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Artificial Neural Networks Model for Multireservoir Water Allocation

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ABSTRACT

This research aimed to develop the multireservoir water allocation model for the Upper Mun basin in Northeast of Thailand where there were 4 large scale multipurpose reservoirs namely Lam Chae, Mun Bon, Lam Phra Ploeng and Lam Takong located. The study area covered 7,190 sq.km. The water in the basin was used for 4 purposes namely agriculture, municipal and industrial water supply, preserving the ecological system equilibrium and the water requirements at the river basin outlet for downstream users. There were 4 big irrigation systems covering the area of 353,650 rai and 8 municipal and industrial water supply systems. 25 years of monthly data were used in the analysis of the water shortage in the basin. The optimum water allocation among the 4 water user groups was derived by the multiobjective optimization techniques called Epsilon-constraint linear programming. The best water allocation policy that satisfied the profitability, equity and reliability criteria was derived by the multicriteria decision making process called AHP. The priority weights for profitability, reliability and equity were 41, 32.3 and 26.7% respectively. The best water allocation policy was then simulated by HEC-3 using the cases of dry and normal year. The simulation result was used to develop the artificial neural networks model for multireservoir water allocation. The 12-16-4-4 MLFF-BP neural networks were the best fitted model. The model showed very high R^2 of 0.9578-0.9900 for training and R^2 of 0.8041-0.9658 for the testing. The 12-16-4-4 MLFF-BP neural networks model was tested by comparison with the actual data in 2001 and 2002. This research illustrated that the artificial neural networks was simple and could practically be applied to the multireservoir water allocation.

Key words: artificial neural networks, water allocation, water shortage, upper Mun Basin

INTRODUCTION

Most of the large scale reservoirs are the multipurpose type. The conflicting uses of water among different purposes usually exist. Most of the major river basins in the world have more than one multi-purposes reservoirs linking in series or parallel or mixed system. The operation of such system can be very complicated. Therefore, it is important to study the behavior of the system from the management and operation point of view such as the effect of water uses on various purposes in order to develop the water allocation strategy and tools for the decision makers. Water allocation is the decision making process to find the amount of water that should be allocated for each water user groups in the most effective and efficient manners. The effective water allocation should satisfy current demands and preserve adequate supply for the future use (Ford *et al.*,1997). The water shortage is

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the reservoir management problem which commonly occurs. The water allocation model is a very important tool for water managers to cope with the water shortage problems. Two common approaches for multireservoir water allocation modeling are simulation and optimization techniques (Fontane, 2000; Bielsa and Duarte, 2001). Although those approaches generally provide the detailed realistic representation of the complex characteristics of the multireservoir system, they are complicated and usually not used in the real time reservoir operations. On the contrary, the artificial neural networks (ANNs) which are considered as a black box type approach and do not have to completely understand the system characteristics, they can also be used to develop the simplified model. The ANNs is inspired by the function of the human brain system that is well suited for the complicated tasks. Recently, the application of ANNs in the field of water resources engineering is fast growing (Hagan and Demuth , 1996). Jain *et al*. (1999) applied the ANNs for reservoir inflows prediction and operation of the Indravati reservoir project, India. Neelakantan and Pundarikanthan (2000) applied the back-propagation neural network based simulation-optimization model for reservoir operations in the Chennai city water supply system in India. Chandramovli and Raman (2001) did the comparative study of the back-propagation neural network model with the linear regression model for the operational study of Parambikulam Aliya reservoir project in India. Those studies showed that ANNs model were very effective tool for multireservoir operations.

The objective of this research is to develop the ANNs model for multireservoir water allocation during water shortage. The Upper Mun basin having Lam Chae, Mun Bon, Lam Phra Ploeng and Lam Takong reservoirs as the major reservoirs was selected as the case study.

