Developing the Regression Relationships for the Critical Period of the Reservoir Systems at Sungai Bekok and Sungai Kesang Catchments in Malaysia

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Abstract. The knowledge of critical period (CR) for determining the behavior type of reservoir systems is very beneficial in the planning process for distinguishing the period of the required streamflow data in the simulation procedure. Generally, for within-year systems (CR < twelve months) utilizing the critical twelve months of the flow data record is required, whereas for the carryover systems (CR > twelve months) employing the annual streamflow data will suffice. Currently, there is no relationship in the literature that can be used for predicting the behavior type of reservoir systems employing reliability and vulnerability performance indices in Sungai Bekok and Sungai Kesang catchments. Hence, the objective of this study is to develop a novel equation involving performance indices for estimating the critical period of the aforementioned reservoir systems. The reservoirs were analyzed employing a Monte Carlo technique by improved sequent peak algorithm. Afterward, new regression equations for the critical period were developed based on simulation results and then verified by comparing the equations' outcomes with simulation results. Finally, it was found that the performance of the new equations is excellent in reproducing the critical period.

1. Introduction
Surface water reservoir systems are built on rivers to regulate the streamflow with saving water for fulfilling the demand at the specified performance level for domestic, industrial and agricultural purposes during shortage periods. Reservoir capacity planning process is usually based on a single historical data record; however, the historical data record is only a sample of the various data that the reservoir might experience in future [1-3]. Hence, each estimate of the reservoir capacity can be considered as a random variable [4-7]. In this study 1000 replicates of synthetic data having similar statistical characteristics to the historical data were used for the reservoir simulation.

The capability of a reservoir to operate satisfactorily under a wide range of probable hydrologic conditions and demands is an essential system characteristic [8-10]. The likely performance of reservoir systems is usually measured by performance indices that are defined based on some particular aspects in the failure periods [11-13]. The failure period is the time during drought periods that the reservoir is not able to provide the target demand completely [14]. The performance indices are very useful in selecting operational policies, storage capacities, system configurations and targets [9, 15-17]. Hashimoto et al. (1982) presented the performance indices to measure the efficiency of reservoir systems. The performance measures were reliability (i.e. how often the system is reliable) and
vulnerability (i.e. how acute the consequences of the failure could be) that were used in this study [9, 11]. For instance, the reliability of 95% means that the reservoir could provide the target demand in 95% of the time and the vulnerability of 15% means the reservoir might not be able to deliver up to 15% of the target demand during failure periods.

The storage-yield analysis of reservoir systems could be carried out by two general methods. The first method is the probability matrix procedure that is based on direct modelling of the reservoir volume [18]. The second method is the critical period procedure that could be carried out by either simulation or optimization processes [19]. Since among the aforementioned methods only simulation process of improved sequent peak algorithm was capable to include both reliability and vulnerability indices in the reservoir system analysis hence, improved sequent peak algorithm was employed in this study to analyze Sungai Bekok and Sungai Kesang reservoirs [16, 20, 21].

Critical Period (CP) is described as a time that a full reservoir goes empty without overflowing in this period [20, 22, 23]. CP is employed to distinguish two major behavior types of reservoir systems. The behavior that concerns with CP > twelve months is termed as carryover behavior whilst the behavior relates to CP < twelve months is called the within year behavior. These behaviors have an important influence on some aspects of reservoir systems such as sustainability, resiliency, reliability, vulnerability and storage capacity [24, 25]. Moreover, the within-year and carryover behaviors could be used to determine the interval of the streamflow data that is required for the reservoir simulation. For instance, if the reservoir shows within-year behavior utilizing twelve critical monthly flows is required for the reservoir analysis; however, when the reservoir has carryover behavior employing only annual streamflow data will suffice. In the case that reservoir shows both within-year and carryover behaviors employing the whole monthly flows will be necessary in the analysis process.

The only general method that is used in literature for distinguishing the behavior type of reservoir systems is the parameter $m$ (i.e. the standardized demand) method as follows [26]:

$$m = \frac{1-D_C}{CV}$$

In Equation (1), $m$ is the standardized demand parameter, $D$ is the demand as a ratio of the average yearly runoff (AYR), and $C_V$ is the coefficient of variation of the annual flow. According to parameter $m$ method if $m < 1$ the system’s behavior will be carryover and if $m > 1$ the system’s behavior will be within-year. Moreover, when $m = 1$ a transitional behavior between within-year and carryover happens [26-28].

