RESEARCH ARTICLE
doi: 10.2306/scienceasia1513-1874.2007.33.411

Regional Flow Duration Model for the Salawin River Basin of Thailand

Pannathat Rojanamon,* Taweep Chaisomphob and Winyu Rattanapitikon

Civil Engineering Program, Sirindhorn International Institute of Technology, Thammasat University, P.O. Box 22 Thammasat Rangsit Post Office, Pathumthani 12121, Thailand.

* Corresponding author, E-mail: pannathat@siit.tu.ac.th

Received 9 Aug 2006
Accepted 6 Jun 2007

ABSTRACT: This study presents a simple model for determination of a monthly flow duration curve for a small ungauged watershed in the Salawin river basin, which is located in the northwestern part of Thailand, to develop a small hydropower project. Flow data from twenty stream gauging stations were used to develop the model. The flow duration curves from all gauging stations were fitted with five distributions equations, i.e. logarithmic, quadratic, cubic, power and exponential equations. The results showed that the logarithmic and exponential equations were very good fits. For regionalization, to make the model simple, the variations of coefficients in the models are expressed in terms of drainage area only. Although the model is simple, reasonable agreements are obtained between measured and computed flow duration curves.

KEYWORDS: Flow duration curve, logarithmic model, small hydropower.

INTRODUCTION

In Thailand, the government has embarked on exploitation of alternative sources of energy based on domestic renewable resources, e.g. bio-diesel, ethanol, and hydropower sources. The geographic and climatic conditions of some regions in Thailand endow them with a high potential for hydropower generation. The development of large hydropower schemes in Thailand faces difficulties due to environmental and resettlement problems. Pichalai[1] (2005) stated that the installed capacity of hydropower in Thailand is 3,424 MW at the end of 2004. Due to environmental problems from large-scale projects, future development of hydropower resources will be limited to a few small-scale projects. Small hydropower projects are considered to be more economical and have less environmental impact than large scale projects. They are defined in the range of 350 MW and have a good potential for development in Thailand. Therefore, this study is concentrated on the small hydropower projects.

Since most of selected sites for small hydropower projects are normally located on small streams where flow records are rarely available, calculation methods must be developed to estimate the streamflow and the power potential of the site. The flow duration curve (FDC) is a common method to estimate the streamflow for small hydropower development. FDC is a graph of the historical record at a site ordered from maximum to minimum flow. It is used to assess the anticipated availability of flow over time and consequently the power and energy on site. Vogel and Fennessey[2] (1995) presented a power duration curve derived from the combination between an FDC and a power discharge rating curve. The area under the power duration curve is the average annual energy that is useful for determination of economic feasibility in a diversity of potential turbine, dam and penstock constellations in hydropower project. Generally, other times series such as monthly, weekly, or daily flow data can be used to construct the relationship. Smakhtin[3] (2001) stated that FDC can be constructed by annual, monthly, or daily streamflow data and calculated on the basis of a whole record period or on the basis of all similar calendar months/seasons from the whole record period. Chiang et al.[4] (2002) stated that monthly streamflow data satisfy the basic data requirement for water resource projects. For the sake of convenience and reliability, it is possible to use monthly flow data in this study.

Based on the previous studies, FDC regionalization can be analyzed by various methods. Yu et al.[5] (2002) divided FDC methods into two groups. The first uses mathematical equations or statistical distributions to fit FDC constructed from gauged data. The second method is the regression between the discharge of some specific exceedance percentage (e.g. 10, 20, 30,…, and 90%) with the catchment characteristics or annual average flow. Castellarin et al.[6] (2004) classified regionalization procedures into three categories: statistical, parametric and graphical approaches. The first category view FDC as the complement of the cumulative frequency distribution. The second and the third are the procedures which do not make any connection between FDC and the probability theory. Smakhtin et al.[7] (1997) suggested that the regionalization technique is preferable in small-scale water projects because of cost and time savings. Regional flow duration curves can be constructed by using the available data of the regionalization techniques, which include streamflow data recorded at other existing gauging stations in the same region. The energy production can be determined from the area under the FDC. The computation of energy production will become very easy, if the flow duration curve is expressed in the form of an equation. In this study, regional parametric method is used for estimating FDC at ungauged sites.

The objective of the study is to develop a simple model to estimate the monthly FDC at ungauged sites in the Salawin river basin of Thailand, which has a high potential to contribute the development of the small hydropower projects.

Data Collection

The Salawin River is an international river originating from Tibet and runs approximately 2,200 km. in north-south direction through Southern China, Eastern Myanmar, Thailand and Myanmar again before draining into Andaman Sea. Only the basin in Thailand is considered in this study. For the study area, the Salawin river basin is in Maehongson and Tak provinces, in the northwestern part of Thailand, approximately between latitude 16° 15′ to 19° 45′ north and longitude 97° 20′ to 99° 00′ east. It covers 17,918 km^2. This area has a high potential for developing hydropower projects because it is a mountainous remote area that has sufficient head to generate electricity. The Department of Water Resources (DWR) is one of the agencies that operates and maintains stream-gauging stations in this area. Data from twenty one representative stream gauging stations of the Salawin river basin have been collected. Characteristics of the stations (name, area and the period of the records) are given in Table 1. These stations had records ranging in length from 6 to 35 years. The drainage areas of the collected gauging stations vary between 43.6 km^2 and 1,376.0 km^2. All stations are equipped with permanent installations for measuring flows with current meters and with staff gauge recorders, and have accurate and reliable data. The general location of the rivers and of the measuring stations is shown in Figure 1. The FDC may be constructed by using different time intervals of streamflow data. The present study mainly concentrates on the monthly flow data.

