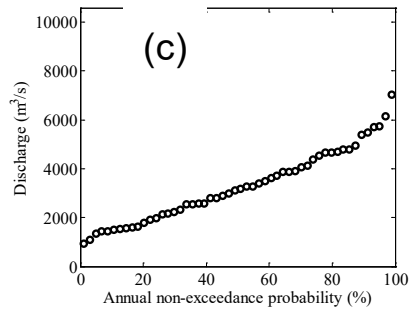
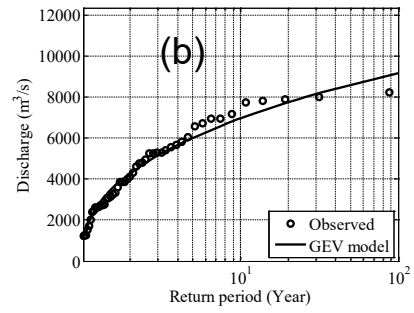
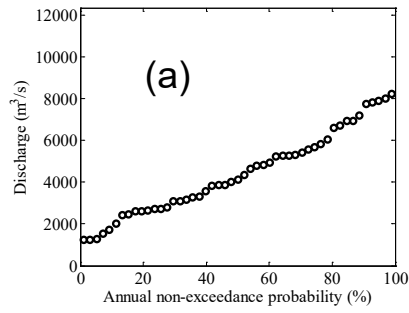


Figure 4.6: Annual non-exceedance probability and return period of maximum flow for (a-b) Sg. Kelantan, (c-d) Sg. Pahang, (e-f) Sg. Linggi, (g-h) Sg. Padas, and (i-j) Sg. Sadong.

Optimized GEV parameters of annual maximum flow for the selected river basins are listed in Table 4.12. For Sg. Kelantan, annual maximum flow revealed the Weibull distribution by the optimized value for ξ of -0.20. In addition, by providing optimized ξ of -0.09, annual maximum flow for Sg. Pahang also followed the Weibull distribution. Moreover, annual maximum flow for Sg. Linggi reflected the Fréchet distribution since ξ parameters of the data was 0.32. Sg. Padas and Sg. Sadong exhibited annual maximum flow following the Weibull and Fréchet distribution by the optimized values for ξ of -0.02 and 0.03, respectively.

Table 4.12: Optimized GEV parameters for Sg. Kelantan, Sg. Pahang, Sg. Linggi, Sg. Padas, and Sg. Sadong

Parameter	Sg. Kelantan	Sg. Pahang	Sg. Linggi	Sg. Padas	Sg. Sadong
μ	3,646.03	2,637.73	78.48	193.65	215.76
σ	1,829.86	1,264.04	34.18	65.63	83.92
ξ	-0.20	-0.09	0.32	-0.02	0.03

4.7 MINIMUM 1-DAY LOW FLOW ANALYSIS

4.7.1 MINIMUM 1-DAY LOW FLOW ANALYSIS: CASE I (RIVER WITH A DAM)

Minimum 1-day low flows at different return periods for selected river basins before and after the dam construction are presented in Table 4.13. Figures 4.7-4.9 show annual non-exceedance probability and return period of minimum 1-day low flow for the river basins before and after the dam construction.

The minimum 1-day low flows for Sg. Johor at return periods of 2, 5, 10, 20, 25, 50, and 100 year are 6.31, 4.22, 3.37, 2.82, 2.69, 2.36, and 2.13 m³/s, respectively. After the completion of dam, the corresponding discharges were 7.48, 5.03, 3.96, 3.23, 3.04, 2.57, and 2.23 m³/s. Higher minimum 1-day low flows after dam construction are possibly due to the regulation of streamflow. It is noted that the dam can be used for the control of river flow not only during flood season but also during drought season. During drought season, the water release from the dam was carried out to maintain the river flow for ecosystem health along the river.

It is obvious from Table 3.13 that Sg. Selangor displayed the minimum 1-day low flows before the presence of the dam at return periods of 2, 5, 10, 20, 25, 50, and

100 years of 15.81, 10.13, 7.03, 4.47, 3.73, 1.67, and 0.11 m³/s, respectively. After the dam completion, the corresponding values were 22.96, 18.96, 15.56, 11.59, 10.17, 5.19, and 0.78 m³/s. It is noted that increase in 1-day minimum flows after dam construction are probably due to the water release from the dam to maintain the river flow for ecosystem health along the river.

Sg. Muda displayed (see Table 3.13) the minimum 1-day low flows before the presence of the dam at return periods of 2, 5, 10, 20, 25, 50, and 100 years of 13.54, 7.62, 5.54, 4.31, 4.03, 3.38, and 2.98 m³/s, respectively. After the dam, the corresponding values were 19.21, 13.53, 12.20, 11.61, 11.51, 11.30, and 11.20 m³/s. It is found that increase in 1-day minimum flows after dam construction for Sg. Muda are possibly because of the water release from the dam to maintain the river flow for ecosystem health along the river. Moreover, 1-day low flows at Sg. Selangor are slightly higher compared to those at Sg. Muda, which is probably because of diversion of water by the dam in Sg. Muda.

Table 4.13: Minimum 1-day low flows at different return periods for selected river basins before and after the dam construction

T (year)	Sg. Johor		Sg. Selangor		Sg. Muda	
	Minimum 1-day low flow before dam (m ³ /s)	Minimum 1-day low flow after dam (m ³ /s)	Minimum 1-day low flow before dam (m ³ /s)	Minimum 1-day low flow after dam (m ³ /s)	Minimum 1-day low flow before dam (m ³ /s)	Minimum 1-day low flow after dam (m ³ /s)
2	6.31	7.48	15.81	22.96	13.54	19.21
5	4.22	5.03	10.13	18.96	7.62	13.53
10	3.37	3.96	7.03	15.56	5.54	12.20
20	2.82	3.23	4.47	11.59	4.31	11.61
25	2.69	3.04	3.73	10.17	4.03	11.51
50	2.36	2.57	1.67	5.19	3.38	11.30
100	2.13	2.23	0.11	0.78	2.98	11.20

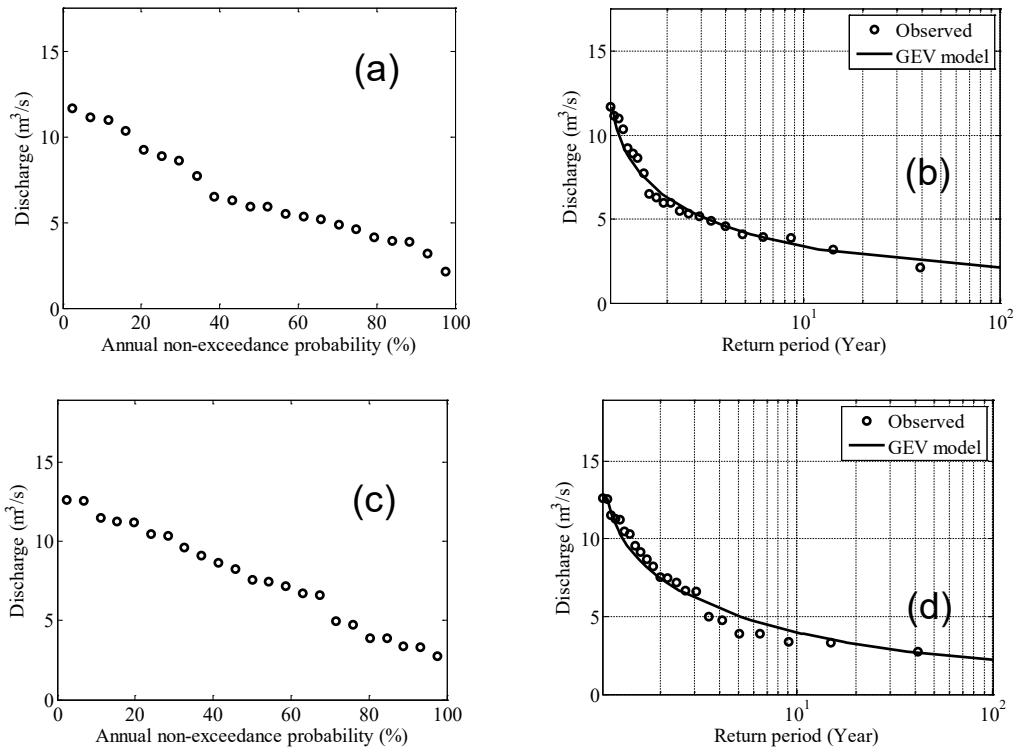


Figure 4.7: Annual non-exceedance probability and return period of minimum 1-day low flow for Sg. Johor (a-b) before and (c-d) after the dam construction

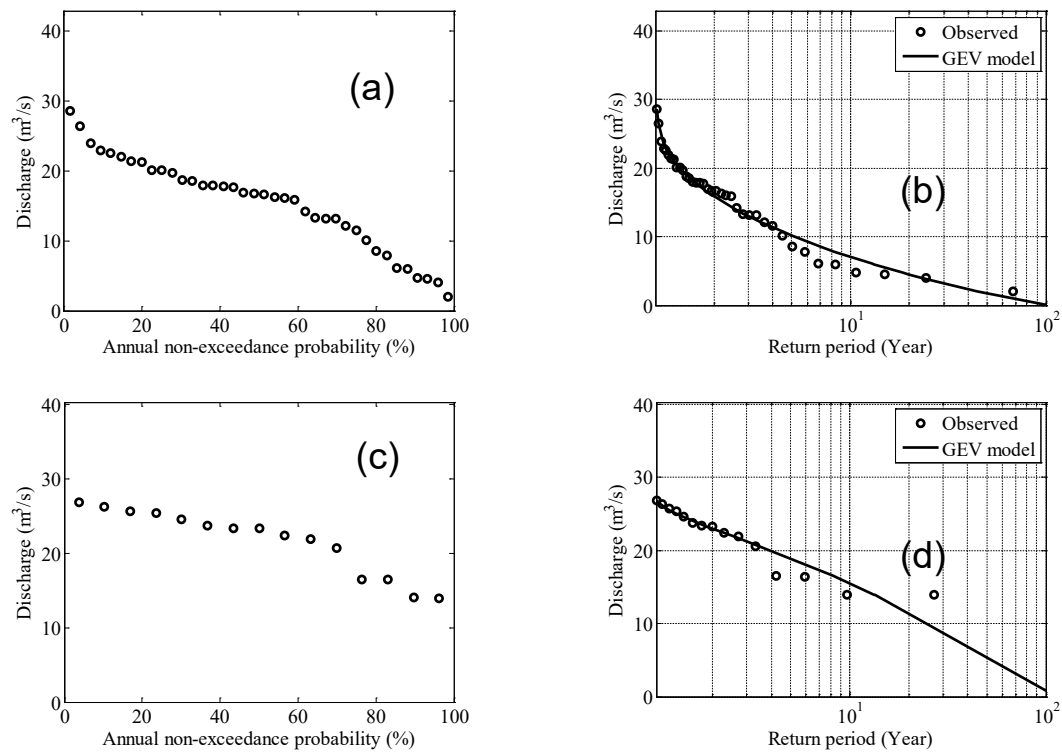


Figure 4.8: Annual exceedance probability and return period of minimum 1-day low flow for Sg. Selangor (a-b) before and (c-d) after the dam construction

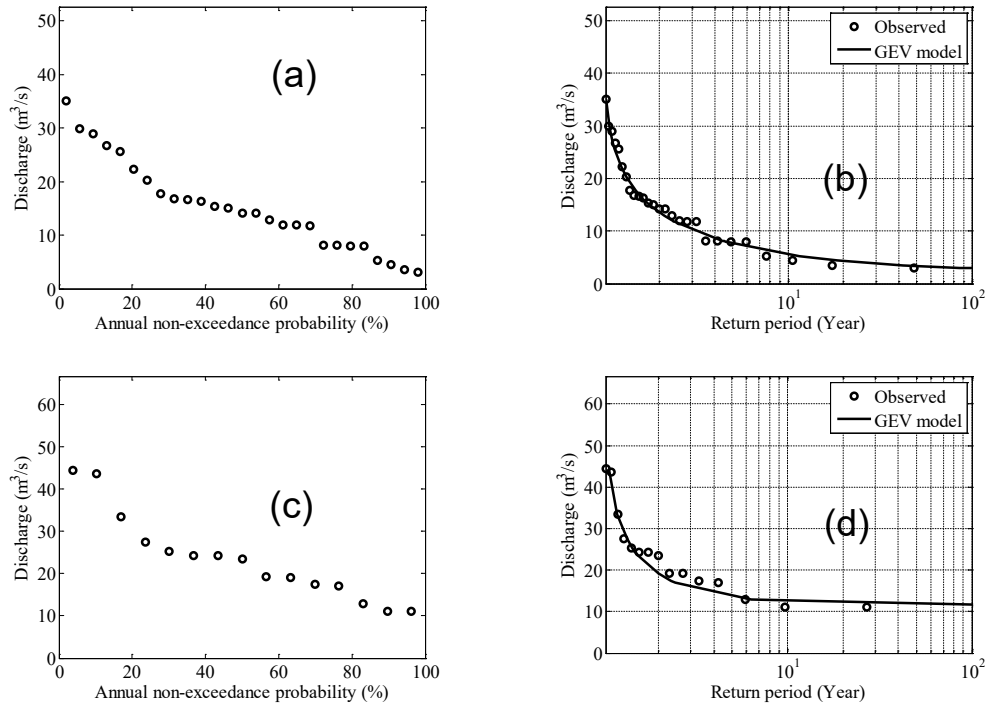


Figure 4.9: Annual exceedance probability and return period of minimum 1-day low flow for Sg. Muda (a-b) before and (c-d) after the dam construction

The optimized GEV parameters for the analysis are listed in Table 4.14. It is noted that the minimum 1-day low flow before and after the dam construction reflected the Weibull distribution because of the negative value of the optimized ξ parameters. The minimum 1-day low flow for Sg. Selangor before and after the dam reflected the Weibull and Fréchet distributions, respectively. The minimum 1-day low flow for Sg. Muda before and after the dam reflected the Weibull distribution because of the negative value of the optimized ξ parameters.

