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MEASURING OPTIMAL CONDITION OF RAINFALL-STREAMFLOW NETWORK MODEL BASED ON MULTIVARIATE LINEAR REGRESSION ANALYSIS FOR FLOOD FORECASTING IN KLONG LUANG SUB-WATERSHED, CHON BURI PROVINCE, THAILAND.

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ABSTRACT

A simplified rainfall-streamflow network model on the basis of multivariate linear regression (MLR) analysis has been proposed. To determine significant coefficient of streamflow network among the area of interests, eleven MLR models, i.e., models 1 to 11, were examined. We used the Geographic Information System (GIS) and Remotely Sensed Data (RS), where data were recorded from Klong Luang (KGT.19 Station) sub-watershed, Phanat Nikhom district, Mueang Chon Buri district, Ban Bueng district, and Phan Thong district, at Chon Buri province, Thailand. The experimental result showed that the MLR based models 8 and 11 were most applicable to be employed for this purpose. The proposed model could considerably be applied to flood forecasting, water resource management, flood hazard planning, and flood early warning.

Keywords: Flood forecasting, multiple regression analysis, rainfall-streamflow network model, rainfall-runoff process, and Klong Luang sub-watershed.

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INTRODUCTION

Thailand had witnessed its worst flooding in half a century in the year 2011 and had left severe impairments to the country's economy, industrial sector, and society. The worst flooding had occurred following the heavy raining during the monsoon season in 2011, which was begun at the end of July triggered by the landfall of Tropical Storm Nock-ten where the flooding was soon spread through several provinces in the North, Northeastern, and Central Thailand. The flooding was spread along the Mekong and Chao Phraya river basins, where floodwaters reached the mouth of the Chao Phraya and inundated several parts of the capital city of Bangkok in October 2011. The Flooding persisted in some areas until mid-January 2012, which resulted in a total of 815 deaths with 3 missing people, while 13.6 million people were affected. According to Thailand Geo-Informatics and Space Technology Development Agency, there were 65 out of Thailand's 77 provinces that declared as flood disaster zones, and over 20,000 km^2 of farmland were damaged. The disaster had been described as "the worst flooding yet in terms of the amount of water and people affected."

Various regions of Thailand are prone to seasonal flash flooding due to their tropical savanna climate. The floods often occur in the North and spread down the Chao Phraya River through the central plains, in the Northeast along the Chi and Mun Rivers flowing either into the Mekong River or into the coastal hillsides of the East and South. Remnants of tropical storms that strike Vietnam or the south peninsular are commonly increased the precipitation resulting in further risks of flooding. Drainage control systems, including multiple dams, irrigation canals, and flood detention basins have been implemented, but they are inadequate to prevent flood damage, especially to rural areas. A lot of effort, including a system of drainage tunnels begun in 2001 has been put into the preventing scheme of the enormous flooding of the capital city, which lies near the mouth of the Chao Phraya River and is prone to the flooding, with considerable success. Bangkok has experienced only a brief and minor flooding since the major floods of 1995, while other regions, however, have experienced severe flooding as recently as 2010.

Several of the manufacturing industries, i.e., seven major industrial estates were inundated by as much three meters during the floods. Disruptions to manufacturing supply chains affected regional automobile production and caused a global shortage of hard disk drives, which lasted throughout 2012. The size and scope of the 2011 flood could, in part, be attributed to the low rainfalls of the 2010 monsoon season. The water levels in Bhumibol Dam hit record lows on June 2010. The evidence showed that early in the season the dams collected large amounts of water building reserves and buffering early flooding. The scale of the rainfalls of 2011 was evidenced by the amount of waters collected behind Bhumibol Dam, where over eight billion cubic meters of water were collected in three months filling this dam to 100%. Once at capacity, continuing rains forced officials to increase flows from the dams despite increasing flooding and this led to accusations that the dams were mismanaged early in the monsoon season. The World Bank had estimated 1,425 billion Baht in economic damages and losses due to flooding, as of December 1, 2011 (World Bank, 2011).

Geographic Information System (GIS) and Remote Sensing (RS) data have been recently proven to be the constructive tools for predicting flood of the flood prone area. On the other hand, the basic theory of water management can be applied to perform the integrated model from meteorology, geography, and hydrographs in terms of the spatial information system. Fotheringham and Rogerson (1994) had proposed the topography, land use, soil properties, and the moisture situation of the study area would be coded in the hydrologic response unit named as the curve number as referred to by U.S. Department of Agriculture and Soil Conservation Service. GIS has been applied to several branches of research in Thailand, i.e., the application for locating the risk area of the threshold, Huai Kha Khaeng Wildlife Sanctuary, was proposed in 1998 (Boonyanuparp, 1998), while

Phuengkul (2000) reported that he had applied GIS. Ratchatawongse (1998) also proposed that the GIS data should be applied for the determination of shore forest management guideline of Samut Songkhram province. The application of GIS for evaluating the suitable area in order to locate the industrial factory in Wang Noi, Phra Nakhon Si Ayutthaya province had been described in the city master planning in 1998(Pongsesuwakon, 1998). A human, in fact, invents the model in order to use as a problem solving-tool instead of using a real thing. The invention of model is a natural's behavior modeling. Flood forecasting is the use of precipitation and streamflow data in rainfall- streamflow routing models to forecast flow rates and water levels for periods ranging from a few hours to days ahead, depending on the size of the watershed or river basin. The future streamflow is mainly dependent on initial catchment states and future rainfall, while the use of the mathematical models together with estimated future rainfall can produce skillful forecasts of future streamflows. The component of the model simulates the streamflow response to the precipitation by means of simple equations that represent surface flow using hypothetical data, e.g., GIS and RS data (Wang et al., 2011).