Model of Flow Duration Curves

The FDC is a relationship between discharge (Q) and the percentage of time during the period analyzed in which the particular flow is equaled or exceeded (D). FDC can also be constructed in terms of dimensionless discharge (discharge (Q) divided by average discharge of the record($\overline{Q}$). During the past decades, various models of FDC have been developed. Quimpo et al.[8] (1983) proposed an exponential model for daily FDC in the Philippines. Mimikou and Kaemaki[9] (1985)

Table 1. Characteristics of stream flow gauging stations in the Salawin river basin.

Sub-basin	No.	Station code	River name	Period of record	Duration(years)	Agency	Drainage area(km^2)
1	1.1	010201	Nam Mae Pai	1974 – 2003	30	DWR	369.0
	1.2	010202	Nam Mae Khong	1974 – 2003	30	DWR	172.0
	1.3	010203	Nam Mae Khong	1983 – 2003	21	DWR	260.0
	1.4	010204	Huay Mae Ping	1983 – 2003	21	DWR	54.4
	1.5	010205	Huay Mae Ya	1983 – 2003	21	DWR	84.8
	1.6	010401	Nam Khong	1987 – 2003	17	DWR	414.0
2	2.1	010502	Nam Mae Hong-Son	1966 – 1979	14	DWR	43.6
	2.2	010505	Nam Mae Sa-Nga	1976 – 2003	28	DWR	123.0
	2.3	010601	Nam Mae Samat	1965 – 1983	19	DWR	589.0
	2.4	010602	Nam Mae Cha	1969 – 2003	35	DWR	297.0
3	3.1	010702	Nam Mae Surin	1995 – 2000	6	DWR	156.0
	3.2	010901	Nam Mae La-Luang	1982 – 2003	22	DWR	450.0
	3.3	010903	Nam Mae La-Luang	1984 – 2003	20	DWR	427.0
	3.4	010904	Nam Mae La-Luang	1994 – 2003	10	DWR	306.0
	3.5	011103	Nam Mae Sa-Raing	1978 – 2003	26	DWR	229.0
	3.6	011104	Nam Mae Sa-Raing	1966 – 1983	18	DWR	378.0
	3.7	011201	Nam Mae Rit	1984 – 1995	12	DWR	1,376.0
4	4.1	011701	Huai Mae La-mao	1972 – 2003	32	DWR	1,100.0
	4.2	011803	Nam Mae Tan	1983 – 2003	21	DWR	55.1
	4.3	011804	Nam Mae U-Su	1983 – 2003	21	DWR	68.0
	4.4	011805	Huay Mae Charao	1986 – 2003	18	DWR	80.4

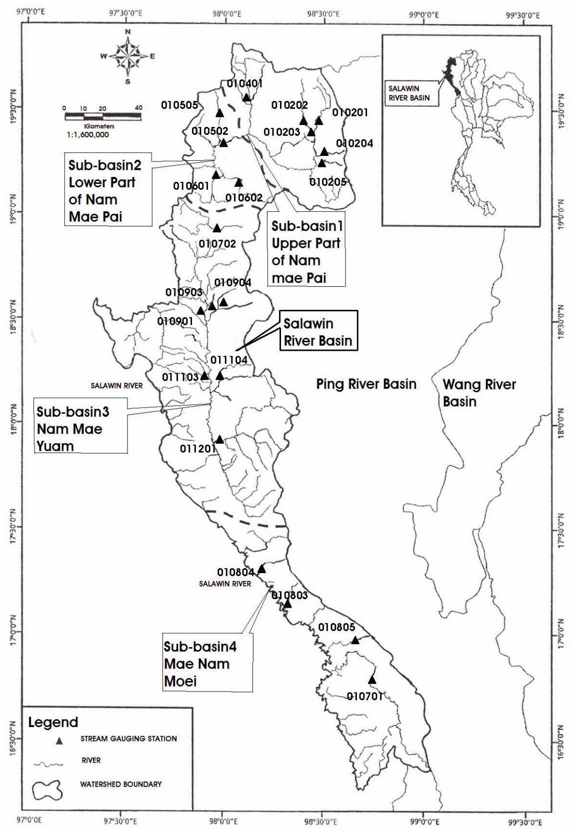

Fig 1. Location of 20 gauging stations in the Salawin river basin.