MATERIALS AND METHODS

Data collection and analysis

The 25 years (1975-1999) of the monthly rainfall data from 7 stations namely 25013, 25062, 25093, 25102, 25112, 25511, and 25541 and the monthly reservoir inflow data of Lam Chae, Mun Bon, Lam Phra Ploeng and Lam Takong reservoirs were collected. The probability distribution functions of the annual reservoir inflow were analyzed in order to identify the dry, normal and wet years for water shortage analysis in the next step. The monthly water requirements for agriculture, municipal and industrial water supply, preserving the ecological system equilibrium of the river downstream of the reservoirs and at the river basin outlet were analyzed.

Water shortage analysis

The water shortages in the multireservoir system of the Upper Mun basin including Lam Chae, Mun Bon, Lam Phra Ploeng and Lam Takong reservoirs were analyzed by simulation using HEC-3 (HEC, 1981) with the selected dry, normal and wet year data.

Generation of the optimal water allocation policy

The optimal water allocation policy under water shortage of the multireservoir system were generated using epsilon-constraint linear programming. The best policy was selected by using the multicriteria decision making process via the analytic hierarchy process (AHP) (Saaty, 1980; Huizingh and Vrolijk, 1994; Vudhivanich, 2003).

Development of multireservoir water allocation model

The selected water allocation policy of the Upper Mun multireservoir system were simulated using HEC-3 with 25 years of data. The simulation results were used to develop the multireservoir water allocation model using ANNs. The model was tested by comparison with the observed data obtained in 2001 and 2002.

The Study area

The Upper Mun basin in Nakhon Ratchasima province, Northeast of Thailand, was selected as a case study. The study area covered the irrigable area of 4 large scale reservoirs including Lam Chae, Mun Bon, Lam Phra Ploeng and Lam Takong. The total study area was 7,190 sq.km. or 10.31% of the Mun basin area. The total irrigable area was 353,650 rai as shown in Table 1. Figure 1 showed the schematic diagram of the multireservoir system in the Upper Mun Basin and the diversion points for irrigation and municipal and industrial water supply.

RESULTS AND DISCUSSION

Hydrological characteristics of the area

The average monthly rainfall of 7 stations of the study area showed that the amount of rainfall was high during May to October and peaked in September. The annual average rainfall was in the range of 840-1,114 mm which was below the average rainfall in North East of Thailand. The average annual reservoir inflow of Lam Chae, Mun Bon, Lam Phra Ploeng and Lam Takong reservoirs were 253.5, 91.3, 169.8 and 250.2 mcm respectively. The Gumbel distribution function was found the best fit to the 25 years annual inflow of 4 reservoirs as tested by Smirnov-Kolmogorov statistics at 5% significant level. It was used to classify the dry, normal and wet years for water shortage analysis of the multireservoir system. Nonexceedence probability of 20% and 80% was used as the criteria for water year classification. It was found that the 4 reservoirs had similar pattern of dry, normal and wet years. There were 6 dry years, 14 normal years and 5 wet years out of 25 years of analysis as shown in Figure 2.

The estimated annual water requirements for agriculture, municipal and industrial (M&I) water supply, preserving the ecological system equilibrium of the river downstream of the reservoirs and at the river basin outlet were 754.81, 35.55, 126.00 and 73.20 mcm as shown in Table 2. The water requirements of the basin are now exceeding the combined inflow to the 4 main reservoirs. Thus the water shortage is unavoidable.

Water shortage analysis

Based on the selected dry, normal and wet years data, HEC-3 was used to simulate the multireservoir system such that the water shortage

Table 1 General data of the four reservoirs in the study area.

Reservoirs	Location		Watershed area (sq.km.)	Minimum storage (mcm.)	Normal storage (mcm.)	Active storage (mcm.)	Irrigable area (rai)	
	Lat.(°N)	Long.(°E)					Wet	Dry
Lam Chae	14-22-30	102-13-43	601	7	275	268	113,750	64,260
Mun Bon	14-28-54	102-09-17	454	7	141	134	44,600	16,330
Lam Phra Ploeng	14-35-15	101-49-02	807	4	110	106	67,760	17,000
Lam Takong	14-51-15	101-31-58	1,430	20	310	290	127,540	37,905
Total			3,292	38	836	798	353,650	135,495