In recent decade, the objectives of hydrological modeling have been broadened to include water level analysis and flood forecasting. Recent studies have shown that the use of precipitation and streamflow data in rainfall and streamflow routing models can be utilized as a parameter for flood forecasting (Tokar and Johnson 1999; Smith and Eli, 1995). Other related studies, i.e., neuron network model (Danh et al., 1999; Supharatid, 2003), and hybrid network (Chau et al., 2005), are used when these models are not really intended for forecasting purposes (Tokar and Johnson, 1999). However, the aforementioned methods require extremely training processes, huge collection of data, and it is difficult to set technical parameters for the real-world applications. Most conceptual rainfall-streamflow models generally produce values for discharge rather than water levels.

In this study, we are mainly focused on the possible flood in Klong Luang sub-watershed since the Department of Water Resources reported that Klong Luang sub-watershed, Chon Buri province, Thailand, covers an area of 1,897 square kilometers, which includes Phanat Nikhom district, all of Ban Bueng district area, some parts of Phan Thong district, Nong Yai district, Bo Thong district, Ko Chan district, and Muang Chon Buri district. This sub-watershed is the most important in Chon Buri province, which is the development center of the Eastern Seaboard of Thailand. The upstream of the watershed drains from the southwest mountain in Bo Thong district resulting in flooding over Phan Thong district every year (Office of Natural Resources and Environment Chon Buri, 2004).

Therefore, we propose the rainfall-streamflow network model based on multivariate linear regression (MLR) analysis to deal with these cases. This is the basis for the ensemble streamflow prediction system, where this approach has not been explored in Thailand. The proposed MLR model is the simplest and well-developed representation of a causal, time-invariant, relationship between an input rainfall of time and the corresponding output streamflow. The proposed model is expected to be able to estimate output magnitude of streamflow for water resources management and decreasing flood areas in Klong Luang sub-watershed, Chon Buri province, Thailand.

MATERIALS AND METHODOLOGY

The rainfall to streamflow process was non-linear in nature and it was proved to be the main difficulty in streamflow modeling. Nevertheless, the rainfall-streamflow model could be reasonably approximated as a linear process (Todini and Bossi, 1986), provided backwater effects were negligible. Therefore, we hypothesized the relationship between the rainfall and streamflow processes on the basis of general forecasting equation (Phien el al., 2003). The MLR used several explanatory variables to forecast the outcome of a response variable, which could be defined as follows:

$$\mathbf{W}_{t+T} = \alpha_0 + \beta_t \cdot \sum \mathbf{B}_t \quad \text{for } t = 1,2,\ldots,n \qquad (1)$$

where $\mathbf{W}_{t-T}$ was an output streamflow, $\mathbf{B}_t$ was a design matrix of predictor variables, β_t was a vector or a matrix of regression coefficients, and α_0 was a constant, with multivariate normal distribution. We used 'mvregress' (Multivariate linear regression functions in MATLAB's Statistics Toolbox) function to determine coefficients for a multivariate normal regression of the d-dimensional responses. Each dimensional response in the multivariate linear regression model had a corresponding design matrix, where the design matrix that was depending on the model, might be comprised of exogenous predictor variables, dummy variables, lagged responses, or a combination of these and other covariate terms. Using the ordinary multivariate normal maximum likelihood estimation (Little and Donald, 2002), the regression coefficients could be obtained. We examined the possible MLR based model by using rainfall database as dependent variable in this preliminary study. We focus on the average monthly streamflow volume in the enclosed drainage area after it was analyzed, where the data in this section demonstrated the MLR based streamflow and rainfall results. The linear regression line and its 95% confidence interval were determined in order to show the results in terms of MLR model. The data showed the forecasted streamflow at KGT 19 station during the rainfall periods from 1965 to 1990. General scheme of flood forecasting model based on MLR model is depicted in Figure 1.