proposed to use a cubic model for monthly FDC in the western and northwestern regions of Greece. Franchini and Suppo[10] (1996) proposed to use an exponential equation for calculating average daily discharge in a limestone area of the Molise in Italy. Yu et al.[5] (2002) found that the cubic model was also fitted well with the daily FDC in the upstream catchments of the Cho-Shuei Creek in central Taiwan. Usually, climatic and basin characteristics are used in the analyses of flow durations. The shape of the curve is determined by rainfall pattern, catchment size and physiographic characteristics, land use type, and the state of water resource development. Vogel and Fennessy[11] (1994) stated that the shape of FDC was dependent on catchment area characteristics, particularly hydrogeology. Most previous research on approaches for determining FDC models depended on the availability of flow record in each studying area and the method to analyze the flow records. Variations in climate, mainly the type, quantity, intensity and frequency of precipitation, have a dominant effect on flow. In fact, the accuracy of the FDC model of an ungauged site is subject to the analysis of the record data from nearby gauging stations and it relies on local physiographic factors. The model that is appropriate for a specific area should use data from its own area. The various models proposed by previous researchers, i.e. Quimpo et al.[8] (1983), Mimikou and Kaemaki[9] (1985), Franchini and Suppo[10] (1996), and Yu et al.[5] (2002), have different results. Due to these reasons, the models proposed by previous researchers may not be applicable for the watershed in Thailand. The objective of this section is therefore to identify a reasonable model of FDC for the Salawin river basin, Thailand.

The curve can be fitted with the five mathematical models, i.e. logarithmic, quadratic, cubic, power, and exponential models. The equation of each model can be written as follows.

$$Q = a_1 + a_2 \ln(D) \quad (1)$$
$$Q = b_1 + b_2 D + b_3 D^2 \quad (2)$$
$$Q = c_1 + c_2 D + c_3 D^2 + c_4 D^3 \quad (3)$$
$$Q = d_1 (D^{d_2}) \quad (4)$$
$$Q = e_1 \exp(e_2 D) \quad (5)$$
$$\frac{Q}{\overline{Q}} = f_1 + f_2 \ln(D) \quad (6)$$
$$\frac{Q}{\overline{Q}} = g_1 + g_2 D + g_3 D^2 \quad (7)$$
$$\frac{Q}{\overline{Q}} = h_1 + h_2 D + h_3 D^2 + h_4 D^3 \quad (8)$$
$$\frac{Q}{\overline{Q}} = i_1 (D^{i_2}) \quad (9)$$
$$\frac{Q}{\overline{Q}} = j_1 \exp(j_2 D) \quad (10)$$

where $a - j$ are the coefficients.

Examples of the fitted line of Q versus D and $Q/\overline{Q}$ versus D from logarithmic model at station 010201 are

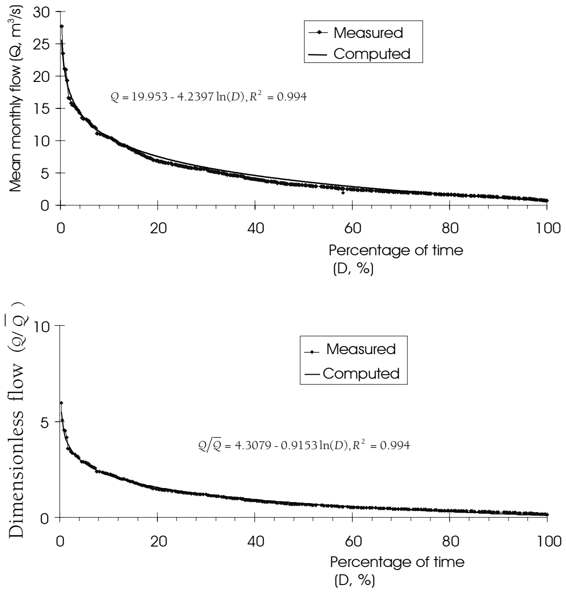

Fig. 2. Examples of measured flow duration curves and the fitted lines from logarithmic model at station 010201.

shown in Fig. 2.

By using the regression analysis, the models in Eqs. (1)– (5) and Eqs. (6)– (10) were fitted to each set of paired values of Q versus D and $Q/\overline{Q}$ versus D respectively. The model with the regression coefficient (R^2) closest to 1 is the best fit. The values of R^2 of Eqs. (1), (2), (3), (4) and (5) are equal to that of Eqs. (6), (7), (8), (9) and (10) respectively. Table 2 shows R^2 of each model for each station.

The results can be summarized as follows:

a) Each mathematical model for the flow duration curves in two parameters, Q and $Q/\overline{Q}$, gives the same values of R^2. The average R^2 for all stations of the logarithmic, quadratic, cubic, power and exponential models are 0.97, 0.86, 0.92, 0.86, and 0.97 respectively (see the last row of Table 2). The accuracy of the exponential model is equal to that of the logarithmic model.

b) No model gives the best fit for all stations. However the logarithmic model and the exponential model seem to fit very well with the FDC. The logarithmic model gives the best fit for 10 stations while the exponential model gives the best fit for 8 stations and the both models give the same accuracy for 3 stations.

Therefore, both the logarithmic and exponential models are considered in the regionalization of FDC models in the next section.

Regional Model

A stream gauge is rarely located at the desired hydropower site. Thus a regional model is needed to transfer streamflow magnitude from gauging stations to a desired hydropower site. In various countries, researchers have presented studies of the development of a regional model.

Mimikou and Kaemaki[9] (1985) proposed to use four parameters in the regional model of FDC in north-western Greece. The four parameters were: 1) the drainage area; 2) the mean annual precipitation; 3) the hypsometric fall; and 4) the length of the main river course, from the divide of the basin to the measuring station.