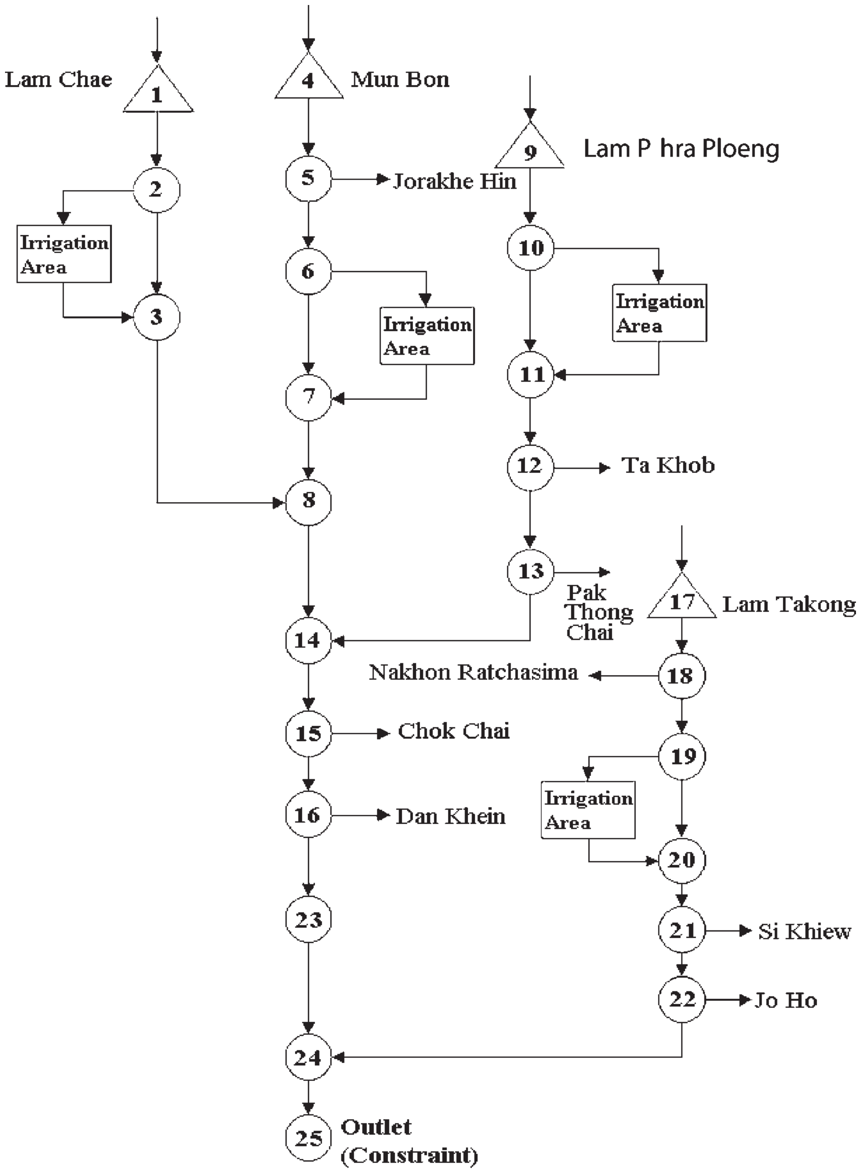


Figure 1 Schematic diagram of the multireservoir system in the Upper Mun basin.

could be analyzed. The simulation results indicated that the water shortage occurred in dry and normal year . The dry year was divided into 3 categories; extremely dry (Dry 1), dry (Dry 2) and slightly dry (Dry 3) according to the magnitude of water shortage of 40.03, 24.56 and 28.61% respectively as shown in Table 3. Similary the normal year was divided into 3 categories; slightly normal (Normal 1), normal (Normal 2) and slightly wet (Normal 3) corresponding to 22.35, 9.56 and 0.35% of water shortage (Table 3). The agriculture sector had the most serious water shortage of 47.19 %, municipal and industrial water supply sector of 17.74% occuring in Nakhon Ratchasima municipality. The water shortage for preserving the downstream ecological system and at the river basin outlet were 15.64 and 25.85% respectively.