Table 4.14: Optimized GEV parameters for selected river basins before and after the dam construction

Parameter	Sg. Johor		Sg. Selangor		Sg. Muda	
	Minimum 1-day low flow before dam (m³/s)	Minimum 1-day low flow after dam (m³/s)	Minimum 1-day low flow before dam (m³/s)	Minimum 1-day low flow after dam (m³/s)	Minimum 1-day low flow before dam (m³/s)	Minimum 1-day low flow after dam (m³/s)
μ	7.29	8.58	17.95	24.02	16.61	23.07
σ	2.96	3.25	6.04	2.74	9.43	12.75
ξ	-0.52	-0.45	-0.20	0.27	-0.66	-1.07

4.7.2 MINIMUM 1-DAY LOW FLOW ANALYSIS: CASE II (RIVER WITHOUT A DAM)

Table 4.15 presents the minimum 1-day low flow for the selected rivers. As expected, the bigger return period produced the smaller low flow (see Figure 4.10). For example, for Sg. Kelantan, the minimum 1-day low flow for 2 and 100 years are 120.8 and 10.1 m³/s, respectively. The minimum 1-day low flow values for other river basins are completely presented in Table 4.15.

Table 4.15: Minimum 1-day low flows at different return periods for the selected rivers

T (year)	Sg. Kelantan (m ³ /s)	Sg. Pahang (m ³ /s)	Sg. Linggi (m ³ /s)	Sg. Padas (m ³ /s)	Sg. Sadong (m ³ /s)
2	120.83	144.61	3.41	23.30	5.37
5	70.00	85.34	1.59	8.21	2.89
10	47.61	60.79	1.08	4.51	2.35
20	31.93	44.37	0.83	2.83	2.13
25	27.88	40.26	0.78	2.51	2.09
50	17.62	30.14	0.68	1.89	2.02
100	10.06	23.01	0.62	1.58	1.98

Optimized GEV parameters of the minimum 1-day low flow for the selected river basins are listed in Table 4.16. It was found that 1-day minimum low flow for Sg. Kelantan revealed the Weibull distribution because of the negative value (-0.43) of the optimized ξ parameter. In addition, 1-day minimum low flow for Sg. Pahang, Sg. Linggi, and Sg. Padas also reflected the Weibull distribution with optimized ξ parameters of -0.49, -0.90, and -1.02, respectively. Moreover, 1-day minimum low flow for Sg. Sadong reflected the Weibull distribution with optimized ξ parameter of -1.14.

Table 4.16: Optimized GEV parameters of 1-day minimum low flow for Sg. Kelantan, Sg. Pahang, Sg. Linggi, Sg. Padas, and Sg. Sadong

Parameter	Sg. Kelantan	Sg. Pahang	Sg. Linggi	Sg. Padas	Sg. Sadong
μ	143.27	171.97	4.53	33.29	7.16
σ	66.14	81.57	3.56	32.68	5.95
ξ	-0.43	-0.49	-0.90	-1.02	-1.14

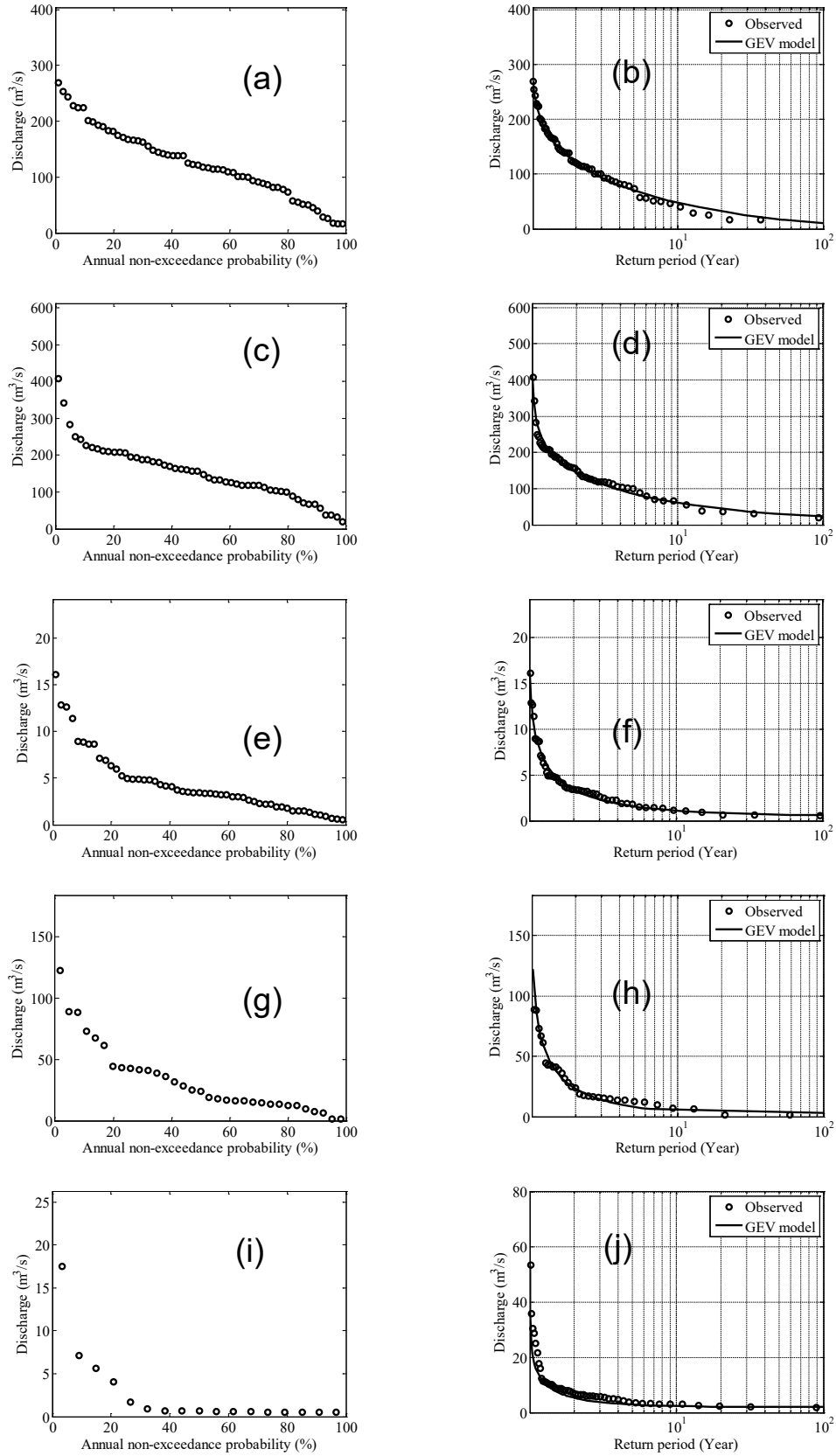


Figure 4.10: Non-exceedance probability and return period of the minimum 1-day low flow for (a-b) Sg. Kelantan, (c-d) Sg. Pahang, (e-f) Sg. Linggi, (g-h) Sg. Padas, and (i-j) Sg. Sadong

4.8 MINIMUM 7-DAY LOW FLOW ANALYSIS

4.8.1 MINIMUM 7-DAY LOW FLOW ANALYSIS: CASE I (RIVER WITH A DAM)

Minimum 7-day low flows at different return periods for selected river basins are presented in Table 4.17. Figures 4.11-4.13 show annual non-exceedance probability and return period of minimum 7-day low flow for the river basins before and after the dam construction.

For Sg. Johor, the minimum 7-day low flows at return periods of 2, 5, 10, 20, 25, 50, and 100 years are 7.14, 4.77, 3.83, 3.21, 3.06, 2.70, and 2.45 m³/s, respectively. After the completion of dam, the corresponding values were 10.01, 6.81, 4.95, 3.33, 2.86, 1.47, and 0.23 m³/s. For the minimum 7-day low flow for Sg. Selangor before the presence of the dam at return periods of 2, 5, 10, 20, 25, 50, and 100 years, the values were 17.02, 10.81, 7.42, 4.60, 3.79, 1.51, and 0.45 m³/s, respectively. After the dam, the corresponding values were 24.02, 19.24, 15.66, 11.89, 10.62, 6.46, and 1.94 m³/s. Increase in 7-day minimum flows after dam construction are probably due to the water release from the dam to maintain the river flow for ecosystem health along the river

The minimum 7-day low flow for Sg. Muda before the presence of the dam for at return periods of 2, 5, 10, 20, 25, 50, and 100, the values were 17.14, 9.75, 7.70, 6.67, 6.46, 6.03, and 5.80 m³/s, respectively. After the dam, the corresponding values were 25.05, 17.99, 15.10, 13.17, 12.69, 11.52, and 10.69 m³/s. This study found that higher 7-day minimum flows after dam construction for Sg. Muda are probably due to the water release from the dam to maintain the river flow for ecosystem health along the river. Although area of the river at Sg. Muda is higher than Sg. Selangor, 7-day low flows at Sg. Selangor are quite similar to those at Sg. Muda, which is probably because of diversion of water by the dam in Sg. Muda.

Table 4.17: Minimum 7-day low flows at different return periods for selected river basins before and after the dam construction

T (year)	Sg. Johor		Sg. Selangor		Sg. Muda	
	Minimum 7-day low flow before dam (m ³ /s)	Minimum 7-day low flow after dam (m ³ /s)	Minimum 7-day low flow before dam (m ³ /s)	Minimum 7-day low flow after dam (m ³ /s)	Minimum 7-day low flow before dam (m ³ /s)	Minimum 7-day low flow after dam (m ³ /s)
2	7.14	10.01	17.02	24.02	17.14	25.05
5	4.77	6.81	10.81	19.24	9.75	17.99
10	3.83	4.95	7.42	15.66	7.70	15.10
20	3.21	3.33	4.60	11.89	6.67	13.17
25	3.06	2.86	3.79	10.62	6.46	12.69
50	2.70	1.47	1.51	6.46	6.03	11.52
100	2.45	0.23	0.45	1.94	5.80	10.69

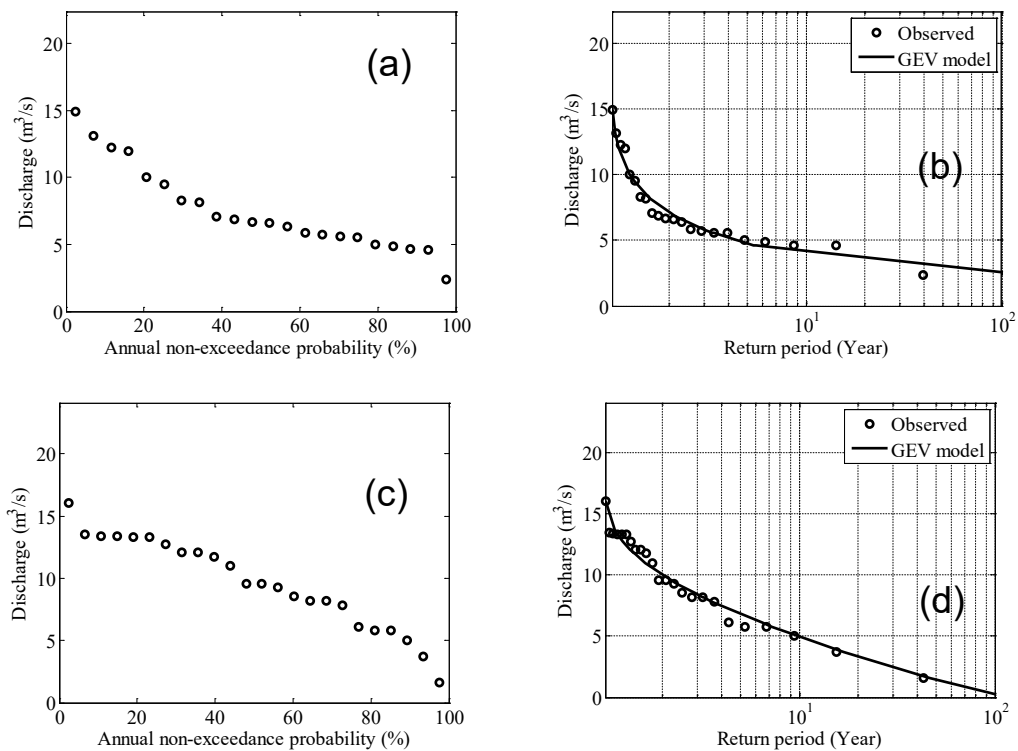


Figure 4.11: Annual non-exceedance probability and return period of the minimum 7-day low flow for Sg. Johor (a-b) before and (c-d) after the dam construction