Franchini and Suppo[10] (1996) divided a regional analysis area in a limestone region of the south of Italy into 2 groups. Group 1 is the site that gives a clear downward concavity FDC. Group 2 is the site that gives a negative exponential behavior FDC. In Group 1, the regional model consisted of four parameters which were: 1) the area of topographic basin; 2) the limestone area; 3) the mean annual rainfall excess; and 4) the mean flow in the month of minimum flow. In group 2, there were five parameters in the regional model which were the area of topographic basin, the limestone area, the mean annual rainfall excess, the total limestone area contributing to the outlet, and limestone area inside the topographic basin.

Yu et al.[5] (2002) compared cubic polynomial and area-index methods to model FDC at the upstream catchments of the Cho-Shuei Creek in central Taiwan. The cubic polynomial method is composed of annual rainfall, altitude, and drainage area parameters, whereas the area-index method is composed of only drainage area parameter. They found that the cubic

Table 2. Regression coefficient (R^2) of the five mathematical models for the FDC and dimensionless FDC.

No.	Station code	Logarithmic Eq.(1), (6)	Quadratic Eq.(2), (7)	Cubic Eq.(3), (8)	Power Eq.(4), (9)	Exponential Eq.(5), (10)
1.1	010201	0.99	0.9	0.95	0.87	0.98
1.2	010202	0.99	0.91	0.96	0.84	0.98
1.3	010203	0.98	0.88	0.93	0.85	0.99
1.4	010204	0.99	0.88	0.94	0.88	0.97
1.5	010205	0.98	0.85	0.92	0.82	0.97
1.6	010401	0.94	0.81	0.91	0.86	0.97
2.1	010502	0.82	0.64	0.73	0.93	0.94
2.2	010505	0.99	0.93	0.98	0.87	0.98
2.3	010601	0.98	0.90	0.95	0.68	0.90
2.4	010602	0.97	0.84	0.92	0.81	0.98
3.1	010702	0.98	0.96	0.99	0.9	0.97
3.2	010901	0.99	0.9	0.96	0.87	0.98
3.3	010903	0.98	0.86	0.91	0.84	0.99
3.4	010904	0.89	0.76	0.85	0.91	0.95
3.5	011103	0.99	0.92	0.94	0.81	0.98
3.6	011104	0.99	0.94	0.97	0.86	0.99
3.7	011201	0.98	0.91	0.93	0.83	0.99
4.1	011701	0.95	0.8	0.88	0.9	0.96
4.2	011803	0.99	0.9	0.94	0.82	0.99
4.3	011804	0.94	0.79	0.88	0.92	0.94
4.4	011805	0.96	0.81	0.9	0.89	0.95
Average		0.97	0.86	0.92	0.86	0.97

polynomial method can give better prediction of FDC at ungauged sites than the area-index method, and that the cubic polynomial method has less uncertainty in estimating FDC than the area-index method

Castellarin et al.[6] (2004) studied the estimation of FDC in eastern-central Italy by using three models, which were the statistical method by Fennessey and Vogel[12] (1990), the parameter method by Quimpo et al.[8] (1983), Mimikou and Kaemaki[9] (1985) and Franchini and Suppo[10] (1996), and the graphical method by Smakhtin et al.[7] (1997). For the parameter method, they used six parameters in the regional models, i.e. the drainage area, the permeable portion of the drainage area, the difference between mean and minimum elevations in metres above sea level, mean annual precipitation, and mean annual net precipitation. All regional models were cross-validated by means of a jack-knife resampling procedure. The results showed that the reliability of the three best performing models was similar to one another, and the empirical FDC based on limited data samples provided a better fit of the long-term FDC than the regional FDC.

Castellarin et al.[13] (2004) developed an index flow model which is the relationship between FDC and annual FDC of daily streamflow data in the eastern-central of Italy. This model assumes that the daily streamflow is equal to the annual flow multiplied by a dimensionless daily streamflow. The authors defined annual flow as index flow.

Other researchers (e.g. Singh[14], 1971; Quimpo et al.[8], 1983 and Singh et al.[15], 2001) proposed to use only the drainage area in the regional model. Nevertheless Mimikou and Kaemaki[9] (1985) found that the most significant parameter was the drainage area. Castellarin et al.[6] (2004) stated that a reduced number of parameters is an important prerequisite for the regionalization of FDC.

For practical proposes, the model should be kept as simple as possible. The model should not contain parameters beyond those that are necessary. Therefore, for the first stage of development, only the drainage area is used in the development of the regional model.

Due to sub-basin division, Office of the National Economic and Social Development Board[16] (NESDB, 1994) classified the Salawin river basin into three main sub-basins, namely Nam Mae Pai, Nam Mae Yuam and Mae Nam Moei sub-basins. In order to expediently analyze the hydrology, it becomes necessary to delineate the main basins into sub-basins based on various factors such as the basin characteristics, climatological characteristics, and locations of gauging stations as well as other points of interest (e.g. projects). In this study, according to the distribution of 21 representative stream gauging stations, the Salawin river basin is divided 4 sub-basins as follows:

Sub-basin 1 is the area of Upper Part of Nam Mae Pai River. 6 gauging stations are located in this area.

Sub-basin 2 is the area of Lower Part of Nam Mae Pai River. 4 gauging stations are located in this area.

Sub-basin 3 is the area of Nam Mae Yuam River. 7 gauging stations are located in this area.

Sub-basin 4 is the area of Mae Nam Moei River. 4 gauging stations are located in this area.