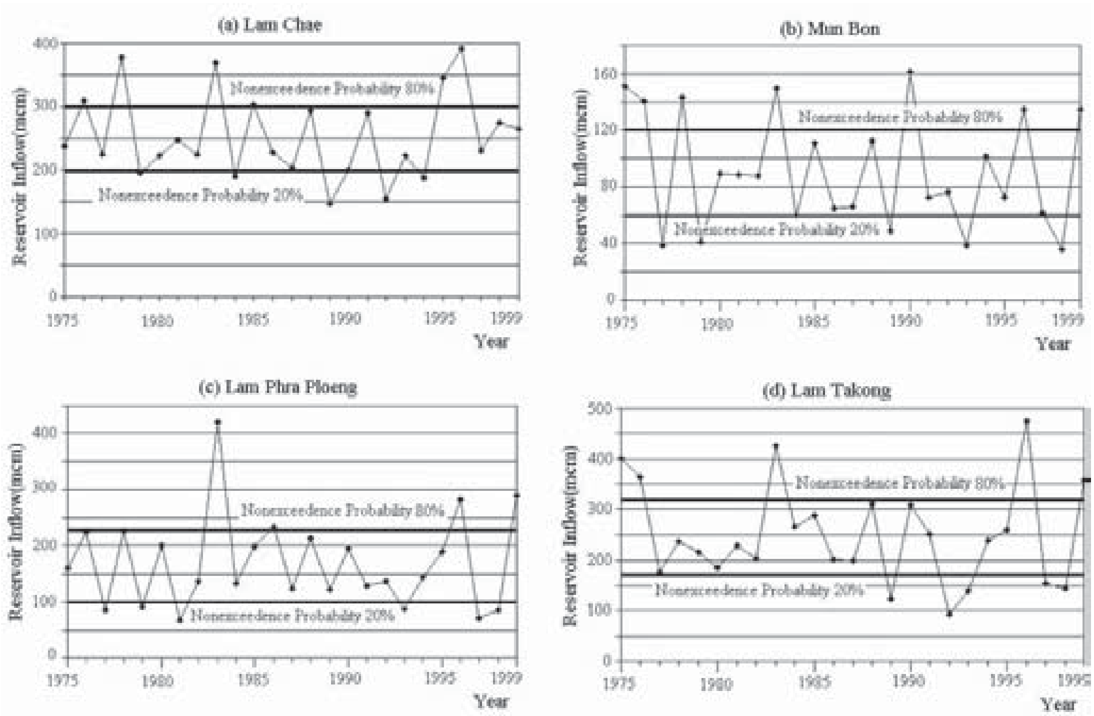


Figure 2 Dry, normal and wet years classification of (a) Lam Chae, (b) Mun Bon, (c) Lam Phra Ploeng and (d) Lam Takong reservoirs.

Table 2 Average water requirements of the multireservoir system in Upper Mun basin (mcm).

Reservoirs	Agriculture	M&I water supply	Ecological system	River basin outlet	Total
Lam Chae	239.52	0.45	54.48		294.45
Mun Bon	97.47	0.36	5.64		103.47
Lam Phra Ploeng	127.04	1.42	5.88		134.34
Lam Takong	290.78	33.32	60.00		384.10
Total	754.81	35.55	126.00	73.20	989.56
%	76.27	3.60	12.73	7.40	100.00

According to the simulation result, the dry year showed more serious shortage than the normal year. There were 2 periods of water shortage. The first period occurred during the dry spell in rainy season (June-September) and second period occurred in the dry season (January-May). Furthermore, if the initial storage of Lam Chae, Mun Bon, Lam Phra Ploeng and Lam Takong at the beginning of April was less than 68.6, 34.1, 44.3 and 72.7 mcm, the water shortage would occur when the inflow to the 4 reservoirs less than 87.5% of the average annual inflow (Kongjun, 2003).