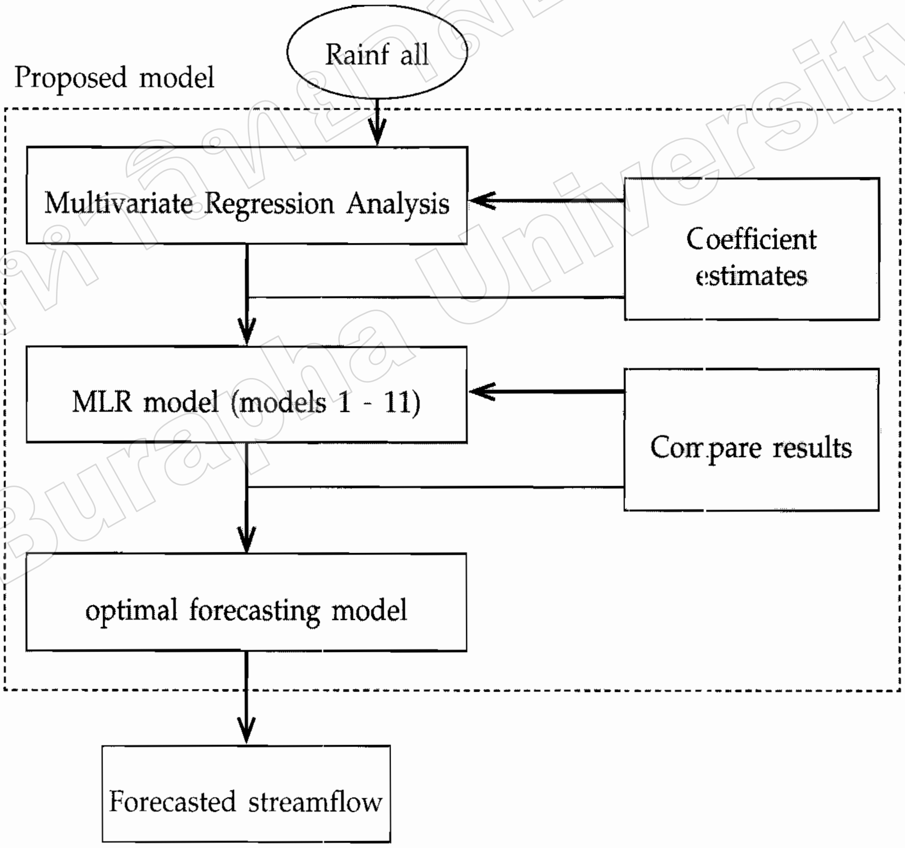
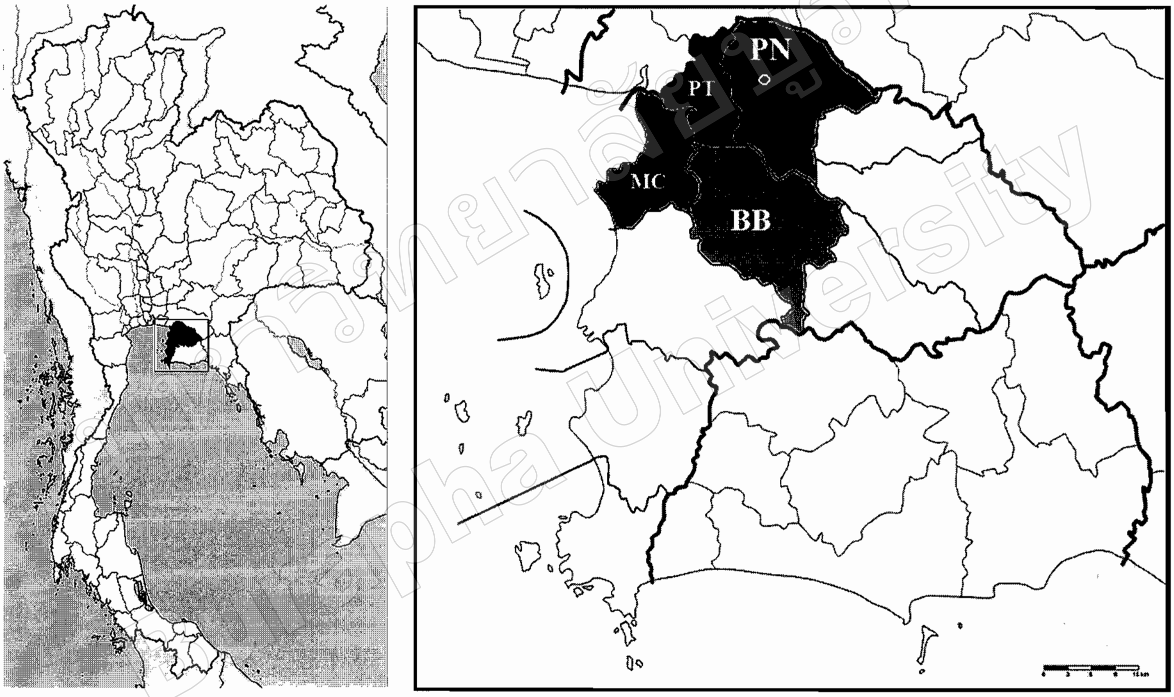


Figure 1. Showing a proposed general scheme of rainfall-streamflow network model.

Figure 1 is the schematic diagram showing the proposed general scheme of the flood-forecasting model, which is based on multivariate regression analysis (MLR) model. The conceptual idea was to forecast the streamflow through MLR with an optimal model. The eleven MLR models were investigated to be compared each other. The best correlation resulted from the comparison with the original streamflow data was selected as an optimal model, i.e., Model 8 and Model 11.

We collected the data as follows: the topographic map from Royal Thai Survey Department (RTSD, 1997) series L 7018 scale 1:50,000 (sheet 5235I - IV 5236 II 5236III 5335III and 5335IV), the remotely sensing data by the LANDSAT-5 SATELLITE 2008, and data were subsequently analyzed by MATLAB R2010B. It was shown the it caused a lot of economic and social damages, on the trade centers, industries, and infrastructures of eastern Thailand, especially in the regions of Muang Chon Buri district, Phanat Nikhom district, Ban Bueng district and Phan Thong district. Therefore, this study was then focused mainly on the four districts nearby Klong Luang sub-watershed, i.e., Phanat Nikhom, Mueang Chon Buri, Ban Bueng, and Phan Thong, as shown in Figure 2.



Legend: KL = Klong Luang KGT.19, PN = Phanat Nikhom, MC = Mueang Chon Buri, BB = Ban Bueng, PT = Phan Thong

Figure 2. The maps of the study areas, where the locations of the selected areas are located: left - A map of Thailand where Chon Buri province is located, right - selected districts.

RESULTS AND DISCUSSIONS

Results of analyzed data are summarized in Figures 3 to 6. Regression parameters of annual rainfall against annual streamflow at Klong Luang sub-watershed are summarized in Tables 1 to 2.

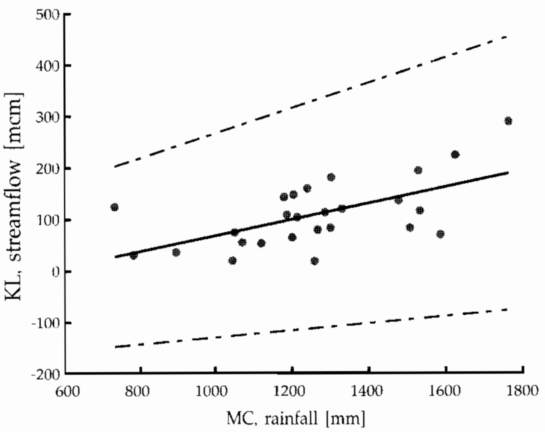


Figure 3. Results of MLR with 95% confidence interval for MC vs KL.