The boundary of each sub-basin is shown in Fig. 1.

To obtain a regional model, the streamflow data in Table 1 is used for model developing and model verification. Data used for model developing and model verification are shown in Tables 3.1 and 3.2 respectively.

Table 3.1. Data used for model developing

Sub-basin	No.	Station code	River name	Drainage area(km^2)
1	1.1	010204	Huay Mae Ping	54.4
	1.2	010205	Huay Mae Ya	84.8
	1.3	010401	Nam Khong	414.0
2	2.1	010502	Nam Mae Hong-Son	43.6
	2.2	010601	Nam Mae Samat	589.0
	2.3	010602	Nam Mae Cha	297.0
3	3.1	010702	Nam Mae Surin	156.0
	3.2	010901	Nam Mae La-Luang	450.0
	3.3	011104	Nam Mae Sa-Raing	378.0
	3.4	011201	Nam Mae Rit	1,376.0
4	4.1	011701	Huai Mae La-mao	1,100.0
	4.2	011804	Nam Mae U-Su	68.0
	4.3	011805	Huay Mae Charao	80.4

Table 3.2. Data used for model verification.

Sub-basin	No.	Station code	River name	Drainage area(km^2)
1	1.1	010201	Nam Mae Pai	369.0
	1.1	010202	Nam Mae Khong	172.0
	1.2	010203	Nam Mae Khong	260.0
2	2.1	010505	Nam Mae Sa-Nga	123.0
3	3.1	010903	Nam Mae La-Luang	427.0
	3.2	010904	Nam Mae La-Luang	306.0
	3.3	011103	Nam Mae Sa-Raing	229.0
4	4.1	011803	Nam Mae Tan	55.1

Because logarithmic and exponential models can give the highest value of average R^2, model developing is created from data in Table 3.1 by plotting the relationship between drainage area and coefficients fromthe logarithmic and exponential models. The spatial variation of coefficients have been attempted to relate with the drainage area. Table 4 shows the coefficients a_1, a_2 and f_1, f_2 from the logarithmic models in Eq. (1) and in Eq. (6), respectively, and the coefficients e_1, e_2 and j_1, j_2 from the exponential models in Eq. (5) and Eq. (10), respectively, of each station.

Table 4. Coefficients of the logarithm models (a_1, a_2 from Eq. (1) and f_1, f_2 from Eq. (6)) and coefficients of the exponential models (e_1, e_2 from Eq. (5) and j_1, j_2 from Eq. (10).

Sub-basin	Station code	Eq. (1)		Eq. (5)		Eq. (6)		Eq. (10)	
		a_1	a_2	e_1	e_2	f_1	f_2	j_1	j_2
1	010204	2.18	-0.47	1.38	-0.03	4.45	-0.96	2.82	-0.03
	010205	3.33	-0.72	2.30	-0.03	4.47	-0.96	3.09	-0.03
	010401	42.09	-9.06	26.39	-0.04	5.75	-1.31	3.61	-0.04
2	010502	4.83	-1.07	2.51	-0.03	5.05	-1.12	2.63	-0.03
	010601	24.52	-5.45	22.20	-0.04	5.15	-1.15	4.67	-0.04
	010602	10.07	-2.30	7.31	-0.04	5.76	-1.32	4.19	-0.04
3	010702	8.51	-1.72	5.43	-0.02	3.81	-0.77	2.43	-0.02
	010901	27.54	-6.00	18.12	-0.03	4.71	-1.02	3.10	-0.03
	011104	42.11	-8.72	28.47	-0.03	4.00	-0.83	2.71	-0.03
	011201	161.46	-34.94	114.65	-0.03	4.66	-1.01	3.31	-0.03
4	011701	56.49	-12.50	32.28	-0.03	5.00	-1.11	2.86	-0.03
	011804	14.76	-3.25	8.15	-0.03	4.94	-1.09	2.73	-0.03
	011805	9.57	-2.09	5.67	-0.03	4.78	-1.04	2.83	-0.03

The drainage area (A) and the coefficients are plotted to identify the relationships. The relationships between drainage area and these coefficients can be fitted by the straight-line equation(Fig. 3.1 and 3.2). The straight-line equations of the coefficients can be written as follow

$$a_1 = k_1 + k_2 A \tag{11}$$
$$a_2 = k_3 + k_4 A \tag{12}$$
$$e_1 = l_1 + l_2 A \tag{13}$$
$$e_2 = l_3 + l_4 A \tag{14}$$
$$f_1 = m_1 + m_2 A \tag{15}$$
$$f_2 = m_3 + m_4 A \tag{16}$$
$$j_1 = n_1 + n_2 A \tag{17}$$
$$j_2 = n_3 + n_4 A \tag{18}$$

The straight-line coefficients (k_1 to k_4, l_1 to l_4, m_1 to m_4 and n_1 to n_4) are determined using the regression analysis. Table 5 shows the results from regression analysis.

The discharges (Q) corresponding to percent of time (D) at the interval increasing 1 % each time up to 100 % for each station were computed and compared between the results from the logarithmic and exponential models to find the best fitted equation.