As can be seen parameter $m$ method determines the reservoir behavior applying only demand and coefficient of variation of annual flows; however, other parameters such as performance measures also play the significant role in the behavior type of reservoir systems [24]. Currently, there is not a relationship in the literature for determining the behavior type of reservoirs considering performance indices for Sungai Bekok and Sungai Kesang catchments as best of the authors knowledge. Hence, the objective of this study is to develop the regression equations for modeling the critical period of Sungai Bekok and Sungai Kesang catchments in Malaysia.

2. Materials and Methods

2.1. Catchments and Data

This study is performed on Sungai Bekok and Sungai Kesang catchments in Peninsular Malaysia. A regression equation employing performance indices was developed for each catchment separately to model the behavior type of reservoir systems. The catchments of Sungai Bekok and Sungai Kesang receive the average yearly rainfall of 1974 and 2688 mm, respectively. They generally have a continuous humid equatorial rainforest weather that is sunny and warm. The monthly flow records from the catchments are employed to simulate the critical period of the reservoir systems. The main specifications of the catchments that are required for reservoir designing are shown in Table 1. The variation coefficients of the annual flow of the study rivers are quite high (0.49 and 0.40) that justifies the need for designing reservoir systems to regulate streamflow in different months.
Table 1. Specifications of the study catchments

| Site | River     | Gauging station | Record length | Catchment area | Annual flow statistics |
|------|-----------|-----------------|---------------|----------------|------------------------|
|      |           |                 | (years)       | (km²)          | Mean | CV | Skewness | ρ |
| 1    | Bekok     | Jln. Y. Peng, Labis | 39 (1974-2012) | 350            | 707 | 0.49 | 0.54    | 0.28 |
| 2    | Kesang    | Chin Chin       | 53 (1960-2012) | 161            | 456 | 0.40 | 1.64    | -0.07 |

Note: ρ is serial correlation (lag-1); mm is millimeter.

The streamflow data were examined using different statistical tests prior to Monte Carlo simulation. That includes homogeneity test that verifies data for consistency [21, 29]. The data were also examined applying trend test and run test to ensure that they are stationary and the result of a random procedure [30-32].

In order to normalize the data for data generation there is need to find the most appropriate density function of the annual and monthly streamflow data. For finding the most appropriate probability distribution the standard error test was used [25, 33]. Since Log Pearson type III produced the minimum standard errors among other probability density functions, hence, Log Pearson type III was selected as the most appropriate density function for both monthly and annual flow data. The fitness of Log Pearson type III density function to the historical annual flow data of Sungai Bekok and Sungai Kesang Catchments is shown in Figure 1.

Figure 1. The fitness of Log Pearson type III distribution to the historical streamflow data of Sungai Bekok and Sungai Kesang catchments

2.2. Synthetic Streamflow Data Generation

Using synthetic data in reservoir system analysis enables the designer to test alternative choices against the range of the streamflow sequences that might occur in future [20, 34-36]. Hence, in this study instead of the traditional methods that use only available data for reservoir simulation, the stochastic procedure that is based on large number of synthetic flow sequences was employed [37-39]. Generally, streamflow data generation models should reproduce the important statistics of the annual and monthly flows such as mean, standard deviation, coefficient of variation, skewness and auto correlation lag one [4, 5, 40]. Since Auto regressive lag one (AR (1)) model for generating annual flows and Valencia and Schaake (V-S) model for disaggregating the generated annual flows to monthly flows could reproduce the important statistics of the streamflow data at both monthly and annual levels, hence, the pair of AR (1) and V-S models was used to generate the flow data for the reservoir analysis in this study [41-43]. Vogel
and Stedinger (1987) showed that AR (1) model is more appropriate than other models to generate annual flows for reservoir system analysis. AR (1) model to generate annual flows is as follows [26]:

\[ r_{j+1} = \mu (r_j - \bar{r}) + r \bar{r} \sqrt{1 - \mu^2} + v \]

(2)

In Equation (2) \( r_{j+1} \) and \( r_j \) are the yearly runoff of the \((j+1)th\) and \(jth\) years, respectively; \( \bar{r} \) is the mean annual runoff; \( t \) is the standard deviation of yearly runoff; \( v \) is the standard normal random variable and \( \mu \) is the auto correlation lag one of the yearly runoff.

Valencia and Schaake (V-S) model was then employed to disaggregate the generated annual flows of the study systems to monthly flows. The pair of AR (1) and V-S models were used to generate 1000 replicates of monthly flow data that has the same length of historical data (i.e. 39 years for Sungai Bekok and 53 years for Sungai Kesang).