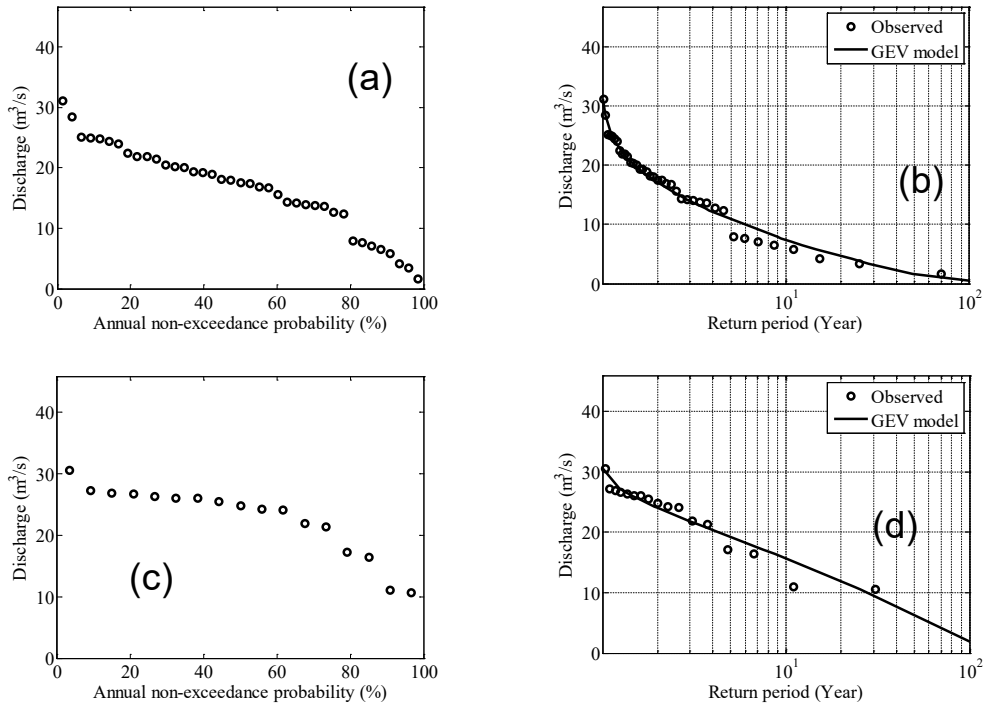


Figure 4.12: Annual exceedance probability and return period of the minimum 7-day low flow for Sg. Selangor (a-b) before the dam and (c-d) after the dam construction

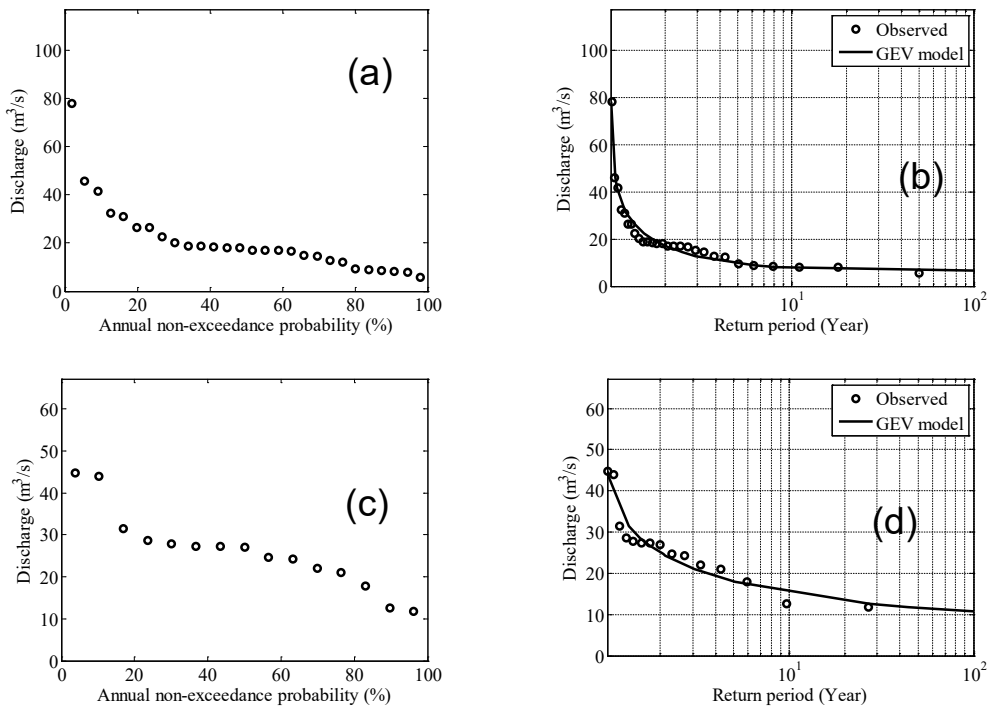


Figure 4.13: Annual exceedance probability and return period of the minimum 7-day low flow for Sg. Muda (a-b) before the dam and (c-d) after the dam construction

The optimized GEV parameters for the analysis are listed in Table 4.18. The minimum 7-day low flow for Sg. Johor before and after the dam construction followed the Weibull distribution. For Sg. Selangor, the minimum 7-day low flow before and after the dam revealed the Weibull and Fréchet distributions, respectively. In addition, the minimum 7-day low flow for Sg. Muda before and after the dam exhibited Weibull distribution.

Table 4.18: Optimized GEV parameters for selected river basins before and after the dam construction

Parameter	Sg. Johor		Sg. Selangor		Sg. Muda	
	Minimum 7-day low flow before dam (m ³ /s)	Minimum 7-day low flow after dam (m ³ /s)	Minimum 7-day low flow before dam (m ³ /s)	Minimum 1-day low flow after dam (m ³ /s)	Minimum 7-day low flow before dam (m ³ /s)	Minimum 7-day low flow after dam (m ³ /s)
μ	8.27	11.16	19.35	25.42	21.63	28.33
σ	3.38	3.22	6.59	3.73	14.37	9.79
ξ	-0.53	-0.14	-0.20	0.13	-0.89	-0.50

4.8.2 MINIMUM 7-DAY LOW FLOW ANALYSIS: CASE II (RIVER WITHOUT A DAM)

Table 4.19 presents the minimum 7-day low flow for the selected river basins at different return periods. Sg. Kelantan exhibited 7-day minimum low flow at return periods of 2, 5, 10, 20, 25, 50, and 100 of 132.07, 79.94, 57.17, 41.32, 37.25, 26.97, and 19.46 m³/s, respectively (see Figure 4.14).

Table 4.19: Minimum 7-day low flows at different return periods for the rivers

T (year)	Sg. Kelantan (m ³ /s)	Sg. Pahang (m ³ /s)	Sg. Linggi (m ³ /s)	Sg. Padas (m ³ /s)	Sg. Sadong (m ³ /s)
2	132.07	162.67	4.13	35.99	12.06
5	79.94	100.87	1.98	16.70	5.27
10	57.17	74.43	1.34	10.82	3.71
20	41.32	56.30	1.01	7.69	3.03
25	37.25	51.69	0.94	7.03	2.90
50	26.97	40.16	0.79	5.59	2.66
100	19.46	31.85	0.70	4.78	2.55

Sg. Pahang exhibited 7-day minimum low flow at return periods of 2, 5, 10, 20, 25, 50, and 100 of 162.67, 100.87, 74.43, 56.30, 51.69, 40.16, and 31.85 m³/s, respectively. Sg. Linggi exhibited 7-day minimum low flow at return periods of 2, 5, 10, 20, 25, 50, and 100 of 4.13, 1.98, 1.34, 1.01, 0.94, 0.79, and 0.70 m³/s, respectively. Sg. Padas exhibited 7-day minimum low flow at return periods of 2, 5, 10, 20, 25, 50, and 100 of 35.99, 16.70, 10.82, 7.69, 7.03, 5.59, and 4.78 m³/s, respectively. Sg. Padas indicated 7-day minimum low flow at return periods of 2, 5, 10, 20, 25, 50, and 100 of 12.06, 5.27, 3.71, 3.03, 2.90, 2.66, and 2.55 m³/s, respectively.

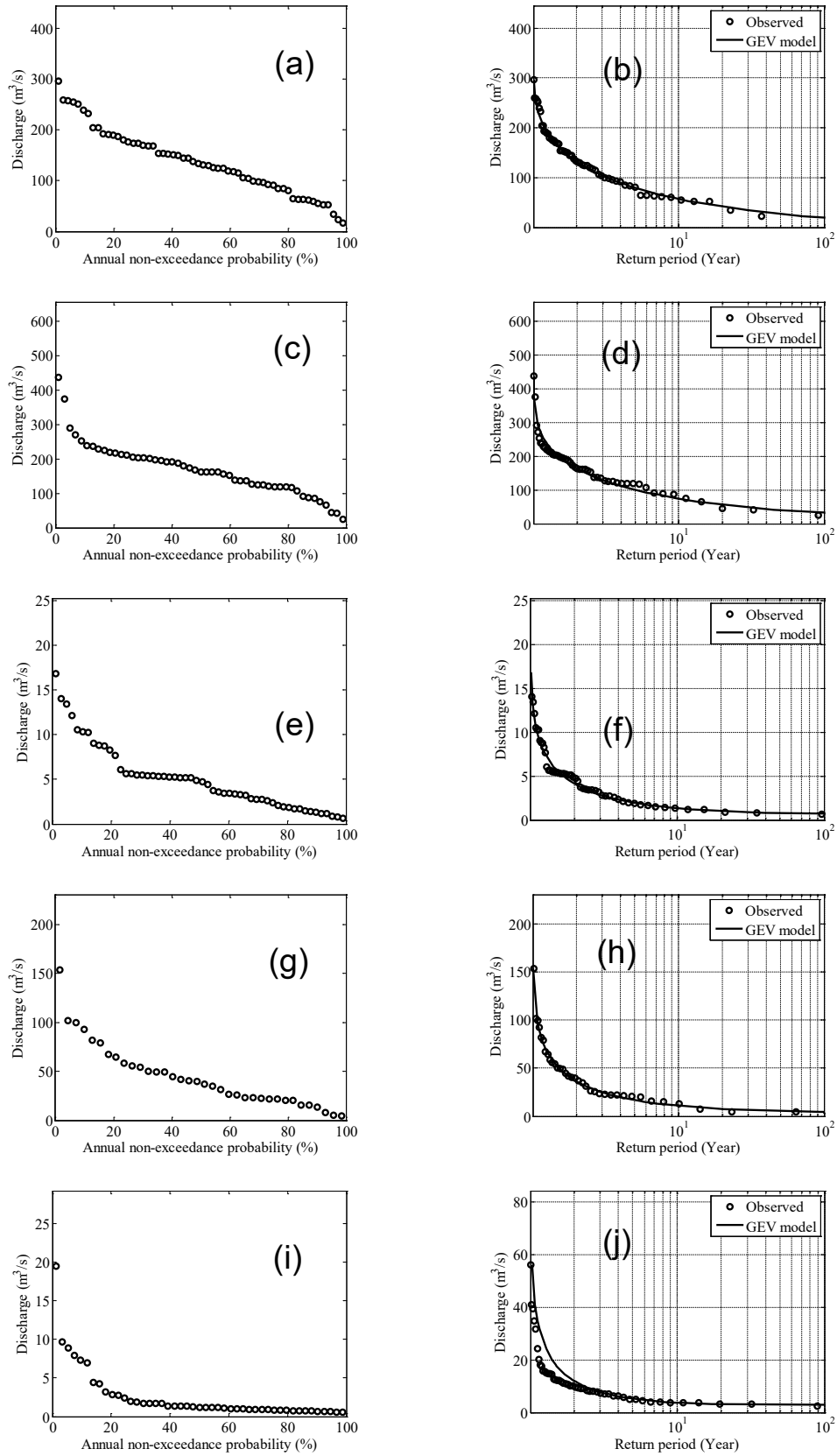


Figure 4.14: Non-exceedance probability and return period of the minimum 7-day low flow for (a-b) Sg. Kelantan, (c-d) Sg. Pahang, (e-f) Sg. Linggi, (g-h) Sg. Padas, and (i-j) Sg. Sadong

Optimized GEV parameters of the minimum 7-day low flow for the selected river basins are listed in Table 4.20. For Sg. Kelantan, 7-day minimum low flow revealed the Weibull distribution by the optimized value for ξ of -0.44. In addition, by providing optimized ξ of -0.46, 7-day minimum low flow for Sg. Pahang also followed the Weibull distribution. Moreover, 7-day minimum low flow for Sg. Linggi, Sg. Padas, and Sg. Sadong reflected the Weibull distribution since ξ parameters of the data were -0.83, -0.80, and -1.08, respectively.

Table 4.20: Optimized GEV parameters of 7-day minimum low flow for Sg. Kelantan, Sg. Pahang, Sg. Linggi, Sg. Padas, and Sg. Sadong

Parameter	Sg. Kelantan	Sg. Pahang	Sg. Linggi	Sg. Padas	Sg. Sadong
μ	155.24	190.53	5.39	47.03	16.73
σ	68.39	82.57	3.98	34.79	15.45
ξ	-0.44	-0.46	-0.83	-0.80	-1.08

4.9 FLOW DURATION CURVE

The flow duration curves for all the river basins are plotted in Figure 4.15 and summarized in Table 4.21. All the curves show similar pattern but the values are generally influenced by the catchment size. For example, for the biggest catchment of Sg. Pahang, 95% of the flow data is greater than 141.4 m³/s whereas the corresponding value for the smallest basin, Sg. Linggi, is 2.24 m³/s.