The results in Figure 3 showed the relationship between the amount of rainfall at Muang Chon Buri (MC) and the streamflow of Klong Luang (KL). The representative linear equation suggested that a relationship that was likely to increase with the regression and correlation coefficients 0.1582 and 0.6062, respectively. The dotted line showed the linear equation with 95% confidence interval for MC vs KL.

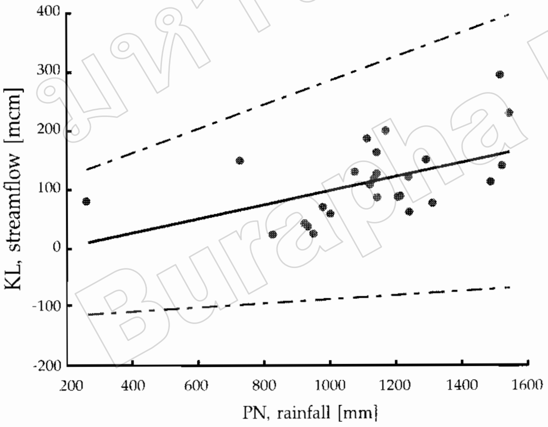


Figure 4. The relationship between the MLR with 95% confidence interval for Phanat Nikhom(PN) vs Klong Luang(KL).

It is shown that the relationship between the amount of rainfall at Phanat Nikhom (PN) and the streamflow of Klong Luang (KL) was a linear relation, where a relationship was likely to increase with the regression, which correlation coefficients were 0.1198 and 0.5037, respectively. The dotted line showed the linear equation with 95% confidence interval for MC vs KL.

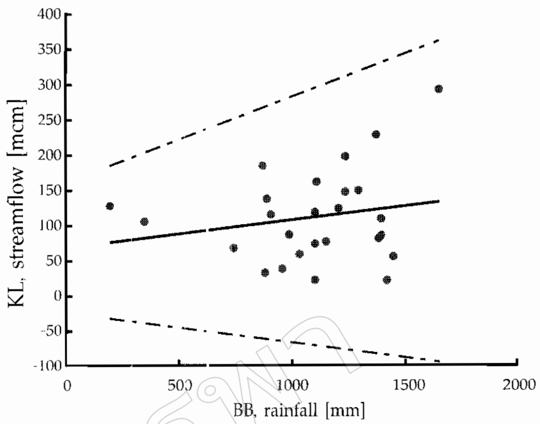


Figure 5. Results of MLR with 95% confidence interval for Ban Bueng (BB) vs Klong Luang(KL).

Results in Figure 5 showed a linear correlation of a relationship between the amounts of rainfall at Ban Bueng (BB) and the streamflow of Klong Luang (KL), where the relationship was likely to increase with the regression, which the correlation coefficients were 0.0402 and 0.2024, respectively. The dotted line showed the linear equation with 95% confidence interval for MC vs KL.

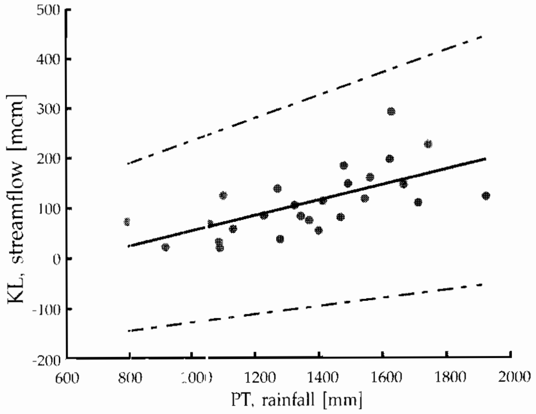


Figure 6. The relationship between the amount of rainfall at Phan Thong (PT) and Klong Luang (KL) using MLR with 95% confidence intervals.

Results in Figure 6 demonstrated a linear correlation of a relationship between the amount of rainfall at Phan Thong (PT) and the streamflow of Klong Luang (KL), where a relationship was likely to increase, which the values of regression and correlation coefficients were 0.1565 and 0.6532, respectively. The dotted line showed the linear equation with 95% confidence interval for MC vs KL.

Table 1. Regression parameters of the MLR model for all districts.

District	**Klong Luang sub-watershed (KL)**	
	Regression coefficient	**Correlation coefficient**
Mueang Chon Buri (MC)	0.1582*	0.6062
Phanat Nikhom (PN)	0.1198	0.5037
Ban Bueng (BB)	0.0402	0.2024
Phan Thong (PT)	0.1565	0.6532**

Note: * = highest positive slope, ** = best correlation

Results in Table 1 showed the highest regression and the best correlation coefficients which were obtained at MC and PT, respectively, while the height slope was a linear effect of MC and KL, whereas a value equal to the zero on the predictor variable had no influence on the slope of the regression line of BB and KL. It is shown that an observation at KL that was extremely high on the predictor variable, where it had the potential affect on the slope greatly to the MC and PT. These results showed that the amount of rainfall at MC, PN and PT could be able to statistically forecast the water streamflow at KL, whereas results of coefficient from BB were less correlated. The positive regression coefficient indicated the increasing trend of rainfall. Since all data had been collected from a short period during 1965 – 1990, the effectiveness in forecasting could be improved by using longer data. In order to apply the proposed model in practice, 95% confidence intervals were determined, as shown in Table 2.

Table 2. Statistical results within 95% confidence intervals from Table 1.