2.3. Simulation of Reservoir Systems

The simulation of reservoir systems was performed using improved sequent peak algorithm (SPA). The improved SPA can identify the critical period (CR) of the reservoir with involving time-based reliability and vulnerability (i.e. maximum amount of shortage during failure period [9, 17, 44, 45]. The time-based reliabilities of 1.00, 0.99, 0.98, 0.97, 0.96, 0.95, 0.93 and 0.90 were employed in the simulation. Moreover, the vulnerability indices of 0.00, 0.05, 0.10, 0.15, 0.20, 0.25 and 0.30 were applied in the improved SPA.

The annual demands of 0.20, 0.30, 0.40, 0.50, 0.60, 0.70 and 0.8 that are considered as a ratio of annual yearly runoff (AYR) were used in the analysis. For demands below 0.20 AYR there is usually no need to build a reservoir and the natural flow of the river can satisfy the demand and for demands above 0.80 AYR the improved SPA does not usually yield a unique critical period. Hence, the lower limit and upper limit of demand is considered as 0.20 and 0.80 AYR, respectively in this study. The monthly demands were also considered to be constant during different months of the year.

The simulation of the study reservoirs was carried out by improved SPA for the aforementioned time-based reliability, vulnerability and demands in 1000 sequences using 1000 replicates of the flow data that was generated in Section 2.2 and 1000 CRs were obtained for each case. The average of 1000 CRs for every case was considered as the most appropriate value of CR in this study.

2.4. Regression Relationships for Critical Period

There are variables that play a significant role in the critical period of reservoir systems. The most significant variable is parameter \( m \) (i.e. Equation 1). Hence, the relationship between CR and parameter \( m \) can be assumed as follows [24]:

\[ CR = P \cdot m^Q \]

(3)

In Equation (3), CR is the critical period and \( m \) is the standard demand parameter. \( P \) and \( Q \) are parameters that could be expressed as a function of other important variables in the critical period of reservoir systems. These variables involve time-based reliability and vulnerability indices. Therefore, the following relationship is proposed for \( P \) and \( Q \) in this study:

\[ \phi = \gamma_0 + \gamma_1 \cdot R_L + \gamma_2 \cdot V_L \]

(4)

In Equation (4), \( \phi \) is dependent variable (i.e. \( P \) or \( Q \)); \( R_L \) is time-based reliability; \( V_L \) is vulnerability; \( \gamma_0, \gamma_1 \) and \( \gamma_2 \) are the regression coefficients.

By combining Equation (3) and Equation (4) the regression relationship for critical period was developed. The performance of the obtained regression equation was verified by comparing the equation results with simulation outcomes.
3. Results and Discussion

3.1. Synthetic Replicates of the Storage Capacities
The box plot diagrams of the generated storage capacities of the reservoirs introduced by Tukey are shown in Figure 2 [24, 46]. The diagrams are presented for the demand of 70% average yearly runoff (AYR). To generalize the results the storage capacities were stated as a ratio of AYR. The box plots show maximum, minimum, 25, 50 and 75 percentiles of the generated storage capacities. The box plots show that reliability and vulnerability indices play a significant role in the storage capacity and by implication in critical period of reservoir systems. (i.e. by increasing reliability or decreasing vulnerability indices the storage capacity and critical period increase.)

Figure 2. The box plots of storage capacities in demand of 70% AYR for different reliability and vulnerability indices in Sungai Bekok and Sungai Kesang catchments

3.2. Regression Relationship for Critical Period

3.2.1. Relationship Between Critical Period and Standard Demand Parameter
The relationship between critical period and standard demand parameter was presented in Section 2.4 (i.e. Equation (3)). In Equation (3), $P$ and $Q$ are parameters that could be found by runs of the improved SPA for each possible pair of reliability and vulnerability indices. Equation (3) was calibrated for every possible pair of reliability and vulnerability indices applying 7 data points that relate to the demands of 20%, 30%, 40%, 50%, 60%, 70% and 80% of average yearly runoff (AYR). The fitness of Equation (3) to the simulation results in Sungai Bekok and Sungai Kesang systems is shown in Figure 3 as a sample. Although the fitted curve is for reliability of 0.95 and vulnerability of 0.15; however, the fits for all pairs of reliability and vulnerability indices are also very appropriate. The fits are generally excellent with $R^2$ varying between 0.9769-0.9984 for the study sites. Table 2 involves the sample estimates of $P$ and $Q$ along with $R^2$ for the applied pairs of reliability and vulnerability indices in this study.