To create model, substituting coefficients a_1 and a_2 from Eqs. (11) and (12) into Eq. (1), e_1 and e_2 from Eqs. (13) and (14) into Eq. (5), f_1 and f_2 from Eqs. (15) and (16) into Eq. (6), j_1 and j_2 from Eq. (17) and (18) into Eq. (10), the calculated discharges by logarithmic and exponential models can be expressed as

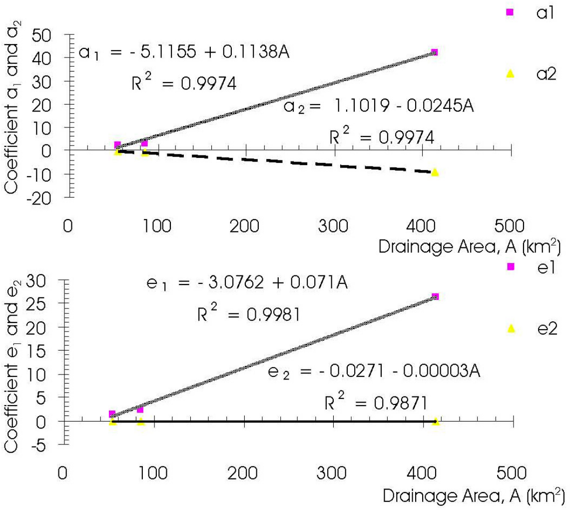

Fig 3.1. Relationship between coefficients a_1, a_2 versus drainage area and coefficients e_1, e_2 versus drainage area at sub-basin 1.

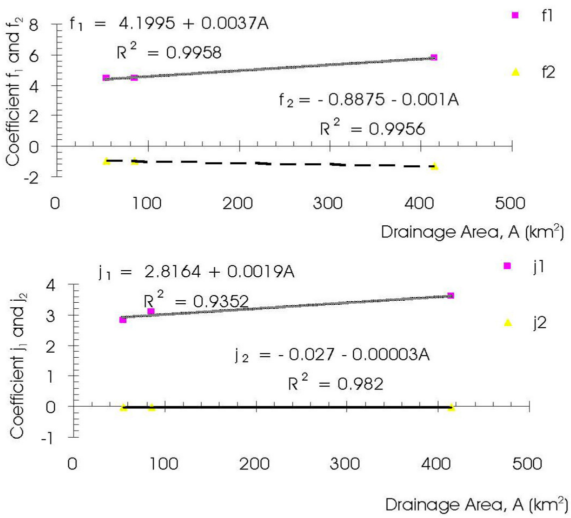

Fig 3.2. Relationship between coefficients f_1, f_2 versus drainage area and coefficients j_1, j_2 versus drainage area at sub-basin 1.

Table 5. Coefficients k_1 to k_4, l_1 to l_4, m_1 to m_4 and n_1 to n_4 of model developing in the Salawin river basin.

Coefficients		Sub-basin 1	2	3	4
$a_1 = k_1 + k_2A$	k_1	-5.116	1.844	-14.927	8.977
	k_2	0.114	0.036	0.127	0.043
	R^2	0.997	0.951	0.978	0.988
$a_2 = k_3 + k_4A$	k_3	1.102	-0.430	3.436	-1.966
	k_4	-0.025	-0.008	-0.028	-0.010
	R^2	0.997	0.958	0.981	0.987
$e_1 = l_1 + l_2A$	l_1	-3.076	-0.627	-11.987	5.085
	l_2	0.071	0.037	0.091	0.025
	R^2	0.998	0.940	0.977	0.991
$e_2 = l_3 + l_4A$	l_3	-0.027	-0.028	-0.024	-0.027
	l_4	-0.00003	-0.00003	-0.00001	-0.000001
	R^2	0.987	0.714	0.592	0.759
$f_1 = m_1 + m_2A$	m_1	4.200	5.280	3.957	4.848
	m_2	0.004	0.0001	0.001	0.0001
	R^2	0.996	0.009	0.460	0.479
$f_2 = m_3 + m_4A$	m_3	-0.888	-1.184	-0.815	-1.064
	m_4	-0.0010	-0.00003	-0.0002	-0.00004
	R^2	0.996	0.007	0.452	0.493
$j_1 = n_1 + n_2A$	n_1	2.816	2.684	2.523	2.773
	n_2	0.002	0.004	0.001	0.00008
	R^2	0.935	0.890	0.718	0.457
$j_2 = n_3 + n_4A$	n_3	-0.027	-0.028	-0.023	-0.028
	n_4	-0.00003	-0.00003	-0.00001	-0.000001
	R^2	0.982	0.737	0.630	0.869

$$Q = (k_1 + k_2A) + (k_3 + k_4A)\ln(D) \quad (19)$$
$$Q = (l_1 + l_2A)\exp((l_3 + l_4A)(D)) \quad (20)$$
$$\frac{Q}{\overline{Q}} = (m_1 + m_2A) + (m_3 + m_4A)\ln(D) \quad (21)$$
$$\frac{Q}{\overline{Q}} = (n_1 + n_2A)\exp((n_3 + (n_4A)(D)) \quad (22)$$

where the constants k_1 to k_4, l_1 to l_4, m_1 to m_4 and n_1 to n_4 are determined from Table 5.