Table 4.21: Percentage exceedance for the selected rivers

River	Percentage Exceedance (%)						
	5	10	25	50	75	90	95
Sg. Muda (m ³ /s)	230.80	162.9	94.73	53.87	32.58	19.73	14.3
Sg. Kelantan (m ³ /s)	1,179.92	848.45	538.92	318.30	215.10	149.6	115
Sg. Pahang (m ³ /s)	1,450.36	1,066.65	659.79	398.14	250.49	177.89	141.4
Sg. Johor (m ³ /s)	83.58	60.88	38.05	23.32	14.73	9.61	6.64
Sg. Linggi (m ³ /s)	47.24	34.59	21.10	12.69	6.98	3.61	2.24
Sg. Selangor (m ³ /s)	141.15	111.84	71.38	43.60	28.14	19.77	15.48
Sg. Padas (m ³ /s)	628.00	488.96	306.15	173.39	95.18	51.93	35.99
Sg. Sadong (m ³ /s)	179.16	143.87	85.11	43.91	22.22	12.07	8.27

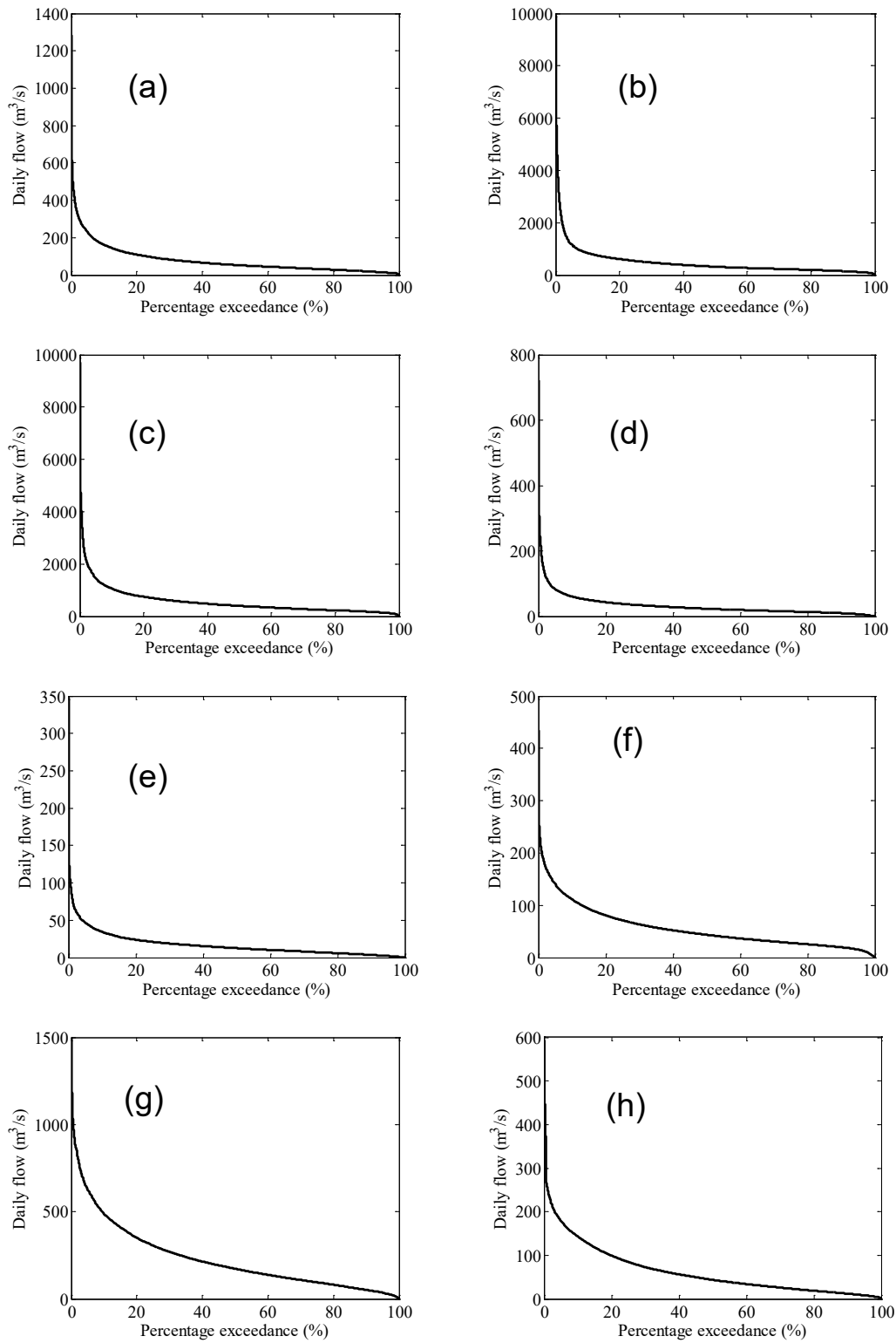


Figure 4.15: Flow duration curves for (a) Sg. Muda, (b) Sg. Kelantan, (c) Sg. Pahang, (d) Sg. Johor, (e) Sg. Linggi, (f) Sg. Selangor, (g) Sg. Padas, and (h) Sg. Sadong

4.10 INTRA-ANNUAL AND INTER-ANNUAL ANALYSIS

Flows at percentiles 5, 10, 25, 50, 75, 90, and 95% for all selected river basins are presented in Tables 4.22-4.29 and are shown in Figures 4.16-4.17. Intra-annual flow variability was analyzed based on mean monthly flow (ordinary scale). It shows the seasonal pattern of the flow regime within a year derived from years with complete flow data.

For example, flows at P5 for Sg. Muda varied with the month ranging from 8 to 73 m³/s with the lowest and highest values were at February and October, respectively. Flows at P95 also varied from 50 to 351 m³/s. For a comprehensive overview, flows at P5, P10, P25, P50, P75, P90, and P95 for other rivers are presented in Tables 4.22-4.29.

Table 4.22: Flows at P5, P10, P25, P50, P75, P90, and P95 for Sg. Muda

Month	P5 (m ³ /s)	P10 (m ³ /s)	P25 (m ³ /s)	P50 (m ³ /s)	P75 (m ³ /s)	P90 (m ³ /s)	P95 (m ³ /s)
Jan	14.41	17.88	29.92	49.09	69.34	83.34	101.72
Feb	8.22	10.09	20.61	35.29	39.30	47.43	50.06
Mar	11.25	15.36	25.83	46.25	58.52	74.05	122.41
Apr	18.61	25.09	37.10	63.48	107.35	164.86	198.50
May	20.19	30.11	43.16	64.34	81.65	125.14	133.63
Jun	16.49	21.18	40.13	54.64	60.61	70.52	80.40
Jul	19.33	27.71	36.55	50.68	66.48	85.60	127.66
Aug	24.91	36.95	47.46	62.25	79.55	97.42	142.05
Sep	49.98	55.66	64.36	97.46	110.75	119.79	121.67
Oct	73.78	89.97	97.77	126.80	184.56	327.24	351.75
Nov	71.73	77.25	92.20	142.09	194.30	258.50	305.62
Dec	34.27	35.66	56.19	75.05	125.32	175.38	204.94

Table 4.23: Flows at P5, P10, P25, P50, P75, P90, and P95 for Sg. Kelantan

Month	P5 (m ³ /s)	P10 (m ³ /s)	P25 (m ³ /s)	P50 (m ³ /s)	P75 (m ³ /s)	P90 (m ³ /s)	P95 (m ³ /s)
Jan	297.74	410.94	481.45	612.96	977.47	1,314.89	1,886.52
Feb	160.40	164.53	228.98	294.44	359.69	411.92	612.43
Mar	90.30	139.19	183.98	242.44	283.43	490.15	543.83
Apr	63.23	127.79	158.88	228.56	253.96	378.32	470.50
May	121.78	140.59	182.58	275.74	377.12	418.35	470.81
Jun	114.49	124.05	168.02	257.89	360.26	414.97	420.32
Jul	91.86	119.52	151.28	240.06	343.95	417.78	501.88
Aug	103.43	125.81	151.58	265.45	373.88	443.48	502.73
Sep	145.03	161.70	243.77	321.85	438.20	584.78	729.52
Oct	202.63	252.20	346.83	521.33	643.51	696.24	719.11
Nov	247.41	277.05	514.37	748.96	846.68	1,125.52	2,004.99
Dec	577.74	635.47	890.87	1,147.32	1,765.60	3,083.31	4,314.25

Table 4.24: Flows at P5, P10, P25, P50, P75, P90, and P95 for Sg. Pahang

Month	P5 (m ³ /s)	P10 (m ³ /s)	P25 (m ³ /s)	P50 (m ³ /s)	P75 (m ³ /s)	P90 (m ³ /s)	P95 (m ³ /s)
Jan	304.04	349.15	460.73	635.80	912.50	1,570.97	1,982.17
Feb	127.25	152.67	224.19	301.13	450.29	862.96	1,236.82
Mar	121.52	155.65	197.17	291.21	451.71	1,131.53	1,927.19
Apr	132.31	148.17	262.34	344.56	658.61	843.40	1,394.56
May	177.38	222.16	285.10	488.45	726.08	1,169.52	1,290.04
Jun	154.74	203.39	246.81	351.17	552.47	665.90	887.94
Jul	154.46	185.99	240.81	286.46	488.83	684.85	736.39
Aug	162.60	182.02	234.06	296.53	398.59	659.31	836.83
Sep	149.97	199.14	269.87	387.41	501.92	703.43	711.39
Oct	308.15	337.48	511.15	635.29	951.47	1,182.88	1,361.31
Nov	441.85	508.39	576.14	800.81	1,317.22	1,593.48	1,869.82
Dec	498.24	636.46	723.95	1,209.68	1,541.63	1,908.56	2,658.65

Table 4.25: Flows at P5, P10, P25, P50, P75, P90, and P95 for Sg. Johor

Month	P5 (m ³ /s)	P10 (m ³ /s)	P25 (m ³ /s)	P50 (m ³ /s)	P75 (m ³ /s)	P90 (m ³ /s)	P95 (m ³ /s)
Jan	13.53	16.23	22.24	37.62	61.91	74.49	90.62
Feb	9.11	12.10	13.74	21.03	27.27	57.13	107.15
Mar	5.15	6.89	15.38	25.83	35.86	49.36	72.16
Apr	4.78	11.95	19.95	27.29	41.45	51.51	58.37
May	9.67	14.09	22.32	25.64	37.88	54.33	60.21
Jun	8.97	13.19	15.12	20.19	28.74	39.30	44.95
Jul	5.74	8.47	13.44	19.90	24.43	33.02	39.73
Aug	6.56	12.35	19.43	21.52	28.87	43.52	45.95
Sep	9.01	12.70	19.01	28.87	31.47	43.76	59.75
Oct	14.73	16.34	21.20	28.57	35.18	51.81	65.15
Nov	12.49	17.68	24.30	37.55	51.59	65.59	75.01
Dec	12.54	18.67	25.70	35.00	69.80	138.70	161.69

Table 4.26: Flows at P5, P10, P25, P50, P75, P90, and P95 for Sg. Linggi

Month	P5 (m ³ /s)	P10 (m ³ /s)	P25 (m ³ /s)	P50 (m ³ /s)	P75 (m ³ /s)	P90 (m ³ /s)	P95 (m ³ /s)
Jan	2.53	2.85	7.64	13.05	19.74	25.78	27.00
Feb	1.33	1.67	5.42	9.34	13.07	21.28	21.85
Mar	3.48	4.53	6.22	12.67	20.04	26.45	30.16
Apr	4.58	6.01	13.48	19.24	27.18	32.35	49.46
May	9.08	9.40	11.97	18.22	23.59	27.62	30.57
Jun	5.11	5.80	8.68	10.21	15.81	19.54	20.81
Jul	3.78	4.25	6.60	10.17	11.74	16.53	17.11
Aug	2.93	3.26	6.09	9.53	15.04	19.89	26.99
Sep	3.43	3.67	6.92	14.08	20.19	25.35	28.15
Oct	6.99	9.11	12.62	18.65	25.08	29.25	31.56
Nov	13.02	14.20	15.68	23.36	36.33	45.24	54.68
Dec	7.32	7.84	14.11	24.36	31.81	38.46	39.84

Table 4.27: Flows at P5, P10, P25, P50, P75, P90, and P95 for Sg. Selangor

Month	P5 (m ³ /s)	P10 (m ³ /s)	P25 (m ³ /s)	P50 (m ³ /s)	P75 (m ³ /s)	P90 (m ³ /s)	P95 (m ³ /s)
Jan	25.20	26.54	39.65	44.86	80.89	100.70	116.97
Feb	17.32	21.38	24.16	36.07	42.29	62.19	67.46
Mar	18.87	24.82	31.75	42.05	60.56	68.05	90.64
Apr	25.30	34.60	51.42	68.04	81.11	98.72	108.73
May	39.00	44.84	51.07	80.66	101.46	113.85	122.27
Jun	21.99	25.73	36.44	41.83	49.37	68.72	73.20
Jul	14.19	18.90	26.29	34.76	42.55	55.56	61.11
Aug	10.61	16.00	26.50	32.90	43.38	48.51	51.23
Sep	21.01	22.26	29.56	40.60	45.21	61.27	91.86
Oct	30.93	33.87	52.49	67.66	91.33	103.11	107.91
Nov	58.97	66.81	72.70	95.88	132.49	147.97	166.11
Dec	39.89	46.35	58.31	88.41	105.79	136.27	162.41

Table 4.28: Flows at P5, P10, P25, P50, P75, P90, and P95 for Sg. Padas

Month	P5 (m ³ /s)	P10 (m ³ /s)	P25 (m ³ /s)	P50 (m ³ /s)	P75 (m ³ /s)	P90 (m ³ /s)	P95 (m ³ /s)
Jan	57.37	77.25	163.71	233.06	321.42	482.11	504.40
Feb	42.39	49.07	86.39	176.91	306.34	381.76	618.56
Mar	41.92	54.92	83.56	135.43	230.71	519.62	610.23
Apr	33.88	51.16	116.75	186.91	308.79	466.31	488.95
May	48.56	97.86	155.72	217.35	320.23	426.28	471.69
Jun	51.24	68.96	101.98	222.24	292.70	498.05	533.53
Jul	54.25	64.05	92.96	165.38	255.14	348.06	384.01
Aug	26.80	44.35	93.75	127.22	201.00	327.36	355.36
Sep	71.63	85.09	120.11	195.47	284.41	322.38	356.96
Oct	89.30	127.16	162.66	223.72	301.96	389.48	455.06
Nov	122.62	143.89	187.29	240.47	367.19	490.14	521.42
Dec	73.74	120.18	194.69	314.19	390.49	495.64	562.25

Table 4.29: Flows at P5, P10, P25, P50, P75, P90, and P95 for Sg. Sadong

Month	P5 (m ³ /s)	P10 (m ³ /s)	P25 (m ³ /s)	P50 (m ³ /s)	P75 (m ³ /s)	P90 (m ³ /s)	P95 (m ³ /s)
Jan	59.26	73.19	84.48	104.55	132.11	168.26	200.44
Feb	19.76	24.78	52.58	81.42	114.87	160.53	169.44
Mar	18.61	30.24	43.85	74.56	104.13	111.90	130.79
Apr	28.86	34.54	42.03	56.56	77.47	99.11	107.76
May	24.31	30.39	41.61	47.96	69.03	78.81	111.60
Jun	13.17	15.41	19.79	27.73	37.88	69.92	73.12
Jul	8.07	10.97	16.89	26.94	38.47	53.75	66.38
Aug	9.58	11.77	17.26	23.73	50.02	65.49	79.80
Sep	5.31	8.00	18.79	36.91	52.06	78.44	102.63
Oct	16.87	20.80	33.46	45.53	62.62	86.66	124.93
Nov	23.69	26.91	43.12	69.99	91.35	130.54	145.45
Dec	37.76	56.29	73.68	90.08	113.94	143.95	179.01

In general, mean monthly pattern shows either single peak, double peak, and consistency flows. The single peak was represented by Sg. Kelantan, Sg. Johor, and Sg. Sadong. Double peak pattern can be observed for Sg. Muda, Sg. Linggi, Sg. Selangor, and Sg. Pahang. Sg. Padas shows a rather consistent flow pattern.