Table 3 The annual water shortage of the Upper Mun basin for the case of dry and normal years as simulated by HEC-3.

Water uses	Annual water shortage (mcm)					
	Dry year			Normal year		
	Dry 1	Dry 2	Dry 3	Normal 1	Normal 2	Normal 3
Agriculture	359.51	211.29	264.90	223.91	88.30	0
M&I water supply	0.79	3.15	6.31	0	3.15	0
Ecological system	19.71	7.88	11.04	4.48	3.15	3.15
River basin outlet	18.92	9.46	15.77	0	0	0
Total shortage(mcm)	398.93	231.78	298.02	228.39	94.60	3.15
Water requirements(mcm)	996.51	943.55	1041.81	1021.75	989.56	913.89
Total(%)	40.03	24.56	28.61	22.35	9.56	0.35

Generation of the optimal water allocation policy

The water shortage analysis showed that the water shortage took place in all water use sectors. The magnitude of water shortage was different among sectors. Besides, the effect of the water shortage to each water use sector was different even though the magnitude of water shortage was the same. Therefore the optimum water allocation policy needed to be generated. The multi-objective optimization techniques called the epsilon-constraint linear programming and the multicriteria decision making process called the analytic hierachy process (AHP) were used to generate and select the best water allocation policy. The extremely dry year (Dry 1) or the worst case was used in the analysis. The objective functions were to maximize the yield for agricultural sector and minimize the water shortage for the municipal and industrial water supply sector and for the downstream ecological requirements. There were 16 optimal water allocation policies generated as shown in Table 4. It was found that in the extremely dry year, the total agricultural product was between 49-60% of the maximum yield, the municipal and industrial water supply sector and the downstream ecological requirements would have the minimum water shortage between 0.00-15.12 and 0.00-55.43 mcm, respectively.

26 stakeholders of the Upper Mun multireservoir system including the 10 water management administrators, 1 expert, 6 representatives of agricultural sectors, 2 representatives of municipal and industrial water supply sectors, 6 representatives of the downstream ecological requirements and 1 researcher were the key informances answering the questionnaires in multicriteria decision making via AHP. Each key informance selected 4 policies based on the three water allocation criteria; profitability, equity and reliability. The AHP outcomes showed that the water allocation in extremely dry year gave the important weights to profitability, reliability and equity criteria by 41, 32.3 and 26.7% respectively. It was noticed that the key informance considered the profitability more important than reliability and equity in the water allocation during water shortage. The best policy obtained the highest priority weight of 29.38% was the fourth policy as shown in Table 5. This policy satisfied 100% of demand for municipal and industrial water supply sector, resulted in 55.43 mcm of water shortage on downstream ecological system and allowed the yield for agriculture reducing to 56% of the maximum yield.

Table 4 Generated 16 water allocation policies**.**

Policies	Agriculture		M&I water supply		Ecological system	
	Max. yield (%)	Yield depletion (%)	Min. shortage (mcm)	Water use depletion (%)	Min. Shortage (mcm)	Water level depletion (%)
1	60	40	15.12	54.32	55.43	7.56
2	59	41	10.08	36.21	55.43	7.56
3	57	43	5.04	18.11	55.43	7.56
4	56	44	0.00	0.00	55.43	7.56
5	58	42	15.12	54.32	37.14	4.16
6	56	44	10.08	36.21	37.14	4.16
7	55	45	5.04	18.11	37.14	4.16
8	54	46	0.00	0.00	37.14	4.16
9	55	45	15.12	54.32	18.69	1.99
10	54	46	10.08	36.21	18.69	1.99
11	52	48	5.04	18.11	18.69	1.99
12	51	49	0.00	0.00	18.69	1.99
13	53	47	15.12	54.32	0.00	0.00
14	51	49	10.08	36.21	0.00	0.00
15	50	50	5.04	18.11	0.00	0.00
16	49	51	0.00	0.00	0.00	0.00

Table 5 The overall weight and priority of the policies as generated by AHP.

