ASSESSMENT OF WEAP MODEL IN SIMULATING RAINFALL-RUNOFF RELATION IN THE PING AND WANG RIVER BASINS, THAILAND

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ABSTRACT

This study aimed at developing the physically–based rainfall–runoff model using the Water Evaluation and Planning system (WEAP) with the simplified coefficient method. The Ping and Wang River Basins in the northern region of Thailand were selected as study area to explain the hydrologic dynamics and responses of the implemented watershed system through rainfall–runoff relation. The monthly hydro–meteorological data during 2000–2020 was used as dataset for hydrological modelling by WEAP. To reflect the lumped hydrologic response, the study area in Ping and Wang River Basins were subdivided into 3 sub–basins; (1) Sub–Basin 1 (Upper Ping Basin), (2) Sub–Basin 2 (Lower Ping Basin), and (3) Sub–Basin 3 (Wang Basin). In addition, the land area was fractionally classified into 16 land use classes to identify the relevant inputs such as crop coefficient, areal rainfall, and reference evapotranspiration. Key model parameters; runoff coefficient, infiltration coefficient, and percent of effective rainfall, were estimated and adjusted manually to improve the model performance statistics. The model calibration and validation were implemented through comparison between monthly observed and simulated streamflow measured at 3 gauging stations; P.12C, P.17, W.4A on the Ping and Wang Rivers as well as the monthly inflow of Bhumibol Dam. The long–term simulation results showed that WEAP model could provide the reasonably good agreement of R^2 of 0.75–0.81 at all gauging stations except P.12C station where the hydrologic response has been strongly affected by the influence of regulated dam release. Based on the overall model performance statistics, predominant capability of WEAP model to simulate behavior of hydrologic responses was found particularly at the outlet of sub–basin (P.17 and W.4A gauging stations) and outflow point (reservoir inflow of BB Dam) where the impact of regulated flow on the model performance has been diminished.

Keywords: Ping River Basin, Wang River Basin, WEAP model, Rainfall–Runoff simulation

1. INTRODUCTION

The changing global climate driven by human–induced activities has drastically impacted on the world's water systems through the frequent occurrences of natural disasters. In Thailand, the impact of climate change has become the serious problems. It has led to the complexity of water resources management issues especially for the dam operation since the 2011 major flood occurred in the Northern and Central regions of Thailand. The significant changes of the regional scale shifts in the rainfall patterns have resulted in the incapability to potentially store water in the major reservoirs such as Bhumibol and Sirikit Dams in the northern region of Thailand. In the recent years, it is observable that the tendency of tropical storms occurring all year round regularly in this region is likely short in duration and sudden delay in the commencement or termination of rain particularly in wet season. Therefore, the considerable attention to unbalancing of the spatio–temporal distribution of water availability and water demands have been paid by the key operational offices to reduce the economic losses caused by flooding and droughts.

Understanding the hydrologic behaviors and watershed responses altered by the influence of climate changes and anthropologic factors has played important role in coping with the hydrologic uncertainty and water supply–demand imbalance. Model–based assessment has been widely used to simulate both natural hydrological processes, land development activities, human–induced effects, and management strategies on water resources [1]. The relation of rainfall and runoff processes, low flow and flood peaks behaviors or the hydrologic properties can be well characterized by the physically–based hydrologic models [2]. The various types of the physically–based hydrologic models have been adopted to enhance understanding of the hydrologic processes and watershed responses [3]. The hydrological modelling practices through lumped and distributed parameter models such as

SWAT, WEAP, HEC–HMS, MIKE HYDRO Basin and others have been made in many parts of the world to explore the potential interactions among involved factors [4].

WEAP (water evaluation and planning) model was developed by the Stockholm Environment Institute (SEI) in 1988 [5]. It is a sort of lumped–parameter hydrologic representation creating the simulations of the natural rainfall–runoff processes and the management of implemented water system [1]. It is well known that WEAP model can be successfully used for climate change adaptation studies and a wide range of operational manageability of water resources [6].

In this study, the WEAP hydrologic model was developed for the Ping and Wang River Basins by aiming to assess the model efficiency in simulating the rainfall–runoff relation and to explain the hydrologic dynamics and responses of the implemented watershed system over long term periods in this region.