District	**Klong Luang sub-watershed (KL)**	
	Regression coefficient (upper)	**Regression coefficient (lower)**
Mueang Chon Buri (MC)	0.2457	0.0708
Phanat Nikhom (PN)	0.2064	0.0332
Ban Bueng (BB)	0.1221	-0.0417
Phan Thong (PT)	0.2329	0.0801

The extended equation (1) was an optimal MLR model in this study could be defined as:

$$W_{t+\tau} = \beta_0 \sum_{j=1}^{m} R_{MC,t-j+1} + \beta_1 \sum_{j=1}^{m} R_{PT,t-j+1} + \beta_2 \sum_{j=1}^{m} R_{BB,t-j-1} + \beta_3 \sum_{j=1}^{m} R_{PN,t-j+1} \qquad (2)$$

Where β was the value of regression coefficients. We then applied the equation (2) to forecast streamflow over the period of 1965 to 1990 (m = 26). It could be solved by the ordinary multivariate normal maximum likelihood estimation (Little and Donald, 2002). The two optimal MLR based models were used for applying in streamflow network, as shown in Figure 7. The proposed model was a new idea to represent the connectivity for rainfall-streamflow based analysis of nearest locations. By using this similar scheme, in particular, we can model other connecting networks.

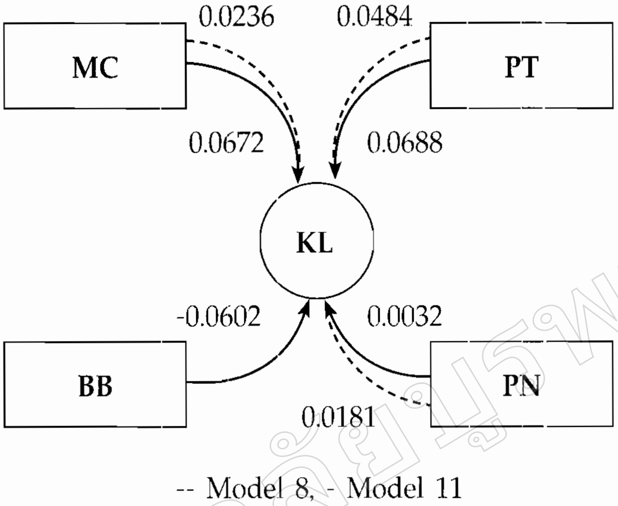


Figure 7. Showing two optimal MLR based models for streamflow network connecting.

Based on the results from Figures 3 to 6, we found that the relational rainfall-streamflow data from nearest locations could be used and modified as a proposed model to extend the network from four districts to connect with Klong Luang sub-watershed where the values of regression coefficients were different.

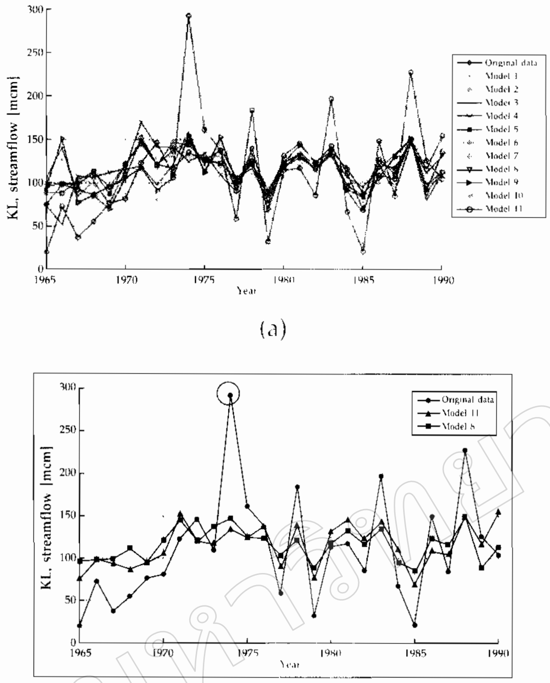
All forecasted results, i.e., from Models 1 to 11 were determined and summarized, as shown in Table 3.

Table 3. Showing all results of comparison using all of statistically different MLR models.

No.	Model	Regression coefficient	Correlation coefficient
1	[MC, PT]	[0.0369, 0.0511]	0.7470
2	[MC, BB]	[0.1231, -0.0368]	0.6041
3	[MC, PN]	[0.0642, 0.0304]	0.6354
4	[PT, BB]	[0.1076, -0.0298]	0.6361
5	[PT, PN]	[0.0579, 0.0326]	0.7455
6	[PN, BB]	[0.0905, 0.0101]	0.5159
7	[MC, PT, BB]	[0.0699, 0.0694, -0.0608]	0.7452
8	[MC, PT, PN]	[0.0236, 0.0484, 0.0181]	0.7833*
9	[MC, BB, PN]	[0.0986, -0.0342, 0.0249]	0.6213
10	[BB, PN, PT]	[-0.0375, 0.0400, 0.0815]	0.7035
11	[MC, PT, BB, PN, PN]	[0.0672, 0.0688, -0.0602, 0.0032]	0.7650

Note: * = best correlation indicates the optimal locations corresponding to the observed KL KGT.19 station.

We employed the MLR model in equation (2) after forecasting in order to show different results from all models. All obtained result that the outlier due to overshoot rainfall data in 1974 were summarized, as shown in Figure 8, where the optimal MLR models were applied in Figure 7



(a)

(b)

Figure 8. (a) Comparison of forecasted streamflow determined by all models. (b) Selected MLR based models 8 and 11 at KL and outlier marked in dotted circle (note: 'mcm' stands for million cubic meters).