Policies	Weight	Priority
2	0.37	16
3	5.78	5
4	29.38	1
6	1.30	10
7	4.67	6
8	24.49	2
10	2.75	7
11	2.74	8
12	14.47	3
14	1.19	11
15	0.63	14
16	8.36	4
17	1.57	9
18	1.11	12
19	0.70	13
20	0.46	15

Remark: Policies 17, 18, 19 and 20 were added by the key informance during questionares process.

Some stakeholders added 4 more policies. Those were the policies 17, 18, 19 and 20 that did not allow water shortage to the downstream ecological requirements but resulted water shortage in municipal and industrial sector by 5%, 7%, 15% and 20% of the demand respectively.

Development of artificial neural networks model for multireservoir water allocation

The Upper Mun multireservoir system was simulated with HEC-3 using inflow data which water shortage took place and the best policy (policy 4) as selected in the previous section. There were 6 years in simulation consisting of 3 dry years; Dry 1, Dry 2, Dry 3 and 3 normal years; Normal 1, Normal 2 and Normal 3 as shown in Table 6. The results of 72 months simulation according to the selected optimal water allocation policy provided the information regarding to the inflow, storage, water demand and the releases of the 4 reservoirs (Kongjun, 2003). These information were used to develop the artificial neural networks model for multireservoir water allocation (Figure 3). The multilayer feed forward with back-propagation algorithm (MLFF-BP) was used.

The 72 patterns of data were divided into 2 sets. The first set of 58 patterns or 80% of the data was used for training the network. The second set of 14 patterns or 20% was used for testing the network.

The monthly inflow, storage, and demand for each reservoir were set as the variables in the input layer, and monthly multireservoir release as the output. The ANNs model for multireservoir water allocation could be formulated as follow:

$$\underline{R}^t = f(\underline{I}^t, \underline{S}^t, \underline{D}^t) \qquad (1)$$

Where $\underline{R}^t$ = vector of the reservoir release
$\underline{I}^t$ = vector of the reservoir inflow
$\underline{S}^t$ = vector of the reservoir storage
$\underline{D}^t$ = vector of the reservoir demand

The structure of MLFF-BP was designed to be 12 neurons input layer and 4 neurons output layer (Figure 3). The numbers of hidden layers were determined by systematic trial and error method. One hidden layer with 2, 4, 8, 12, 16 and 18 neurons and 2 hidden layers with 8-4, 8-8, 12-4, 12-8, 16-4 and 16-8 neurons were tried. There were 12 structures of neural network models analyzed in this study to determine the best model (Table 7). The 12-16-4-4 MLFF-BP neural networks models were trained by varying the learning rates and the momentum between 0.1, 0.2, 0.4, 0.6 and 0.8 with 25,000 target epochs. Table 7 showed that the 12-16-4-4 MLFF-BP model with the learning rate of 0.4 and the momentum of 0.8. had the minimum mean square

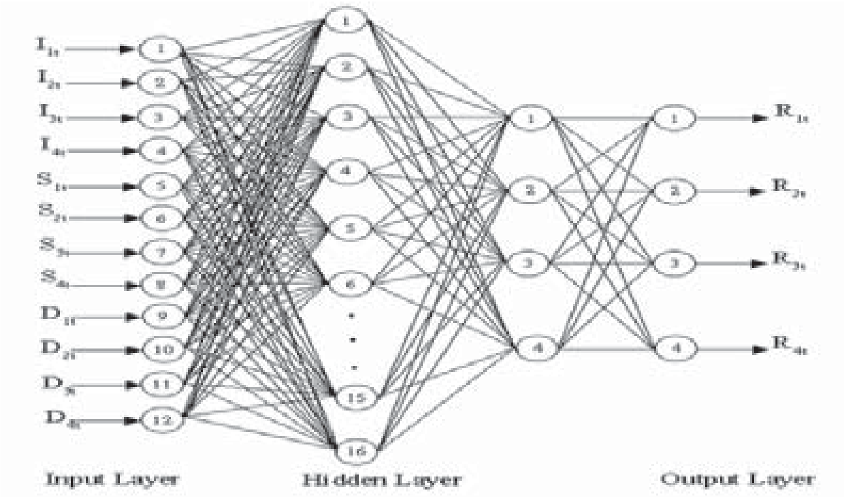
Table 6 Dry and normal years annual inflow used in the HEC-3 simulation with the selected optimum water allocation policy.