2. METHODOLOGY

2.1 Study Area

Ping and Wang River Basins are located in the northern region of Thailand with the total drainage area of 45,499 km^2 as shown in Fig.1. Ping and Wang River Basins have been considered as major sources of water to help support in supplying irrigation water for the Lower Ping and Chao Phraya Irrigation Schemes as well as for non–irrigation water uses downstream of the Bhumibol Dam. Ping River Basin covers 6 provinces in Thailand; Chiang Mai, Lamphun, Tak, Kamphaeng Phet, Nakhon Sawan, and Mae Hong Son. Approximately 67.32% of the land cover in the Ping River Basin is forest and agricultural land area is 25.17%. The urban and built–up land and miscellaneous land are 3.71% and 2.08%, respectively. The remaining portion of 1.71% is surface water body. The average monthly rainfall over the entire basin are approximately 163.99 mm/month in wet season (May–Oct) and 22.23 mm/month in dry season (Nov–Apr) showing high temporal variability of the rainfall amount [7].

Wang River Basin is situated close to Ping River Basin covering 4 provinces; Chiang Rai, Lampang, Tak, and Phrae in the North. Wang River is one of the principal tributaries of the Chao Phraya River flowing southwards to join the Ping River in Tak Province before discharging into the Chao Phraya River and the Gulf of Thailand. Most of the land area in the Wang River Basin is forest accounting for 73.09% of the entire basin. The percentage share of agricultural and urban and built–up land areas over the entire basin are 18.29% and 3.98%, respectively. The remaining 2.08% and 1.17% are miscellaneous land and water body. It is recorded that average monthly rainfall in wet and dry seasons in Wang River Basin are 160.21 mm/month and 22.85 mm/month, respectively which are not much deviated from rainfall amount in Ping River Basin [7]. In other words, approximately 88% of the yearly rainfall falls during wet season and 12% exists during dry season in the Ping and Wang River Basins.

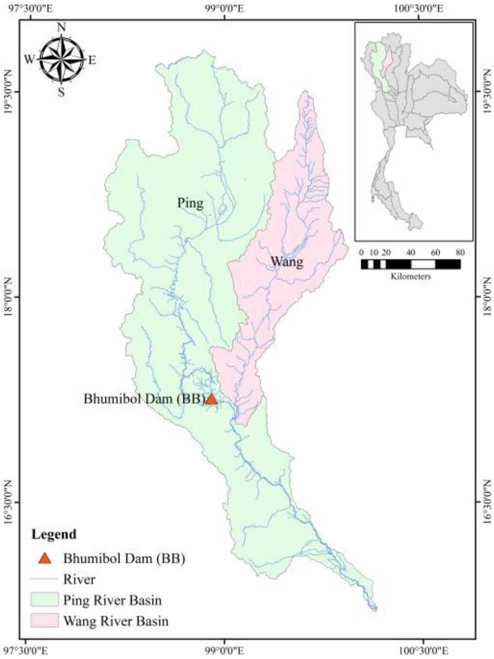

Figure 1 Location of the Ping and Wang River Basins in the northern region in Thailand

2.2 Hydrological Model Development

2.2.1 Data Collection

Data collection procedures was firstly conducted in this study to gather the input data required for the formulation of WEAP model in the Ping and Wang River Basins. The long–term hydro–meteorological data during 2000–2020 was preliminarily investigated and used. In addition, WEAP requires catchment and land use data, climate data, water demand site data, as well as reservoir data to accomplish the modelling processes of rainfall–runoff simulation in the implemented watershed system. This primary data was collected mainly from the Royal Irrigation Department (RID), Electricity Generating Authority of Thailand (EGAT), Thai Meteorological Department (TMD), Land Development Department (LDD), and other secondary sources as summarized in Table 1.