Results in Figure 8 showed the obtained results that the outliers were due to the overshoot rainfall data in 1974. The optimal MLR models were applied in Figure 7 in order to simulate forecasting streamflow for the upcoming years and for the future. The forecasted results showed that the level of streamflow at KL sub-watershed was increased linearly. We assumed that the rainfall data in equation (1) were independent, where the records of rainfall had nothing to do with those of another variable. In this study, we found that the streamflow variable was usually affected by the rainfall variables, whereas the MLR model could not show the causation by itself. Therefore, the presence of outliers, as shown in Figure 8, could seriously affect the results.

Results in Figure 8(a) showed results of forecasting streamflow for the upcoming years and for the future after the application of all MLR models. The forecasted results showed that the level of streamflow at KL sub-watershed was increased linearly. Results in Figure 8(b) showed the outliers, which were due to the overshoot rainfall data in 1974. In this study, we found that the streamflow variable was usually affected by the rainfall variables, whereas the MLR model could not show the causation by itself. The presence of outliers was shown in dotted circle. The MLR in this case might not give a high-precise result due to the linear combination in equation (2). We proposed the possible three solutions, i.e., by excluding it while determining regression coefficient, by sub-dividing data as a shorter period, and by using nonlinear or other intelligent models, in order to deal with this problem. However, the process of nonlinear or intelligent models was iterative, which required an initial value and more computational process, where it made difficult in finding the optimal model. We could get the better results in other perspectives, such as in terms of the normal probability distribution. The proposed MLR model and the original water streamflow were compared to reveal capability in forecasting streamflow, as shown in Figure 9.

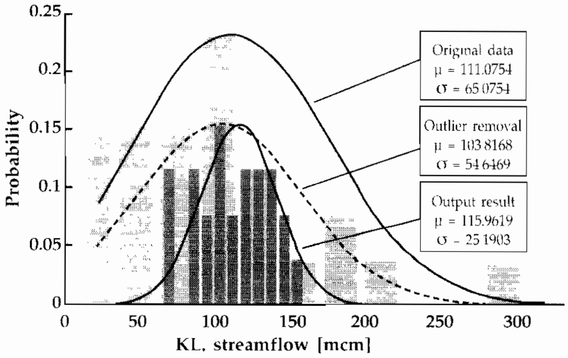


Figure 9. The comparison of real KL streamflow and forecasted normal distributions.

The results of the analytic MLR were evaluated as the normal probability distribution function. The results were better than those in Figure 8 in terms of probabilistic domain. The comparisons among the actual data (original data), outlier data (outlier removal), and the prediction (output result), yielded the average streamflow data values, which were 111.0754, 103.8168 and 115.9619 mcm, respectively. We also found that the interesting results of both expected values (μ) were similar, where μ_0 = 115.9619, μ = 111.0704 (in million cubic meter: mcm) for the proposed MLR model and the original water streamflow, respectively. The probability curve had been changed to close to the proposed MLR model when removing outlier. We applied the optimal model (Model 8) to forecast streamflow during the period 1991 to 2004, as shown in Figure 10, where the results showed that the correlation coefficient was very high value. *R* = 0.8240.

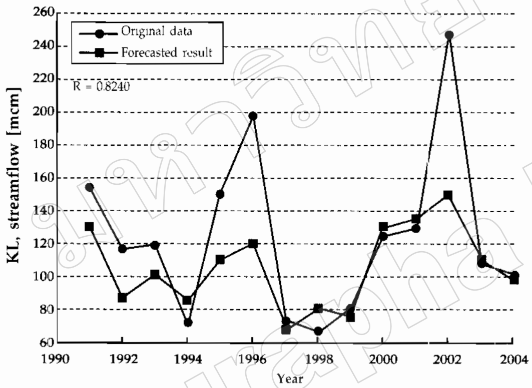


Figure 10. Showing results of applying optimal model to forecast streamflow during the period 1991 to 2004

We applied the optimal model, Model 8, to forecast streamflow during the period of 1991 to 2004. The results showed that the correlation coefficient was very high value, *R* = 0.8240.

The result of streamflow consisted of the analysis of monthly streamflow data for the classification of a watershed system in Klong Luang, and was calculated by means of the maximum and minimum streamflow. We found that the most of the streamflow occurred from May to October, whereas the maximum monthly rainfall was in September and October.

Flood stage forecast maps on a map identify their location relative to expected flood inundation as topographical flood forecasting. It was found after the application of the optimal rainfall-streamflow network model that the map of a direction of streamflow was increased in accordance to the rainfall data, where it was supposed to be in the same character of geography. Results in Figure 12 showed that the forecasted flood level was very high along the stream due to the soil properties and the moisture situation of the study area as a result of the hydrologic response. The urban area was the place that supposed to show the future forecasted flood map. as shown in Figure 13. The corresponding results were also suggested that the area along the stream must be monitored carefully for the next century, especially the urban area which policies to encourage economic growth and development would be implemented.

In conclusion, three objectives have been accomplished in this study, as follows: 1) to develop a novel approach as a mathematical model based on MLR analysis for optimally water level forecasting, 2) to determine a most significant coefficient of rainfall-streamflow network among on an area of interests nearby Klong Luang sub-watershed KGT.19 station, and 3) to apply the optimal MLR model for water level and flood forecasting maps in Klong Luang Sub-watershed. The proposed model may be useful for strategic planning and water resources management, and we would like to suggest the use of the optimal MLR based model for constructing the streamflow network. It is most likely that the MLR Model 8 is the most suitable approach to be used as the benchmark for water level forecasting in Klong Luang sub-watershed KGT.19 station, Chon Buri province, Thailand, where the model yields fastest computation without training process. This network can considerably be applied to other flood-forecasting model. The MLR based model is basically concerned with collection, manipulation, management, organization and analysis of numeric data. This investigation concludes with recommendations as a choice of methods for determining the significance of rank different coefficients. The MLR based model 8 is suggested as a model of choice due to the best correlation that has been found. In this study, we proposed the preliminary results by using rainfall-streamflow network model. In terms of landscape planning, which is directly related to regional planning, the result from forecasted mapping is very typically useful for a landscape architect as well because it provides information for advance planning to have a basic understanding and the environment together with development.