Reservoirs	Annual inflow (mcm)					
	Dry 1	Dry 2	Dry 3	Normal 1	Normal 2	Normal 3
Lam Chae	146.5	187.3	195.6	200.6	228.2	293.8
Mun Bon	36.0	39.2	48.8	59.8	76.4	112.5
Lam Phra Ploeng	68.2	84.9	91.0	122.6	144.2	226.7
Lam Takong	92.2	140.7	154.8	176.8	118.4	310.2

Remarks: Dry 1 = extremely dry, Dry 2 = dry , Dry 3 = slightly dry
Normal 1 = slightly normal, Normal 2 = normal, Normal 3 = slightly wet

error (MSE) of 4.652. The R^2 of the ANNs model predicted release and the simulated release was in the range of 0.9578-0.9900 for training (Figure 4). The 12-16-4-4 MLFF-BP neural networks model as shown in Figure 3 was selected for the multireservoir water allocation of the Upper Mun basin.

The 12-16-4-4 MLFF-BP neural networks model for multireservoir water allocation was also tested by comparison with the actual data in 2001



Notation : 1 = Lam Chae, 2 = Mun Bon, 3 = Lam Phra Ploeng and 4 = Lam Takong

I_{1t}, I_{2t}, I_{3t} and I_{4t} = inflow of month t for reservoir 1,2,3 and 4. S_{1t}, S_{2t}, S_{3t} and S_{4t} = storage at the beginning of month t for reservoir 1, 2, 3 and 4. D_{1t}, D_{2t}, D_{3t} and D_{4t} = demand of month t from reservoir 1, 2, 3 and 4. R_{1t}, R_{2t}, R_{3t} and R_{4t} = release for month t from reservoir1, 2, 3 and 4.

Figure 3 Artificial neural networks model for multireservoir water allocation of the Upper Mun basin.

Table 7 Performance of the 12 MLFF-BP artificial neural networks models.

MLFF-BP model	Learning rate	Momentum	Mean square error (MSE)
12-2-4	0.1	0.1	25.059
12-4-4	0.4	0.8	12.971
12-8-4	0.1	0.8	9.288
12-12-4	0.6	0.8	5.804
12-16-4	0.2	0.1	4.784
12-18-4	0.4	0.6	4.719
12-8-4-4	0.2	0.4	5.558
12-8-8-4	0.8	0.6	5.707
12-12-4-4	0.6	0.1	5.014
12-12-8-4	0.1	0.6	5.243
12-16-4-4	0.4	0.8	4.652
12-16-8-4	0.4	0.2	4.684