3.2.2. Linear Regression Relationships for $P$ and $Q$
Considering other important variables in the critical period of reservoir systems such as time-based reliability and vulnerability Equation (4) was proposed for $P$ and $Q$ in Section 2.4. The regression coefficients of Equation (4) were estimated for all available data points of each site separately (i.e. 48: 8 (time-based reliability indices) × 6 (vulnerability indices)) using the least square method.
Figure 3. Fitness of the proposed relationship for critical period at reliability of 95% and vulnerability of 15% for Sungai Bekok and Sungai Kesang catchments.

Table 2. Regression coefficients P and Q along with $R^2$ for different pairs of vulnerability and time-based reliability indices for Sungai Bekok and Sungai Kesang catchments

| $V_L$ | $R_L$ | Bekok | Kesang |
|-------|-------|-------|-------|
|       |       | $P$   | $Q$   | $R^2$ | $P$   | $Q$   | $R^2$ |
| 0.00  | 1.00  | 2.36  | -1.49 | 0.9860| 1.39  | -1.82 | 0.9912|
| 0.99  | 1.00  | 2.30  | -1.49 | 0.9869| 1.32  | -1.84 | 0.9933|
| 0.98  | 1.00  | 2.27  | -1.49 | 0.9874| 1.27  | -1.80 | 0.9905|
| 0.97  | 1.00  | 2.24  | -1.49 | 0.9869| 1.23  | -1.76 | 0.9878|
| 0.96  | 1.00  | 2.21  | -1.48 | 0.9879| 1.19  | -1.70 | 0.9859|
| 0.95  | 1.00  | 2.19  | -1.48 | 0.9888| 1.16  | -1.66 | 0.9831|
| 0.93  | 1.00  | 2.15  | -1.46 | 0.9906| 1.11  | -1.58 | 0.9812|
| 0.90  | 1.00  | 2.11  | -1.43 | 0.9916| 1.06  | -1.49 | 0.9826|
| 0.99  | 0.99  | 2.24  | -1.49 | 0.9868| 1.25  | -1.84 | 0.9948|
| 0.98  | 0.99  | 2.18  | -1.50 | 0.9870| 1.15  | -1.77 | 0.9943|
| 0.97  | 0.99  | 2.12  | -1.49 | 0.9877| 1.09  | -1.70 | 0.9902|
| 0.96  | 0.99  | 2.06  | -1.48 | 0.9905| 1.04  | -1.63 | 0.9886|
| 0.95  | 0.99  | 2.03  | -1.47 | 0.9908| 0.99  | -1.54 | 0.9844|
| 0.93  | 0.99  | 1.95  | -1.44 | 0.9941| 0.92  | -1.40 | 0.9806|
| 0.90  | 0.99  | 1.87  | -1.37 | 0.9957| 0.86  | -1.25 | 0.9764|
| 0.99  | 0.98  | 2.19  | -1.50 | 0.9873| 1.19  | -1.87 | 0.9954|
| 0.98  | 0.98  | 2.09  | -1.50 | 0.9887| 1.05  | -1.79 | 0.9960|
| 0.97  | 0.98  | 2.00  | -1.49 | 0.9898| 0.97  | -1.70 | 0.9961|
| 0.96  | 0.98  | 1.93  | -1.48 | 0.9926| 0.91  | -1.59 | 0.9938|
| 0.95  | 0.98  | 1.87  | -1.46 | 0.9941| 0.86  | -1.48 | 0.9922|
| 0.93  | 0.98  | 1.76  | -1.39 | 0.9965| 0.79  | -1.32 | 0.9875|
| 0.90  | 0.98  | 1.65  | -1.29 | 0.9984| 0.73  | -1.15 | 0.9769|

$V_L$ = Vulnerability; $R_L$ = Time-Based Reliability

The regression coefficients along with $t$-statistics and $p$-values for P and Q at the study sites are presented in Table 3. Moreover, Table 4 shows the main statistics of the linear regression equations such as $R^2$ (i.e. coefficient of determination), SEE (i.e. standard error of estimate, DF (i.e. degrees of freedom), $F$-stat (i.e. $F$-statistics), $p$-value (i.e. the probability that a high value of $F$-stat happened by chance). Since according to Table 4 $F$-stats are high and the values of $R^2$ are close enough to 1 hence, the developed regression equations for P and Q at the study sites are statistically sufficient. Additionally, in Table 3 the $p$-values corresponding to $t$-statistics of the regression coefficients are less than 0.05 that indicate both time-based reliability and vulnerability indices are important in the regression analysis for P and Q at the usual 5% probability level.
Table 3. Coefficient estimates, t-statistics and p-values for P and Q