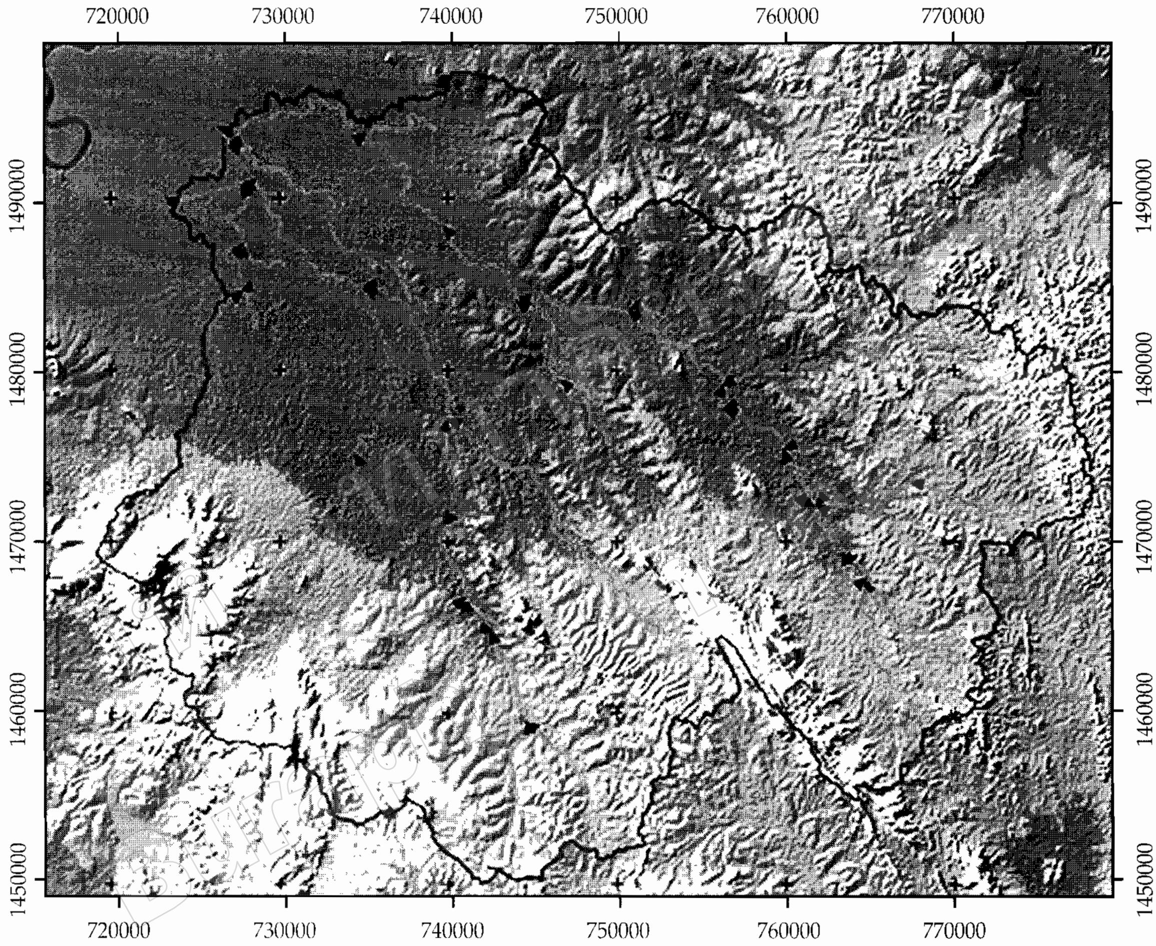


Figure 11. Digital elevation model (DEM) shows the earth's surface and includes all objects on it. This map is the relief map of Klong Luang sub-watershed at Chon Buri province.