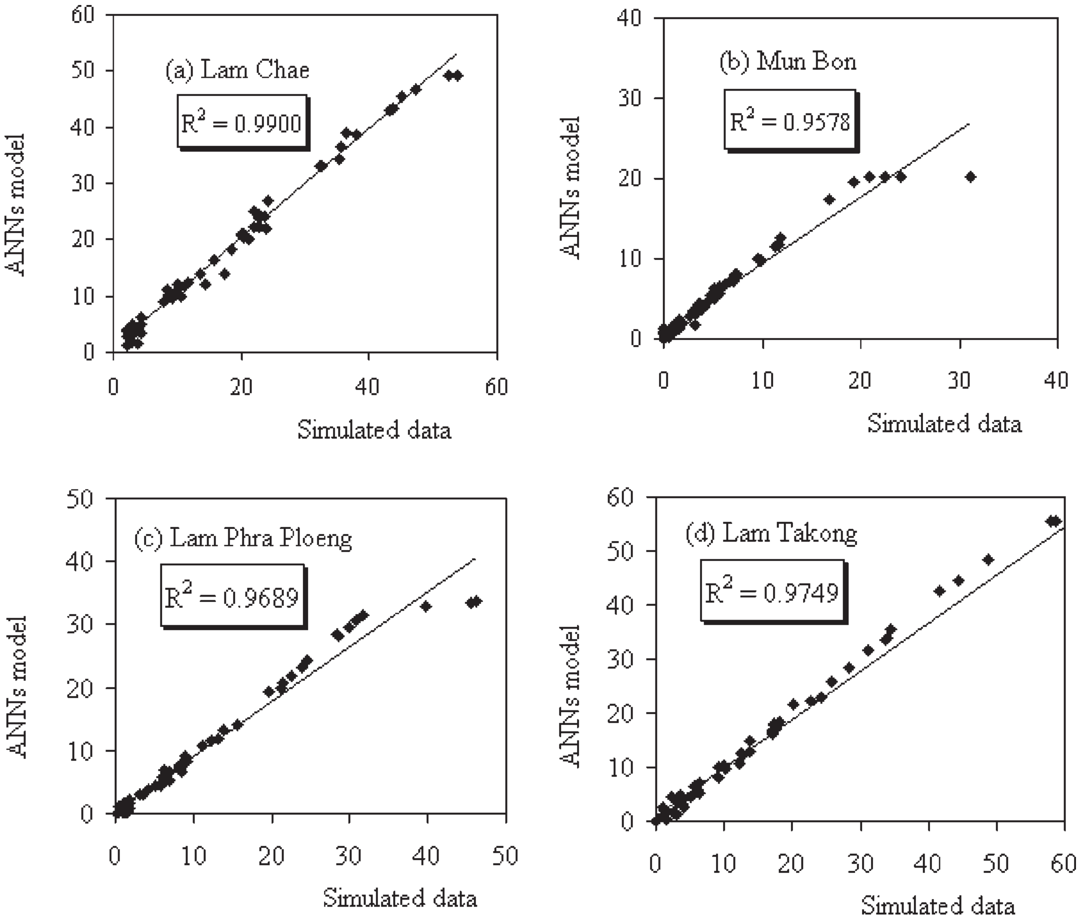


Figure 4 Goodness of fit of ANNs model predicted reservoir release and the simulated data**.**

and 2002. The goodness of fit of ANNs predicted reservoir release and the actual release in term of R^2 was between 0.5779-0.8324 for the year 2001 and between 0.5609-0.8444 for the year 2002. The testing of ANNs model showed R^2 of the testing with the actual data was less than that of the training due to the difference of water allocation criteria used in the model and in the actual operation of the Upper Mun basin multireservoir system. However both training and testing of ANNs medel showed the potential application of ANNs model in multireservoir water allocation under shortage.

CONCLUSION

The artificial neural networks model for multireservoir water allocation was developed. The Upper Mun basin having 4 large scale reservoirs namely Lam Chae, Mun Bon, Lam Phra Ploeng and Lam Takong was selected as the case study. 25 years of monthly data were used in the analysis of the water shortage in the basin. The optimum water allocation among the 4 water user groups namely agriculture, municipal and industrial water supply, ecological system and the downstream users was derived by the multiobjective optimization techniques called Epsilon-constraint linear programming. The best water allocation policy that satisfied the profitability, equity and reliability criteria was derived by the multicriteria decision making process called AHP. The best policy was then simulated by HEC-3 using the cases of dry and normal year. The simulation result was used to develop the artificial neural networks model for multireservoir water allocation. The 12-16-4-4 MLFF-BP neural networks model was the best fit. The model showed very high R^2 of 0.9578-0.9900 for training and R^2 of 0.8041-0.9658 for the testing. The 12-16-4-4 MLFF-BP neural networks model was tested by comparison with the actual data in 2001 and 2002. This research illustrated that the artificial neural networks model was simple and could practically be applied to the multireservoir water allocation.

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