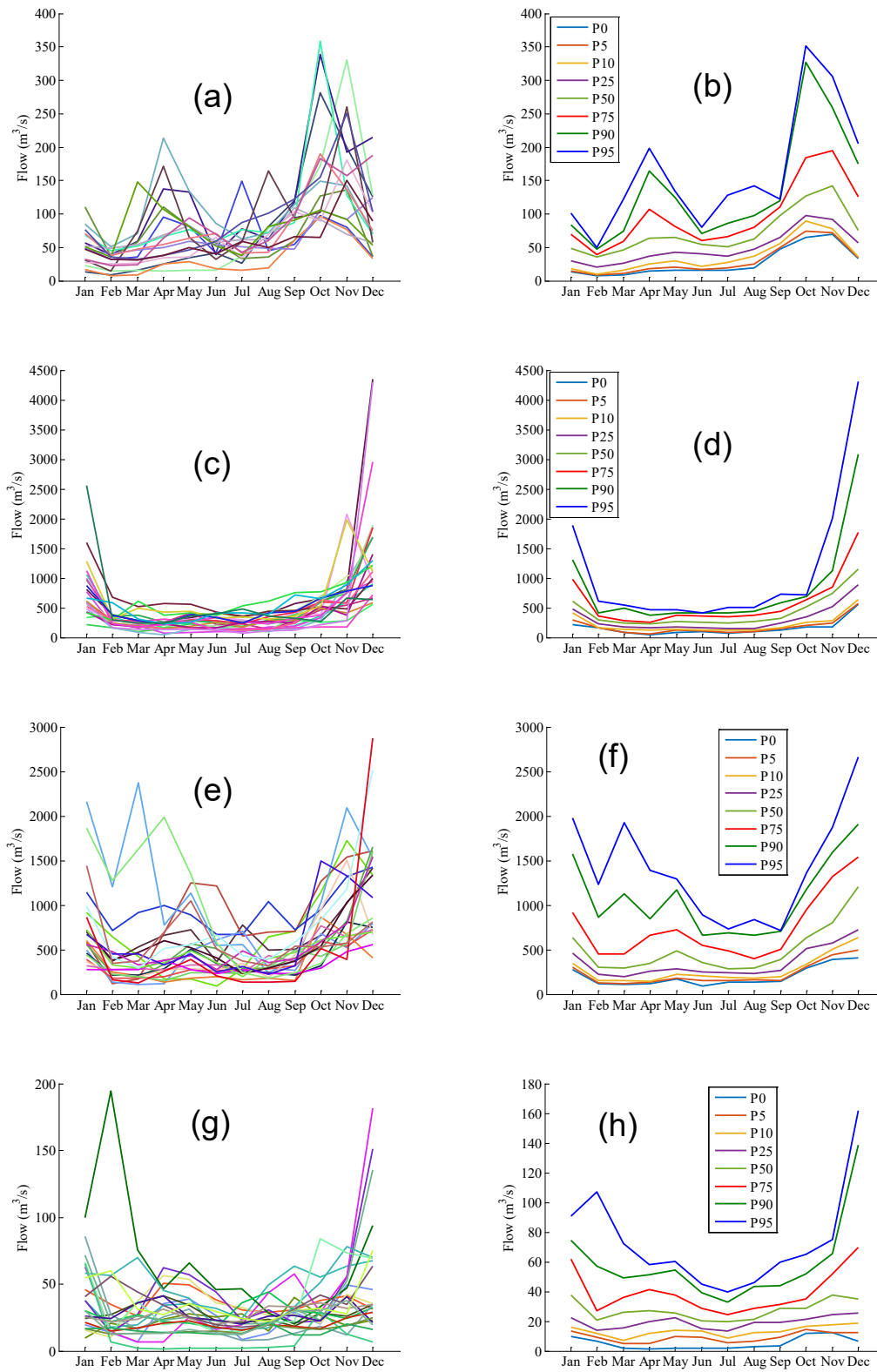


Figure 4.16: Intra and inter-annual range variability of flows for (a-b) Sg. Muda, (c-d) Sg. Kelantan, (e-f) Sg. Pahang, and (g-h) Sg. Johor

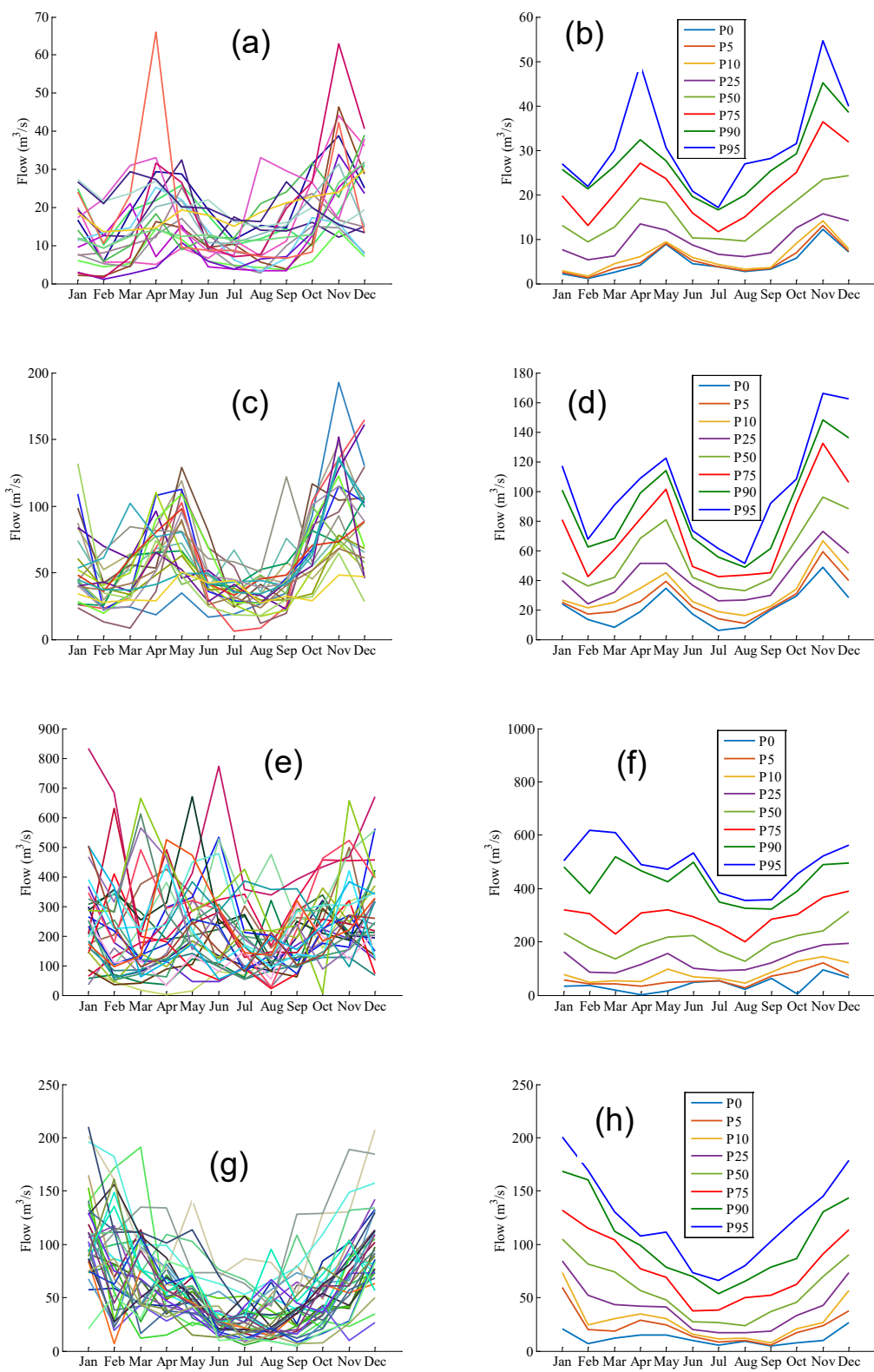


Figure 4.17: Intra and inter-annual range variability of flows for (a-b) Sg. Linggi, (c-d) Sg. Selangor, (e-f) Sg. Padas, and (g-h) Sg. Sadong.

4.11 HYDROLOGIC CONDITIONS

Tables 4.30-4.37 list range of flows at percentiles 0, 5, 10, and 75, which represent very dry, dry, average, and wet conditions, respectively. It is noted that the flow values for each flow category is different for each catchment. For example, very dry category for Sg. Muda ranges from 9 to 69 m³/s while for Sg. Kelantan it ranges from 43 to 559 m³/s. For the same category in the same river basin, the flow values also vary with month. More detail of range of flows at percentiles 0, 5, 10, and 75 are given in Tables 4.30-4.37 and Figure 4.18.

Table 4.30: Range of flows at percentiles 0, 5, 10, and 75 for Sg. Muda

Month	P0 (m ³ /s)	P10 (m ³ /s)	P25 (m ³ /s)	P75 (m ³ /s)
Jan	13.28	17.88	29.92	69.34
Feb	7.75	10.09	20.61	39.30
Mar	9.10	15.36	25.83	58.52
Apr	15.18	25.09	37.10	107.35
May	15.41	30.11	43.16	81.65
Jun	15.44	21.18	40.13	60.61
Jul	15.57	27.71	36.55	66.48
Aug	19.21	36.95	47.46	79.55
Sep	47.52	55.66	64.36	110.75
Oct	65.25	89.97	97.77	184.56
Nov	69.14	77.25	92.20	194.30
Dec	33.63	35.66	56.19	125.32

Table 4.31: Range of flows at percentiles 0, 5, 10, and 75 for Sg. Kelantan

Month	P0 (m ³ /s)	P10 (m ³ /s)	P25 (m ³ /s)	P75 (m ³ /s)
Jan	218.04	410.94	481.45	977.47
Feb	159.80	164.53	228.98	359.69
Mar	83.23	139.19	183.98	283.43
Apr	43.53	127.79	158.88	253.96
May	90.94	140.59	182.58	377.12
Jun	96.99	124.05	168.02	360.26
Jul	72.87	119.52	151.28	343.95
Aug	98.12	125.81	151.58	373.88
Sep	121.97	161.70	243.77	438.20
Oct	172.65	252.20	346.83	643.51
Nov	179.29	277.05	514.37	846.68
Dec	559.18	635.47	890.87	1,765.60

Table 4.32: Range of flows at percentiles 0, 5, 10, and 75 for Sg. Pahang

Month	P0 (m ³ /s)	P10 (m ³ /s)	P25 (m ³ /s)	P75 (m ³ /s)
Jan	277.18	349.15	460.73	912.50
Feb	119.31	152.67	224.19	450.29
Mar	113.45	155.65	197.17	451.71
Apr	120.87	148.17	262.34	658.61
May	174.91	222.16	285.10	726.08
Jun	92.83	203.39	246.81	552.47
Jul	136.35	185.99	240.81	488.83
Aug	138.95	182.02	234.06	398.59
Sep	141.34	199.14	269.87	501.92
Oct	295.81	337.48	511.15	951.47
Nov	392.94	508.39	576.14	1,317.22
Dec	407.84	636.46	723.95	1,541.63

Table 4.33: Range of flows at percentiles 0, 5, 10, and 75 for Sg. Johor

Month	P0 (m ³ /s)	P10 (m ³ /s)	P25 (m ³ /s)	P75 (m ³ /s)
Jan	9.94	16.23	22.24	61.91
Feb	6.60	12.10	13.74	27.27
Mar	2.07	6.89	15.38	35.86
Apr	1.45	11.95	19.95	41.45
May	1.89	14.09	22.32	37.88
Jun	1.89	13.19	15.12	28.74
Jul	1.85	8.47	13.44	24.43
Aug	2.66	12.35	19.43	28.87
Sep	3.62	12.70	19.01	31.47
Oct	12.10	16.34	21.20	35.18
Nov	12.25	17.68	24.30	51.59
Dec	6.48	18.67	25.70	69.80