| Site  | Estimate | t-statistic | p-value | Estimate | t-statistic | p-value |
|-------|----------|-------------|---------|----------|-------------|---------|
| Bekok | γ₀       | -0.543      | -2.816  | 0.004    | -0.435      | -3.418  | 0.001  |
|       | γ₁       | 2.978       | 9.720   | 0.000    | -1.084      | -8.305  | 0.000  |
|       | γ₂       | -1.182      | -12.351 | 0.000    | 0.058       | 2.414   | 0.016  |
| Kesang| γ₀       | -1.760      | -6.866  | 0.000    | 2.968       | 7.308   | 0.000  |
|       | γ₁       | 3.203       | 12.187  | 0.000    | -4.885      | -11.729 | 0.000  |
|       | γ₂       | -1.223      | -14.896 | 0.000    | 0.441       | 3.387   | 0.001  |

Table 4. Main statistics of the linear regression relationships for P and Q

| Site | P   | Q   | P   | Q   |
|------|-----|-----|-----|-----|
| Bekok| 0.88| 0.65| 0.92| 0.81|
| Kesang| 0.06| 0.03| 0.05| 0.09|
| DF   | 45.0| 45.0| 45.0| 45.0|
| F-stat| 172 | 42  | 259 | 94  |
| p-value| 0.00| 0.00| 0.00| 0.00|

3.2.3. The Performance of the Developed Regression Relationship in Critical Period Prediction

According to regression statistics in Sections 3.2.1 and 3.2.2, the developed regression relationships for critical period at Sungai Bekok and Sungai Kesang are statistically sufficient; however, the practical method to verify the performance of a regression equation is to see how precise it could reproduce the observed data. By uniting Equations (3) and (4) and applying statistics of Table 3 the final relationships for predicting the critical period of Sungai Bekok and Sungai Kesang could be presented as follow:

\[ CR_{(\text{Bek})} = (-0.54 + 2.98R_L - 1.18V_L)m^{0.44 + 1.08R_L + 0.05V_L} \]  (5)

\[ CR_{(\text{Kes})} = (-1.76 + 3.20R_L - 1.27V_L)m^{2.97 - 4.88R_L + 0.44V_L} \]  (6)

In Equations (5) and (6) \( CR_{(\text{Bek})} \) and \( CR_{(\text{Kes})} \) are the critical periods of Sungai Bekok and Sungai Kesang systems, respectively in years; \( R_L \) is time-based reliability measure between 0.90 and 1.00; \( V_L \) is vulnerability measure between 0.00 and 0.30 and \( m \) is the standard demand parameter.

Equations (5) and (6) were applied to produce the critical period of Sungai Bekok and Sungai Kesang systems in Figure 4. 336 points (i.e. 7 (demands) × 6 (vulnerability indices) × 8 (time-based reliability indices)) were applied for each system. As can be seen in Figure 4 Equations (5) and (6) could reproduce the simulated critical periods efficiently specially at low values corresponding to within-year behavior.

The novelty, these equations are the first relationships that were developed for modeling the behavior of reservoir system employing performance indices at Sungai Bekok and Sungai Kesang systems as the best of the authors knowledge. The calculated \( R^2 \) between the predicted and simulated critical periods are 0.9827 and 0.9752 for Sungai Bekok and Sungai Kesang systems, respectively that also indicate the excellent performance of the developed regression equations in predicting the critical period.
Figure 4. Comparison between simulated critical periods and predicted critical periods applying Equations (5) and (6) in Sungai Bekok and Kesang catchments, respectively

4. Conclusion

Multiple regression relationships were proposed for predicting the behavior type of reservoir systems at Sungai Bekok and Sungai Kesang systems. The presented equations could be used for the planning of reservoir systems in the study catchments to determine the interval of the required streamflow data for the simulation purpose. If the reservoir shows within-year behavior the critical twelve months of the flow records are applied in the analysis; however, when reservoir shows carryover behavior the annual flow data would be enough for the analysis. In the case that reservoir has both within-year and carryover behaviors the whole historical monthly flows is applied in the system analysis. The reservoir systems were analyzed by improved sequent peak algorithm applying 1000 replicates of synthetic streamflow data. The multiple regression relationships were developed applying stochastic analysis results for different reliability and vulnerability indices. Generally, the developed regression equations could reproduce the critical period efficiently. This is promising given that the developed equations are the first relationships that were developed for modeling the critical period of study systems applying the performance indices.

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