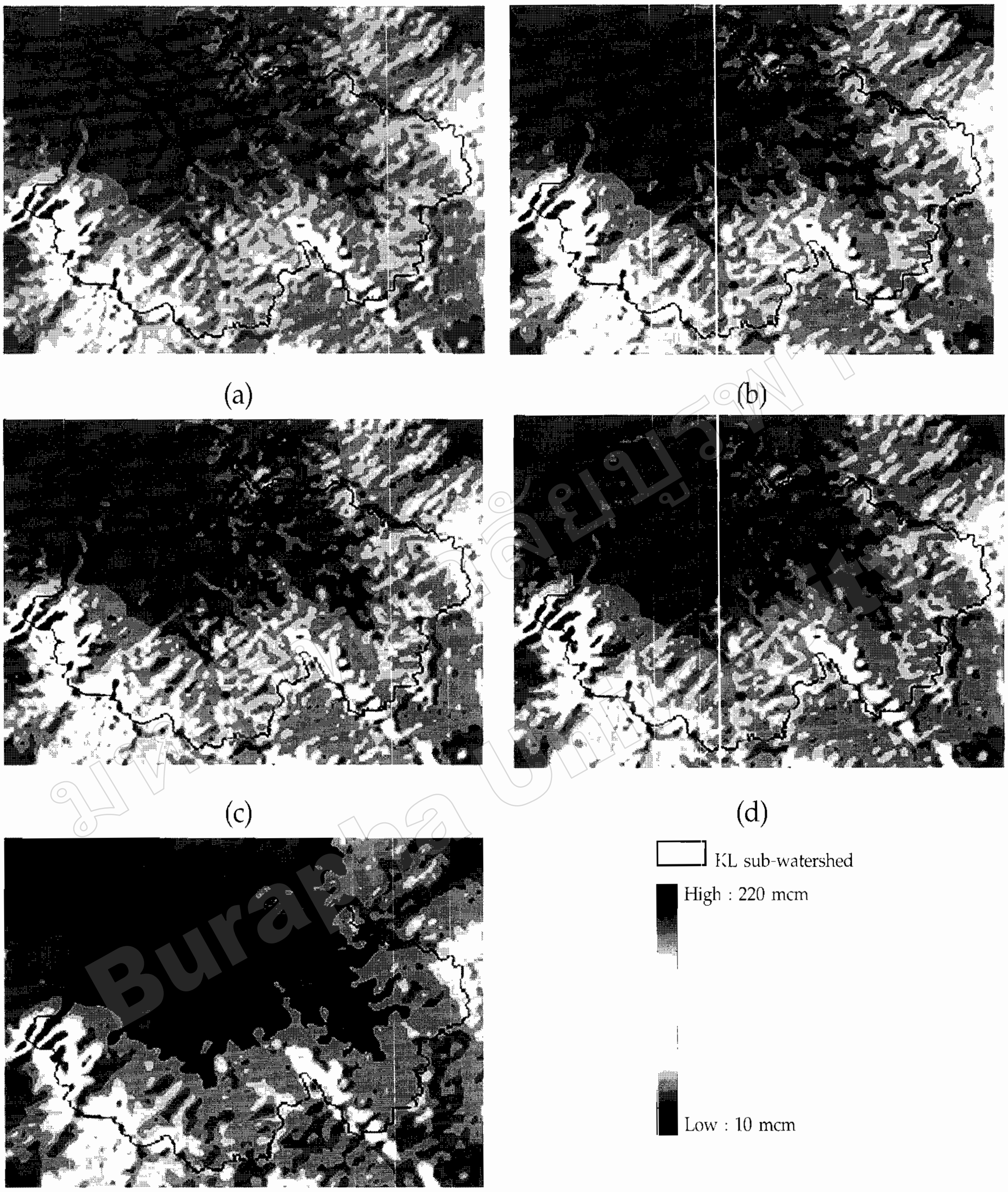


Figure 12. Topographical mapping at the return periods of: (a) 5 years, (b) 10 years, (c) 50 years, (d) 100 years, and (e) 500 years.

Results in Figure 12 showed that the topographical mapping of water level forecasted by the optimal model, where the results were simulated covering the area of Klong Luang sub-watershed.

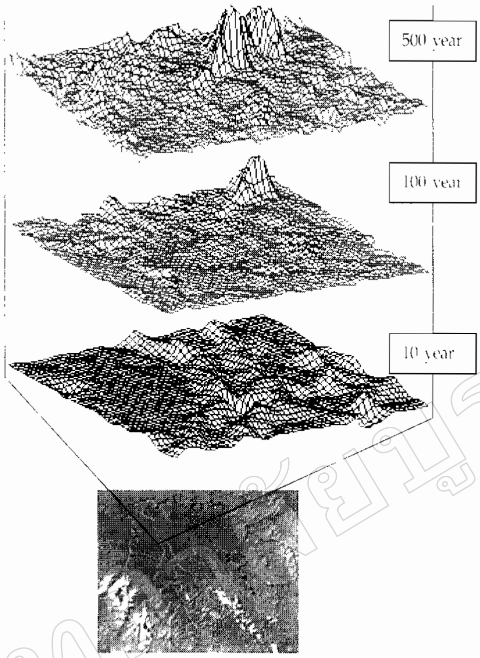
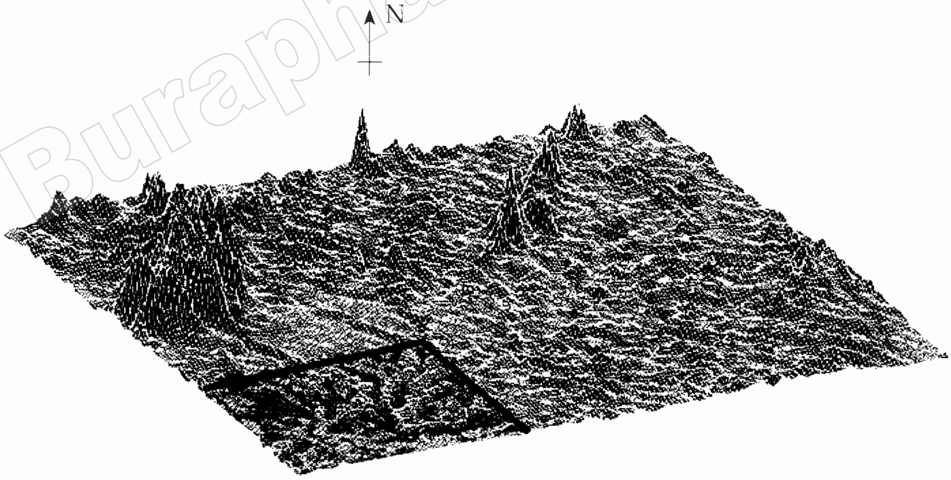


Figure 13. Showing the forecasted water level by return periods of 10, 100, and 500 years.

The sampling point was on the measured streamflow of Klong Luang sub-watershed. We found that the water level was increased every year. We believed that these results were useful in planning water management and urban structure in the future.



Small inset = urban area cover 7 km^2

Figure 14. Typical simulated map with the forecasted flood at the return periods of 500 years. Area of interest cell size 100 m2 in top view (small inset).

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