The estimation of each sub-basin representative average flow ($\overline{Q}$) in Eqs. (21) and (22) is performed by the relationship between mean annual flow and drainage area, which is written as

$$\overline{Q} = aA^b \quad (23)$$

where A is drainage area in km^2, a and b are constants. In Table 6, the coefficients a, b and $\overline{Q}$ for each station are shown as follows

Table 6. Coefficients a, b and $\overline{Q}$ of model developing in the Salawin river basin.

Sub-basin	No.	Station	Drainage area (km^2)	a	b	$\overline{Q} = aA^b$ (m^3/s)
1	1.1	010204	54.4	0.002	1.3617	0.462
	1.2	010205	84.8			0.845
	1.3	010401	414.0			7.321
2	2.1	010502	43.6	0.1088	0.5507	0.342
	2.2	010601	589.0			11.833
	2.3	010602	297.0			4.658
3	3.1	010702	156.0	0.0047	1.2291	2.332
	3.2	010901	450.0			8.574
	3.3	011104	378.0			6.920
	3.4	011201	1,376.0			12.616
4	4.1	011701	1,100.0	0.223	0.5584	11.133
	4.2	011804	68.0			2.353
	4.3	011805	80.4			2.583

When $\overline{Q}$ is substituted into Eq. (21) and (22), the calculated flow models can be expressed as

$$Q = (m_1 + m_2A) + (m_3 + m_4A)\ln(D) \times aA^b \quad (24)$$
$$Q = (n_1 + n_2A)\exp((n_3 + (n_4A)(D)) \times aA^b \quad (25)$$

where the constants m_1 to m_4, n_1 to n_4, and a, b are determined from Table 5 and Table 6, respectively.

Model Calibration and Model Verification

Model calibration and model verification are required to evaluate the accuracy of regional model that develops from data of gauging stations in Table 3.1. These were achieved by comparing between measured discharge and computed discharge from regional models [Eq. (19), (20), (24) and (25)]. Measured discharge from gauging stations in Table 3.1 and 3.2 are used to construct model calibration and model verification respectively.

The accuracy of regional models is examined by using the measured discharges. In order to evaluate the accuracy of the prediction, the verification results are presented in term of root mean square relative error (*ER*), which is defined as

$$ER = 100\sqrt{\frac{\sum_{D=1}^{100}(Q_{D_c} - Q_{D_m})^2}{\sum_{D=1}^{100} Q_{D_m}^2}} \quad (26)$$

where D is the percent of time between 1 to 100 %, Q_{Dc} is the computed discharge at any percent of time, Q_{Dm} is the measured discharge at any percent of time.

Using the coefficients k_1 to k_4, l_1 to l_4, m_1 to m_4 and n_1 to n_4, from Table 5, constants a, b from Table 6, and drainage area of each station, the predicted discharges at 1 to 100 % with interval 1 % for each step or percentage, of time (D) are determined from Eq. (19), (20), (24) and (25) respectively. The errors *ER* of model calibration and model verification for each station and sub-basins are shown in Tables 7.1 and 7.2. The average errors for all cases by model calibration are 30.59 %, 39.49 %, 24.19 %, 28.14 %, and by model verification are 33.96 %, 36.81 %, 21.71 %, and 25.55 % respectively. It can be seen that the logarithmic model using dimensionless parameter gives reasonably well estimations of the FDC for the Salawin river basin. The model that gives the smallest ER value can be used to predict flow at the ungauged site which is located within sub-basin.

The comparison of ER in Table 7.1 and 7.2 indicates that the Eq. (24) has better result than Eq. (19). On the other hand, the regression analysis results in Table 5 show that the parameters a_1 and a_2 have the best value of R^2 for all sub-basins, while parameters f_1 and f_2 can not obtain good results. The contrasts of these values (ER and R^2) should not be related because ER is used to measure the prediction error of the proposed models (Eqs. (19), (20), (24) and (25)) whereas the values of R^2 indicate how strong linear relationship is between the coefficients($a_1, a_2, e_1, e_2, f_1, f_2, j_1, j_2$)and the drainage area ($A$).

Conclusions

The model of discharge estimation at ungauged sites is a useful tool for small run-of-river hydropower project development especially in remote area. In this study, the flow duration curves of gauging stations at the Salawin river basin were constructed and fitted by five distribution equations, i.e. logarithmic, quadratic, cubic, power, and exponential equations. It was found that the logarithmic and the exponential models gave better prediction than others. This finding is different from that of previous researchers such as Quimpo et al.[8] (1983) who proposed to use exponential equation and Mimikou and Kaemaki[9] (1985) who proposed to use cubic equation in modeling the flow duration curve. The differences may be because of the variance in topographic and climatic conditions that were used in the calibrations. The characteristics of each river basin are unique, thus no single model is applicable to every river basin. It means that the FDC model may not be a universal model (the model developed for one country or region may not suitable to apply for other countries).

The logarithmic and exponential equations were used to calculate the discharge. The equations come from fitted lines with the relations between all recording

Table 7.1. Comparison of root mean square relative errors ER of model calibration between logarithmic and exponential equations.