Table 4.34: Range of flows at percentiles 0, 5, 10, and 75 for Sg. Linggi

Month	P0 (m ³ /s)	P10 (m ³ /s)	P25 (m ³ /s)	P75 (m ³ /s)
Jan	2.23	2.85	7.64	19.74
Feb	1.21	1.67	5.42	13.07
Mar	2.51	4.53	6.22	20.04
Apr	4.12	6.01	13.48	27.18
May	8.88	9.40	11.97	23.59
Jun	4.42	5.80	8.68	15.81
Jul	3.72	4.25	6.60	11.74
Aug	2.74	3.26	6.09	15.04
Sep	3.29	3.67	6.92	20.19
Oct	5.76	9.11	12.62	25.08
Nov	12.18	14.20	15.68	36.33
Dec	7.05	7.84	14.11	31.81

Table 4.35: Range of flows at percentiles 0, 5, 10, and 75 for Sg. Selangor

Month	P0 (m ³ /s)	P10 (m ³ /s)	P25 (m ³ /s)	P75 (m ³ /s)
Jan	23.78	26.54	39.65	80.89
Feb	13.44	21.38	24.16	42.29
Mar	8.34	24.82	31.75	60.56
Apr	18.48	34.60	51.42	81.11
May	34.59	44.84	51.07	101.46
Jun	16.95	25.73	36.44	49.37
Jul	6.30	18.90	26.29	42.55
Aug	8.21	16.00	26.50	43.38
Sep	19.67	22.26	29.56	45.21
Oct	28.95	33.87	52.49	91.33
Nov	48.44	66.81	72.70	132.49
Dec	28.20	46.35	58.31	105.79

Table 4.36: Range of flows at percentiles 0, 5, 10, and 75 for Sg. Padas

Month	P0 (m ³ /s)	P10 (m ³ /s)	P25 (m ³ /s)	P75 (m ³ /s)
Jan	34.88	77.25	163.71	321.42
Feb	35.46	49.07	86.39	306.34
Mar	18.39	54.92	83.56	230.71
Apr	1.65	51.16	116.75	308.79
May	15.10	97.86	155.72	320.23
Jun	47.18	68.96	101.98	292.70
Jul	52.88	64.05	92.96	255.14
Aug	22.73	44.35	93.75	201.00
Sep	62.34	85.09	120.11	284.41
Oct	5.50	127.16	162.66	301.96
Nov	96.15	143.89	187.29	367.19
Dec	65.85	120.18	194.69	390.49

Table 4.37: Range of flows at percentiles 0, 5, 10, and 75 for Sg. Sadong

Month	P0 (m ³ /s)	P10 (m ³ /s)	P25 (m ³ /s)	P75 (m ³ /s)
Jan	21.01	73.19	84.48	132.11
Feb	6.81	24.78	52.58	114.87
Mar	11.88	30.24	43.85	104.13
Apr	14.68	34.54	42.03	77.47
May	14.84	30.39	41.61	69.03
Jun	9.80	15.41	19.79	37.88
Jul	5.49	10.97	16.89	38.47
Aug	9.19	11.77	17.26	50.02
Sep	4.65	8.00	18.79	52.06
Oct	7.44	20.80	33.46	62.62
Nov	9.58	26.91	43.12	91.35
Dec	26.34	56.29	73.68	113.94

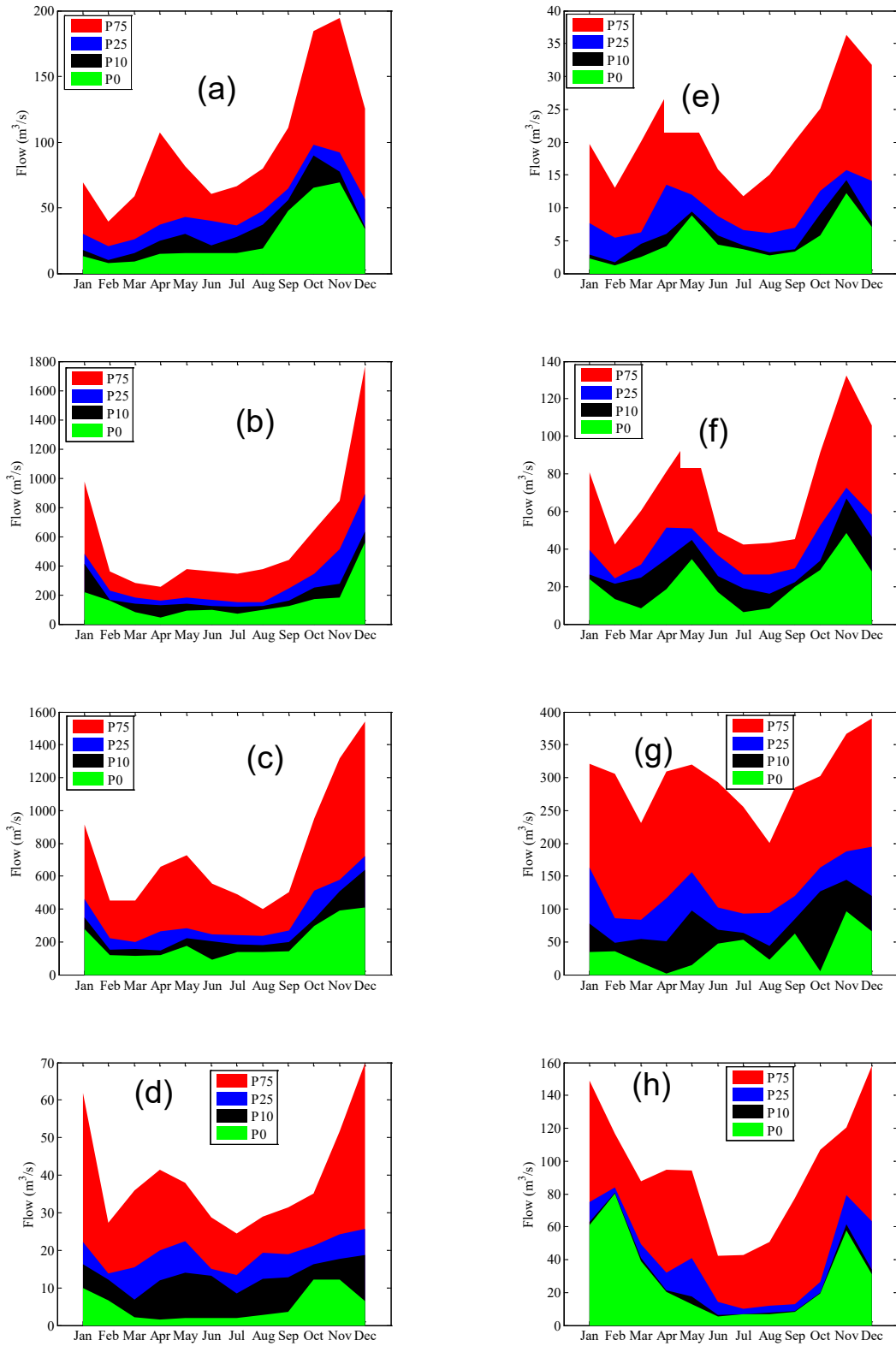


Figure 4.18: Inter-annual flow variability at four hydrological yearly conditions of very dry, dry, average and wet for (a) Sg. Muda, (b) Sg. Kelantan, (c) Sg. Pahang, (d) Sg. Johor, (e) Sg. Linggi, (f) Sg. Selangor, (g) Sg. Padas, and (h) Sg. Sadong.

4.12 ENVIRONMENTAL WATER ALLOCATIONS

Tables 4.38-4.45 present environmental water allocations which represent four categories i.e. very good ecological condition (Eflow class A), good ecological condition (Eflow class B), medium ecological condition (Eflow class C), and deficient ecological condition (Eflow class D). Sg. Muda is difficult to achieve environmental flow class A by using the current water demand (5,376 MLD). The river can only achieve environmental flow classes B, C, and D only for November, October-November, and October-November, respectively. A strategy is recommended by reducing the current water demand. For example, reduction of the demand by 50% can improve environmental flow classes. Although the river cannot achieve environmental classes B, C and D for all months, an additional strategy for the complete achievement can be carried out as follows: (a) For Eflow class D, the excess water for December-January must be stored and be released for February, (b) For Eflow class C, water deficit for February can be solved by storing excess water for December-January. In addition, water deficit for June can be solved by storing the excess water for May, (c) For the complete achievement Eflow class B for all months, the excess water in October-December and April must be stored and be released in other months. Reduction of the demand by 50% and additional strategy cannot achieve the environmental flow class A for all months since it only improves as follows. By storing the excess water for October-November, the river can achieve Eflow class A only for December-February.

Table 4.38 Environmental water allocations proposed for Sg. Muda

Month	Natural flow average (m ³ /s)	Eflow class A (m ³ /s)	Eflow class B (m ³ /s)	Eflow class C (m ³ /s)	Eflow class D (m ³ /s)
Jan	50.51	33.73	26.92	18.45	15.12
Feb	31.04	20.96	16.75	11.26	8.69
Mar	47.06	28.60	22.61	14.95	11.60
Apr	77.20	46.55	36.13	23.52	19.14
May	68.25	45.47	37.54	26.84	21.29
Jun	50.62	37.97	31.56	22.68	17.74
Jul	56.02	38.67	32.70	24.62	20.43
Aug	67.35	48.95	41.87	31.96	26.31
Sep	90.84	70.21	63.02	54.14	50.77
Oct	159.46	110.32	97.61	81.64	75.14
Nov	157.27	107.33	93.32	77.00	72.39
Dec	91.93	63.66	52.43	38.96	34.44

Sg. Kelantan can achieve Eflow classes A, B, C, and D for all months since the demand is always lower than the water availability.

Table 4.39: Environmental water allocations proposed for Sg. Kelantan

Month	Natural flow average (m ³ /s)	Eflow class A (m ³ /s)	Eflow class B (m ³ /s)	Eflow class C (m ³ /s)	Eflow class D (m ³ /s)
Jan	790.51	540.21	457.22	347.88	295.20
Feb	307.89	235.31	208.88	175.53	161.69
Mar	264.30	184.84	160.34	125.76	105.61
Apr	234.13	160.14	135.99	100.30	77.24
May	283.22	203.93	171.11	129.13	110.80
Jun	266.43	190.57	159.85	122.02	107.82
Jul	251.77	175.62	145.34	107.21	91.53
Aug	276.15	185.54	155.39	119.89	109.20
Sep	354.03	254.06	214.23	162.22	137.86
Oct	490.65	369.82	313.27	239.31	204.47
Nov	759.29	499.86	409.39	285.41	218.40
Dec	1,487.04	981.57	835.38	656.03	589.69

It is found that Sg. Pahang can be able to achieve Eflow classes A, B, C, and D for all months since the demand is always lower compared to the water availability for all months.

Table 4.40: Environmental water allocations proposed for Sg. Pahang

Month	Natural flow average (m ³ /s)	Eflow class A (m ³ /s)	Eflow class B (m ³ /s)	Eflow class C (m ³ /s)	Eflow class D (m ³ /s)
Jan	783.08	510.41	435.72	342.68	305.97
Feb	405.37	244.62	204.37	153.63	132.66
Mar	465.53	231.40	193.42	147.07	130.33
Apr	481.07	304.61	239.42	160.08	131.79
May	571.00	349.69	288.28	215.85	193.81
Jun	415.44	283.86	233.55	167.85	137.05
Jul	370.46	269.01	228.28	177.10	156.21
Aug	357.98	247.04	215.88	175.20	156.18
Sep	407.79	289.28	246.15	190.16	164.46
Oct	723.62	542.95	460.01	355.54	312.47
Nov	948.66	692.49	593.28	475.76	439.12
Dec	1,222.79	838.38	716.25	562.51	499.29

Sg. Johor is difficult to achieve environmental flow class A by using the current water demand (2,322 MLD). The river can only achieve environmental flow classes B only for December. In addition, Sg. Johor can achieve environmental flow classes C and D only for December-January.

Reduction of the demand by 50% and additional strategy can improve environmental flow classes for the river. The improvements are as follows: (a) For Eflow class D, the river can achieve environmental flow classes D for all months, (b) the river can achieve environmental flow classes C for all months, (c) For Eflow class B, the excess water for November-April must be stored and be released for April-October for the complete Eflow class B achievement.

Reduction of the demand by 50% and additional strategy cannot achieve the environmental flow class A for all months since it only improve as follows. By storing the excess water for December-February, the river can achieve Eflow class A only until May.

Table 4.41: Environmental water allocations proposed for Sg. Johor

Month	Natural flow average (m ³ /s)	Eflow class A (m ³ /s)	Eflow class B (m ³ /s)	Eflow class C (m ³ /s)	Eflow class D (m ³ /s)
Jan	41.83	27.74	21.94	14.92	12.46
Feb	31.03	15.41	13.17	10.23	8.80
Mar	27.11	16.45	12.22	6.66	4.00
Apr	29.96	20.80	16.00	9.35	5.65
May	30.64	21.74	17.32	10.86	6.77
Jun	22.83	16.13	13.26	9.06	6.41
Jul	20.39	13.49	10.73	6.82	4.50
Aug	24.17	18.22	14.89	9.89	6.54
Sep	27.84	18.70	15.29	10.33	7.26
Oct	31.15	22.11	19.32	15.61	13.80
Nov	38.62	27.23	22.63	16.83	14.43
Dec	56.34	31.19	24.16	15.20	11.35

Sg. Linggi is difficult to achieve environmental flow class A for all months by using the current water demand (623 MLD) since it achieves only for April, November, and December. The river can achieve environmental flow classes B, C, and D for all months using the current demand by implementing additional strategy as follows: (a) For Eflow class D, the excess water in other months can be stored and released for June and July, (b) For Eflow class C, the excess water in other months can be stored and released for June and July, (c) For Eflow class B, the excess water in other months can be stored and released for February and May-August.

Table 4.42: Environmental water allocations proposed for Sg. Linggi

Month	Natural flow average (m ³ /s)	Eflow class A (m ³ /s)	Eflow class B (m ³ /s)	Eflow class C (m ³ /s)	Eflow class D (m ³ /s)
Jan	14.13	8.56	6.33	3.56	2.48
Feb	9.79	5.78	4.22	2.24	1.39
Mar	14.07	8.28	6.36	4.06	3.32
Apr	21.14	13.79	10.74	6.75	4.88
May	18.27	13.47	11.74	9.71	9.09
Jun	11.83	9.10	7.68	5.82	4.97
Jul	9.86	6.87	5.83	4.51	3.93
Aug	11.22	6.98	5.47	3.62	2.95
Sep	14.02	8.56	6.55	4.17	3.44
Oct	18.71	13.72	11.44	8.47	7.10
Nov	26.86	19.16	16.60	13.69	12.99
Dec	23.49	15.69	12.59	8.78	7.37

Sg. Selangor is difficult to achieve environmental flow class A and B by using the current water demand (3,109 MLD). The river can achieve environmental flow class C only for May, November, and December. In addition, it can achieve environmental flow classes D only for April-May and October-December. By reducing the demand of 50%, the river can achieve environmental classes A only for May, November, and December. The river can achieve environmental classes D for all months. An additional strategy for the complete achievement can be carried out as follows: (a) For Eflow class C, water deficit for February and August can be solved by storing excess water in other months and (b) For Eflow class B, water deficit for February and June-September can be solved by storing excess water in other months.

Table 4.43: Environmental water allocations proposed for Sg. Selangor

Month	Natural flow average (m ³ /s)	Eflow class A (m ³ /s)	Eflow class B (m ³ /s)	Eflow class C (m ³ /s)	Eflow class D (m ³ /s)
Jan	57.30	43.69	36.66	28.05	24.88
Feb	36.24	26.15	22.99	18.76	16.61
Mar	46.74	33.78	27.87	19.61	14.93
Apr	66.96	50.70	42.75	31.52	24.93
May	78.38	58.26	50.95	41.99	38.69
Jun	43.96	34.93	30.62	24.36	20.46
Jul	35.06	26.07	21.70	15.34	11.34
Aug	32.49	25.95	21.38	14.98	11.33
Sep	42.49	30.24	26.96	22.69	20.71
Oct	70.99	54.18	46.08	35.63	30.92
Nov	102.93	81.05	72.06	60.64	55.79
Dec	87.40	62.40	53.45	41.48	35.46

Sg. Padas can be able to achieve Eflow classes A, B, C, and D for all months since the demand is always lower compared to the water availability for all months.

Table 4.44: Environmental water allocations proposed for Sg. Padas

Month	Natural flow average (m ³ /s)	Eflow class A (m ³ /s)	Eflow class B (m ³ /s)	Eflow class C (m ³ /s)	Eflow class D (m ³ /s)
Jan	259.64	165.08	127.78	77.60	51.83
Feb	214.02	117.82	87.00	51.09	40.90
Mar	199.51	100.74	76.65	46.03	33.00
Apr	226.02	130.53	93.26	44.47	21.46
May	244.66	162.99	126.69	76.33	48.20
Jun	233.38	128.04	100.19	66.86	55.89
Jul	180.84	115.61	92.49	65.36	57.35
Aug	157.17	98.22	75.45	45.58	31.38
Sep	202.36	140.19	114.48	82.99	71.44
Oct	237.72	167.70	134.51	85.59	54.16
Nov	283.10	205.48	174.03	133.48	115.25
Dec	294.51	206.07	166.15	113.35	87.58

It is found that Sg. Sadong can achieve Eflow classes A, B, C, and D for all months since the demand is always lower compared to the water availability for all months.

Table 4.45: Environmental water allocations proposed for Sg. Sadong

Month	Natural flow average (m ³ /s)	Eflow class A (m ³ /s)	Eflow class B (m ³ /s)	Eflow class C (m ³ /s)	Eflow class D (m ³ /s)
Jan	110.89	85.40	73.16	54.58	41.88
Feb	86.65	54.90	41.31	23.15	14.00
Mar	74.97	49.99	39.40	25.62	19.22
Apr	61.16	44.89	37.86	28.09	22.62
May	55.16	42.18	35.64	26.42	21.06
Jun	33.34	21.53	18.29	14.04	12.04
Jul	30.41	18.88	14.99	9.96	7.68
Aug	34.16	21.91	17.28	11.84	10.22
Sep	39.65	21.87	16.05	8.82	5.99
Oct	51.35	34.16	27.37	17.99	12.78
Nov	73.80	46.17	36.37	23.22	16.51
Dec	97.94	73.52	63.02	47.79	38.32

In general, environmental water allocations proposed for (a) Sg. Muda, (b) Sg. Kelantan, (c) Sg. Pahang, (d) Sg. Johor, (e) Sg. Linggi, (f) Sg. Selangor, (g) Sg. Padas, and (h) Sg. Sadong are presented in Figure 4.19.

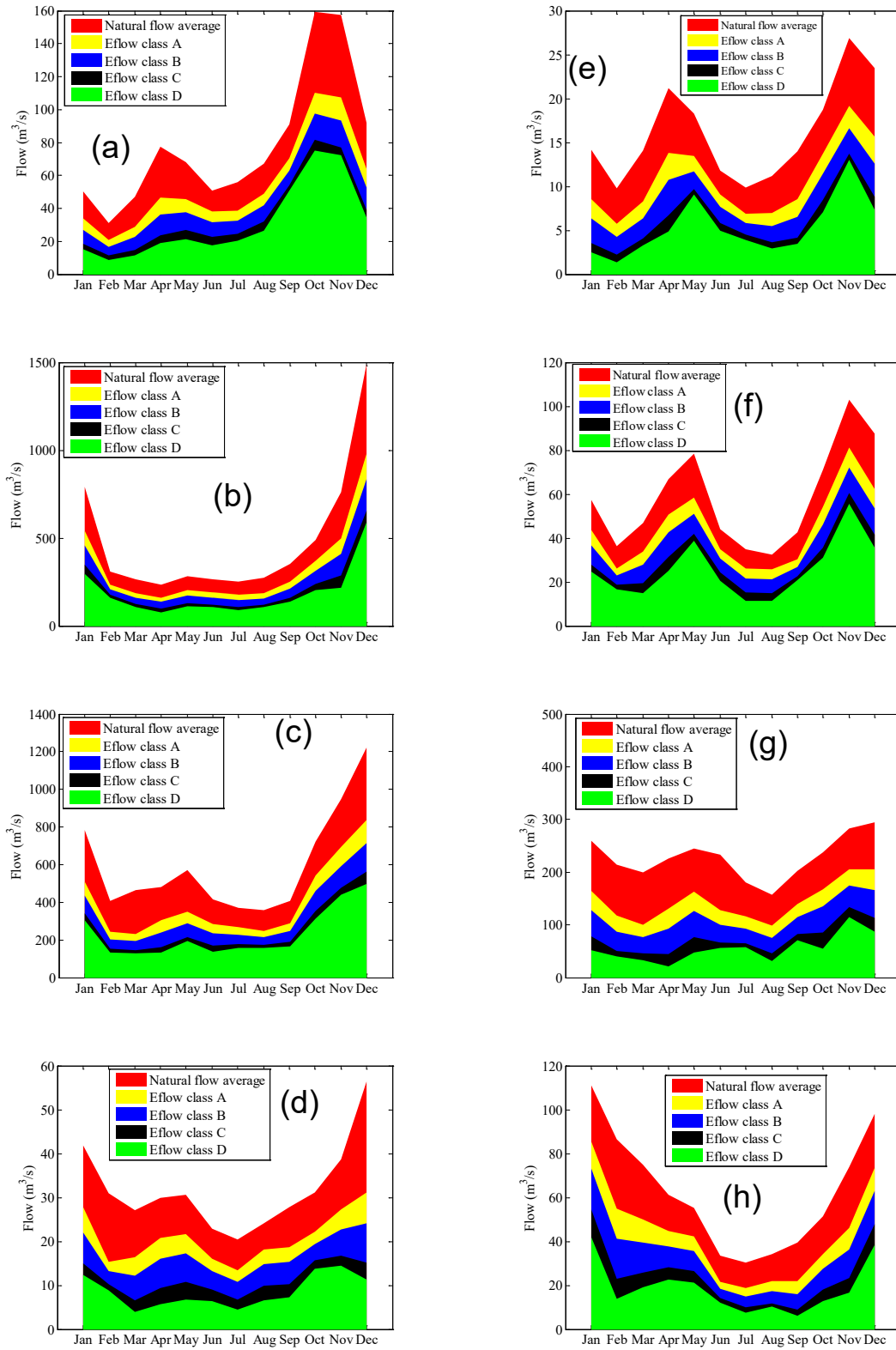


Figure 4.19: Environmental water allocations proposed for (a) Sg. Muda, (b) Sg. Kelantan, (c) Sg. Pahang, (d) Sg. Johor, (e) Sg. Linggi, (f) Sg. Selangor, (g) Sg. Padas, and (h) Sg. Sadong.

4.13 FLOOD REGIMES

Flood flow regime for all selected river basins was calculated based on four categories of flood magnitude, which are 1.0, 1.5, 5.0, and 10 years period of return obtained from statistical distributions. It is noted that the flood regimes for each river basin is unique depending on the flood categories. For examples, flood magnitude for Sg. Kelantan at different return periods of 1.0, 1.5, 5.0 and 10 years are 1,898.7, 3,472.3, 6,020.6, and 6,968.8 m³/s, respectively. Rate of change of the flood is 113.5 and -76.6 m³/s for rise and fall patterns, respectively. Completed results for these analyses are presented in Tables 4.46-4.56.

Table 4.46: Flood regime for Sg. Kelantan

Flood Regime		Flood Events Per Category & Years of Return Period			
		Category I	Category II	Category III	Category IV
Flow attribute (year)		1.0	1.5	5.0	10.0
Magnitude	m ³ /sec	1,898.7	3,472.3	6,020.6	6,968.8
	Mm ³ /day	164.0	300.0	520.2	602.1
Environmental Management Class	"A"	10.0	6.0	2.0	1.0
	"B"	5.0	3.0	2.0	1.0
	"C"	3.0	2.0	1.0	1.0
	"D"	2.0	1.0	1.0	1.0
Duration	No. of days	5	3	2	1
Timing	Months	November-January			
Rate of change	Rise	113.5			
	Fall	-76.6			

Table 4.47: Flood regime for Sg. Pahang

Flood Regime		Flood Events Per Category & Years of Return Period			
		Category I	Category II	Category III	Category IV
Flow attribute (year)		1.0	1.5	5.0	10.0
Magnitude	m ³ /sec	2,576.2	3,012.9	4,405.7	5,200.6
	Mm ³ /day	222.6	260.3	380.7	449.3
Environmental Management Class	"A"	10.0	6.0	2.0	1.0
	"B"	5.0	3.0	2.0	1.0
	"C"	3.0	2.0	1.0	1.0
	"D"	2.0	1.0	1.0	1.0
Duration	No. of days	5.0	5.0	5.0	3.0
Timing	Months	November-January			
Rate of change	Rise	105.8			
	Fall	-73.6			

Table 4.48: Flood regime for Sg. Linggi

Flood Regime		Flood Events Per Category & Years of Return Period			
		Category I	Category II	Category III	Category IV
Flow attribute (year)		1.0	1.5	5.0	10.0
Magnitude	m ³ /sec	52.5	75.3	144.5	191.7
	Mm ³ /day	4.5	6.5	12.5	16.6
Environmental Management Class	"A"	10.0	6.0	2.0	1.0
	"B"	5.0	3.0	2.0	1.0
	"C"	3.0	2.0	1.0	1.0
	"D"	2.0	1.0	1.0	1.0
Duration	No. of days	2	2	1	1
Timing	Months	November-January			
Rate of change	Rise	6.8			
	Fall	-4.0			

Table 4.49: Flood regime for Sg. Padas

Flood Regime		Flood Events Per Category & Years of Return Period			
		Category I	Category II	Category III	Category IV
Flow attribute (year)		1.0	1.5	5.0	10.0
Magnitude	m ³ /sec	135.7	187.5	290.4	337.6
	Mm ³ /day	11.7	16.2	25.1	29.2
Environmental Management Class	"A"	10.0	6.0	2.0	1.0
	"B"	5.0	3.0	2.0	1.0
	"C"	3.0	2.0	1.0	1.0
	"D"	2.0	1.0	1.0	1.0
Duration	No. of days	20	13	8	4
Timing	Months	September-May			
Rate of change	Rise	58.7			
	Fall	-42.0			

Table 4.50: Flood regime for Sg. Sadong

Flood Regime		Flood Events Per Category & Years of Return Period			
		Category I	Category II	Category III	Category IV
Flow attribute (year)		1.0	1.5	5.0	10.0
Magnitude	m ³ /sec	90.76	207.88	344.95	412.14
	Mm ³ /day	7.8	18.0	29.8	35.6
Environmental Management Class	"A"	10.0	6.0	2.0	1.0
	"B"	5.0	3.0	2.0	1.0
	"C"	3.0	2.0	1.0	1.0
	"D"	2.0	1.0	1.0	1.0
Duration	No. of days	2	1	1	1
Timing	Months	November-February			
Rate of change	Rise	22.1			
	Fall	-14.6			