Sub-basin	Station	*ER* of model calibration			
		FDC model		Dimensionless model	
		Logarithmic, Eq. (19)	Exponential, Eq. (20)	Logarithmic, Eq. (24)	Exponential, Eq. (25)
1	010204	50.29	60.66	8.22	19.13
	010205	37.69	21.32	17.02	22.10
	010401	26.64	37.47	27.09	29.14
2	010502	19.31	68.27	17.37	25.21
	010601	12.26	14.98	20.43	21.22
	010602	47.34	47.86	54.47	38.60
3	010702	35.16	64.21	9.78	9.99
	010901	60.01	63.05	37.22	38.73
	011104	25.73	28.00	35.15	38.12
	011201	8.91	10.75	10.95	10.57
4	011701	15.38	26.22	14.43	36.14
	011804	21.31	39.09	23.79	49.40
	011805	37.70	31.45	38.50	27.48
Average		30.59	39.49	24.19	28.14

Table 7.2. Comparison of root mean square relative errors (ER) of model verification between logarithmic and exponential equations.

Sub-basin	Station	*ER* of model verification			
		FDC model		Dimensionless model	
		Logarithmic, Eq. (19)	Exponential, Eq. (20)	Logarithmic, Eq. (24)	Exponential, Eq. (25)
1	010201	81.76	41.50	31.71	13.64
	010202	22.86	36.27	8.19	14.83
	010203	18.68	15.24	11.71	17.96
2	010505	27.78	72.14	40.89	64.44
3	010903	45.07	48.66	25.06	28.68
	010904	8.97	20.46	6.16	13.09
	011103	19.05	28.32	17.61	28.59
4	011803	47.54	31.86	32.31	23.19
Average		33.96	36.81	21.71	25.55

data of discharge (Q) versus the percentage of time that discharge equaled or exceeded (D), and the relations between the dimensionless discharges, that is the ratio of discharge to average discharge $Q/\overline{Q}$, versus D. Each relation was fitted by the logarithmic and exponential equations. The calculated discharges from four equations were examined using the root mean square relative error (ER) with the actual value from gauging stations. It was found that the logarithmic model from the relation of $Q/\overline{Q}$ and D gave the best flow prediction (ER equal 24.19 % for model calibration and 21.71 % for model verification). The variations of coefficients in the models are expressed in term of drainage area (A) and the percent of time (D). Although the model is simple, reasonably good agreements are obtained between measured and computed flow duration curves. Therefore the simple regional flow duration model that used only the drainage area, is appropriate, when seeking for potential sites of small run-of-river hydropower project, as a first stage in feasibility study because of the availability of data and less cost and time consuming.

Acknowledgements

The authors express their thanks and appreciation to the Joint Graduate School of Energy and Environment (JGSEE), King Mongkut's University of Technology Thonburi for fund support to the first author. The authors would like to thank the Department of Water Resources (DWR) for providing the data used in this study.

References

1. Pichalai C (2005) The role of Thai energy policy and strategies in sustainable development. *The Journal of the Royal Institute of Thailand* **30** (3), 717-31.
2. Vogel RM and Fennessy N (1995) Flow duration curve II: A review of applications in water resource planning. *Water Resource Bulletin* **31** (6), 1029-39.
3. Smakhtin VU (2001) Low flow hydrology: a review *Journal of Hydrology* **240**, 147-86.
4. Chiang SM, Tsay TK and Nix SJ (2002) Hydrologic regionalization of watershed. II: Applications *Journal of Water Resources Planning and Management* **128** (1), 12-20.
5. Yu PS, Yang TC and Wang YC (2002) Uncertainty analysis of regional flow duration curves. *Journal of Water Resources Planning and Management* **128** (6), 424-30.
6. Castellarin A, Galeati G, Brandimarte L, Montanari A and Brath A (2004) Regional flow-duration curves: reliability for ungauged basins. *Advances in Water Resources* **27**, 953-65.
7. Smakhtin VY, Hughes DA and Creuse-Naudin E (1997) Regionalization of daily flow characteristics in part of the Eastern Cape, South Africa. *Hydrol. Sci. Journal* **42** (6), 919-36.
8. Quimpo RG, Alejandrino AA and McNally TA (1983) Regionalized flow duration for Philippines. *Journal of Water Resources Planning and Management* **109** (4), 320-30.
9. Mimikou, M. and Kaemaki, S. (1985) Regionalization of flow duration characteristics. *Journal of Hydrology* **82**, 77-91.
10. Franchini M and Suppo M (1996) Regional analysis of flow duration curves for a limestone region. *Water Resources Management* **10**, 199-218.
11. Vogel RM and Fennessy N (1994) Flow-duration curves. I: New interpretation and confidence intervals. *Journal of Water Resources Planning and Management* **120** (4), 485-504.
12. Fennessy N and Vogel RM (1990) Regional flow-duration curves for ungauged sites in Massachusetts. *Journal of Water Resources Planning and Management* **116** (4), 530-49.
13. Castellarin A, Vogel RM and Brath A (2004) A stochastic index flow model of flow duration curves. *Water Resources Research* **40**, W03104, doi: 10.1029/2003WR002524.
14. Singh KP (1971) Model flow duration and stream flow variability. *Water Res. Research*. **7** (4), 1031-6.
15. Singh RD, Mishra SK and Chowdhary H (2001) Regional flow-duration models for large number of ungauged Himalayan catchments for planning microhydro projects. *Journal of Hydrologic Engineering* **6** (4): 310-6.
16. Office of the National Economic and Social Development Board (1994) Study of potential development of water resources in the Salawin river basin (Prepared by Asian Institute of Technology), pp 3-1 to 3.5.