Table 4.51: Flood regime for Sg. Muda before dam construction

Flood Regime		Flood Events Per Category & Years of Return Period			
		Category I	Category II	Category III	Category IV
Flow attribute (year)		1.0	1.5	5.0	10.0
Magnitude	m ³ /sec	249.8	425.6	795.15	974.15
	Mm ³ /day	21.6	36.8	68.7	84.2
Environmental Management Class	"A"	10.0	6.0	2.0	1.0
	"B"	5.0	3.0	2.0	1.0
	"C"	3.0	2.0	1.0	1.0
	"D"	2.0	1.0	1.0	1.0
Duration	No. of days	3	2	1	1
Timing	Months	July-December			
Rate of change	Rise	25.6			
	Fall	-16.8			

Table 4.52: Flood regime for Sg. Muda after dam construction

Flood Regime		Flood Events Per Category & Years of Return Period			
		Category I	Category II	Category III	Category IV
Flow attribute (year)		1.0	1.5	5.0	10.0
Magnitude	m ³ /sec	298.9	380.5	566.80	664.55
	Mm ³ /day	25.8	32.9	49.0	57.4
Environmental Management Class	"A"	10.0	6.0	2.0	1.0
	"B"	5.0	3.0	2.0	1.0
	"C"	3.0	2.0	1.0	1.0
	"D"	2.0	1.0	1.0	1.0
Duration	No. of days	2	2	1	1
Timing	Months	August-December			
Rate of change	Rise	22.3			
	Fall	-12.9			

Table 4.53: Flood regime for Sg. Johor before dam construction

Flood Regime		Flood Events Per Category & Years of Return Period			
		Category I	Category II	Category III	Category IV
Flow attribute (year)		1.0	1.5	5.0	10.0
Magnitude	m ³ /sec	99.75	170.2	345.2	444.6
	Mm ³ /day	8.6	14.7	29.8	38.4
Environmental Management Class	"A"	10.0	6.0	2.0	1.0
	"B"	5.0	3.0	2.0	1.0
	"C"	3.0	2.0	1.0	1.0
	"D"	2.0	1.0	1.0	1.0
Duration	No. of days	8	6	4	1
Timing	Months	November-February			
Rate of change	Rise	7.3			
	Fall	-4.6			

Table 4.54: Flood regime for Sg. Johor after dam construction

Flood Regime		Flood Events Per Category & Years of Return Period			
		Category I	Category II	Category III	Category IV
Flow attribute (year)		1.0	1.5	5.0	10.0
Magnitude	m ³ /sec	73.9	110.3	243.7	351.6
	Mm ³ /day	6.4	9.5	21.1	30.4
Environmental Management Class	"A"	10.0	6.0	2.0	1.0
	"B"	5.0	3.0	2.0	1.0
	"C"	3.0	2.0	1.0	1.0
	"D"	2.0	1.0	1.0	1.0
Duration	No. of days	7	6	4	1
Timing	Months	November-February			
Rate of change	Rise	6.1			
	Fall	-4.6			

Table 4.55: Flood regime for Sg. Selangor before dam construction

Flood Regime		Flood Events Per Category & Years of Return Period			
		Category I	Category II	Category III	Category IV
Flow attribute (year)		1.0	1.5	5.0	10.0
Magnitude	m ³ /sec	145.9	183.3	255.9	288.6
	Mm ³ /day	12.6	15.8	22.1	24.9
Environmental Management Class	"A"	10.0	6.0	2.0	1.0
	"B"	5.0	3.0	2.0	1.0
	"C"	3.0	2.0	1.0	1.0
	"D"	2.0	1.0	1.0	1.0
Duration	No. of days	5	3	1	1
Timing	Months	October-December			
Rate of change	Rise	12.1			
	Fall	-7.9			

Table 4.56: Flood regime for Sg. Selangor after dam construction

Flood Regime		Flood Events Per Category & Years of Return Period			
		Category I	Category II	Category III	Category IV
Flow attribute (year)		1.0	1.5	5.0	10.0
Magnitude	m ³ /sec	200.7	234.3	321.4	372.8
	Mm ³ /day	17.3	20.2	27.8	32.2
Environmental Management Class	"A"	10.0	6.0	2.0	1.0
	"B"	5.0	3.0	2.0	1.0
	"C"	3.0	2.0	1.0	1.0
	"D"	2.0	1.0	1.0	1.0
Duration	No. of days	2	2	1	1
Timing	Months	October-December			
Rate of change	Rise	16.6			
	Fall	-12.6			

4.14 ENVIRONMENTAL WATER RESERVE

Environmental water reserve is estimated from annual ordinary seasonal flows + flood regime. Percentage of mean annual runoff is defined as the mean annual runoff that can be reserved by achieving the related environmental management class. It can be estimated by dividing the environmental water reserve with water availability in river basin. For example, by achieving environmental class D to A, Sg. Muda can reserve water by 1,000 to 1,800 Mm³/year, which represent 38 to 70% of the mean annual runoff. Moreover, environmental water reserve for the river basins are listed in Tables 4.57-4.64.

Table 4.57: Environmental water reserve at annual scale for Sg. Muda before and after dam construction

Sg. Muda	(Ordinary Seasonal Flows + Flood Regime)				
	Environmental Management Class	Ordinary seasonal flows (Mm ³ /year)	Flood regime (Mm ³ /year)	Total (Mm ³ /year)	Percentage of mean annual runoff (%)
Before Dam Construction	"A"	1,714.56	131.03	1,845.59	70.80
	"B"	1,451.86	76.59	1,528.46	58.63
	"C"	1,119.58	49.42	1,169.00	44.84
	"D"	980.40	35.59	1,015.99	38.97
After Dam Construction	"A"	1,714.56	106.64	1,821.20	69.86
	"B"	1,451.86	61.09	1,512.95	58.04
	"C"	1,119.58	39.28	1,158.86	44.46
	"D"	980.40	27.54	1,007.95	38.67

Table 4.58: Environmental water reserve at annual scale for Sg. Kelantan

Sg. Kelantan	(Ordinary Seasonal Flows + Flood Regime)				
	Environmental Management Class	Ordinary seasonal flows (Mm ³ /year)	Flood regime (Mm ³ /year)	Total (Mm ³ /year)	Percentage of mean annual runoff (%)
Sg. Kelantan	"A"	10,463.30	1,628.53	1,2091.84	73.50
	"B"	8,846.87	948.41	9795.28	59.54
	"C"	6,755.77	590.32	7346.10	44.65
	"D"	5,806.59	418.30	6224.89	37.84

Table 4.59: Environmental water reserve at annual scale for Sg. Pahang

Sg. Pahang	(Ordinary Seasonal Flows + Flood Regime)				
	Environmental Management Class	Ordinary seasonal flows (Mm ³ /year)	Flood regime (Mm ³ /year)	Total (Mm ³ /year)	Percentage of mean annual runoff (%)
	"A"	12,624.23	2,409.31	15,033.54	79.38
	"B"	10,655.52	1,462.38	12,117.90	63.98
	"C"	8,208.37	919.32	9,127.69	48.19
	"D"	7,251.55	677.87	7,929.41	41.87

Table 4.60: Environmental water reserve at annual scale for Sg. Johor before and after dam construction

Sg. Johor	(Ordinary Seasonal Flows + Flood Regime)				
	Environmental Management Class	Ordinary seasonal flows (Mm ³ /year)	Flood regime (Mm ³ /year)	Total (Mm ³ /year)	Percentage of mean annual runoff (%)
Before Dam Construction	"A"	654.92	149.59	804.51	39.25
	"B"	528.04	88.64	616.69	30.09
	"C"	356.78	54.10	410.88	20.05
	"D"	267.98	38.38	306.36	14.95
After Dam Construction	"A"	654.92	98.88	753.81	36.78
	"B"	528.04	59.38	587.43	28.66
	"C"	356.78	36.30	393.08	19.18
	"D"	267.98	26.12	294.09	14.35

Table 4.61: Environmental water reserve at annual scale for Sg. Linggi

Sg. Linggi	(Ordinary Seasonal Flows + Flood Regime)				
	Environmental Management Class	Ordinary seasonal flows (Mm ³ /year)	Flood regime (Mm ³ /year)	Total (Mm ³ /year)	Percentage of mean annual runoff (%)
	"A"	341.53	21.03	362.57	29.38
	"B"	277.39	12.59	289.98	23.50
	"C"	198.10	8.23	206.33	16.72
	"D"	167.96	6.02	173.98	14.10

Table 4.62: Environmental water reserve at annual scale for Sg. Selangor before and after dam construction

Sg.Selangor	(Ordinary Seasonal Flows + Flood Regime)				
	Environmental Management Class	Ordinary seasonal flows (Mm ³ /year)	Flood regime (Mm ³ /year)	Total (Mm ³ /year)	Percentage of mean annual runoff (%)
Before Dam Construction	"A"	1,386.01	98.45	1,484.46	60.00
	"B"	1,191.72	52.68	1,244.40	50.30
	"C"	933.07	33.12	966.19	39.05
	"D"	804.30	22.06	826.36	33.40
After Dam Construction	"A"	1,386.01	67.75	1,453.76	58.76
	"B"	1,191.72	38.26	1,229.98	49.72
	"C"	933.07	24.50	957.57	38.71
	"D"	804.30	16.98	821.28	33.20

Table 4.63: Environmental water reserve at annual scale for Sg. Padas

Sg. Padas	(Ordinary Seasonal Flows + Flood Regime)				
	Environmental Management Class	Ordinary seasonal flows (Mm ³ /year)	Flood regime (Mm ³ /year)	Total (Mm ³ /year)	Percentage of mean annual runoff (%)
	"A"	4,568.70	412.66	4,981.36	65.60
	"B"	3,596.89	232.24	3,829.13	50.43
	"C"	2,335.58	144.21	2,479.79	32.66
	"D"	1,756.66	99.70	1,856.36	24.45

Table 4.64: Environmental water reserve at annual scale for Sg. Sadong

Sg. Sadong	(Ordinary Seasonal Flows + Flood Regime)				
	Environmental Management Class	Ordinary seasonal flows (Mm ³ /year)	Flood regime (Mm ³ /year)	Total (Mm ³ /year)	Percentage of mean annual runoff (%)
	"A"	1,354.47	35.98	1,390.45	24.53
	"B"	1,105.70	22.75	1,128.46	19.91
	"C"	766.11	14.84	780.95	13.78
	"D"	584.26	11.47	595.73	10.51

CHAPTER 5

5. CONCLUSION AND RECOMMENDATIONS

5.1 INTRODUCTION

The major objective of the present study is to evaluate and investigate the environmental flow characteristics of eight river basins in Malaysia. Therefore, this conclusion chapter highlights the main findings according to the research objective and suggests recommendation for future work.

5.2 MAJOR FINDINGS

Major findings related to the assessment of environmental flow characteristics of eight river basins are as follows:

- i. Based on the water exploitation indexes, the study found that the rivers that fall under severe stress are Sg. Muda, Sg. Johor, and Sg. Selangor; not stress for Sg. Kelantan, Sg. Pahang, Sg. Padas, and Sg. Sadong; low stress for Sg. Linggi.
- ii. Flow values for each flow category (very dry, dry, average and wet) is unique for each catchment. The values also vary with the month of the year.
- iii. The study has successfully identified the range of flow for environmental water allocations under Eflow class A (very good ecological condition), Eflow class B (good ecological condition), Eflow class C (medium ecological condition), and Eflow class D (deficient ecological condition) categories.
- iv. Study on the environmental flow is important for water resource management in Malaysia. By providing flow values based on certain ecological conditions, the water resource can be well managed not only in point of view of quantity but also in the quality, which is also beneficial for ecosystem health along the river.
- v. Sg. Muda is difficult to achieve environmental flow class A by using the current water demand (5,376 MLD). The river can only achieve environmental flow classes B, C, and D only for November, October-November, and October-November, respectively
- vi. Sg. Kelantan can achieve Eflow classes A, B, C, and D for all months since the demand is always lower than the water availability.
- vii. Sg. Pahang can be able to achieve Eflow classes A, B, C, and D for all months since the demand is always lower compared to the water availability for all months.

- viii. Sg. Johor is difficult to achieve environmental flow class A by using the current water demand (2,322 MLD). The river can only achieve environmental flow classes B only for December. In addition, Sg. Johor can achieve environmental flow classes C and D only for December-January.
- ix. Sg. Linggi is difficult to achieve environmental flow class A for all months by using the current water demand (623 MLD) since it achieves only for April, November, and December. The river can achieve environmental flow classes B (except for February and May-August), C (except for June and July), and D (except for June and July) for all months using the current demand.
- x. Sg. Selangor is difficult to achieve environmental flow class A and B by using the current water demand (3,109 MLD). The river can achieve environmental flow class C only for May, November, and December. In addition, it can achieve environmental flow classes D only for April-May and October-December
- xi. Sg. Padas can be able to achieve Eflow classes A, B, C, and D for all months since the demand is always lower compared to the water availability for all months.
- xii. Sg. Sadong can achieve Eflow classes A, B, C, and D for all months since the demand is always lower compared to the water availability for all months.

5.3 RECOMMENDATION

Recommendations for future studies are as follows:

- i. It is interesting to establish water exploitation index based on upper, medium, and lower of the river basins. However, this analysis requires detail data on water demand and resource availability points.
- ii. It is also interesting to determine water stress index based on regulated and non-regulated river basins by providing additional data such as variance control factor (VF) and river fragmentation (RF) ratio.
- iii. It is necessary to investigate the effects of environmental flow at the selected river basins on the chemical and biological properties of the water.

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