Table 1 Data required for this study

No.	Data Type	Data Source
1	Reservoir Data	EGAT
2	Hydro–Meteorological Data	
	• Rainfall	RID and TMD
	• Runoff	RID

	• Climate Data	TMD
3	Land use Data	LDD
4	Water Demand Data	
	• Agricultural Water Demand	Secondary Source [8]
	• Non–Agricultural Water Demand	Secondary Source [8]

2.2.2 Development of Rainfall–Runoff Model by WEAP Model

(1) Hydrological Method Selected

The WEAP hydrologic model was developed to simulate the watershed processes in term of rainfall–runoff relation in the Ping and Wang River Basins using the simplified coefficient method. The modelling processes were carried out according to process flow diagram as shown in Fig.2. The rainfall–runoff simulation by the simplified coefficient method in WEAP principally determines evapotranspiration for irrigated and rainfed crops using crop coefficients (Kc). The remainder of rainfall amount which is not consumed by crop evapotranspiration, is simulated as runoff to a river. In other words, it can be proportioned among runoff to a river and flow to groundwater via runoff/infiltration links [5].

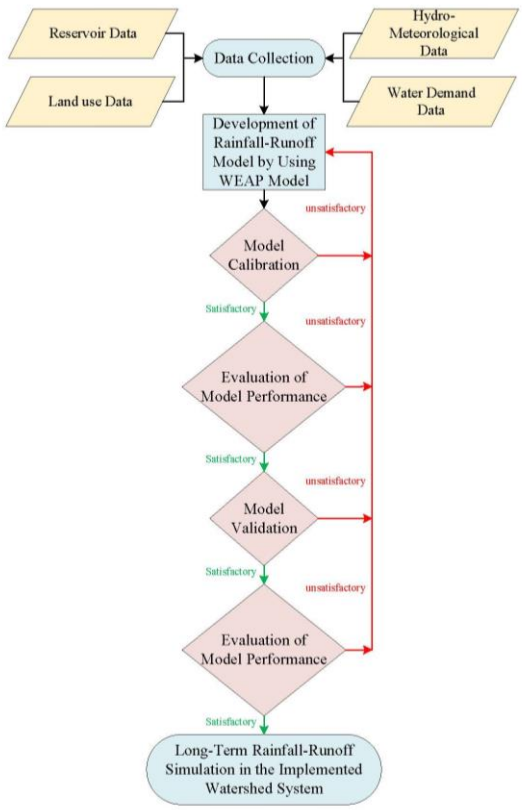

Figure 2 Process flow diagram of WEAP model development in the study area

(2) Basin Division

To reflect the lumped hydrologic response in WEAP model, the study area in Ping and Wang River Basins were subdivided into 3 sub–basins; (1) Sub–Basin 1 (Upper Ping Basin, SB1), (2) Sub–Basin 2 (Lower Ping Basin, SB2), and (3) Sub–Basin 3 (Wang Basin, SB3) as shown in Fig.3. In addition, the land area was fractionally classified into 16 land use classes: paddy field (A1), field crop (A2), perennial crop (A3), orchard (A4), horticulture (A5), shifting cultivation (A6), pasture and farmhouse (A7), aquatic plant (A8), aqua–cultural land (A9), evergreen forest (F1), deciduous forest (F2), rangeland (M1), marsh and swamp (M2), city town (U1), village (U2), and water body (W). The percentage share of land use classes was presented as a percentage of total area as summarized in Table 2

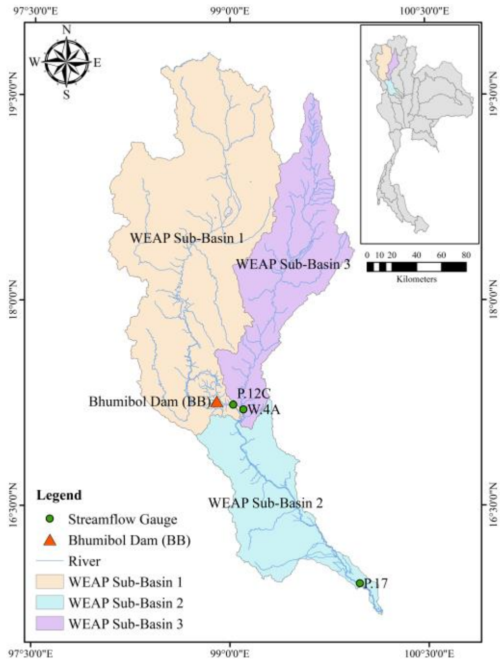

Figure 3 Basin division and key streamflow gauges used for model calibration and validation

Table 2 Land use data classified in each sub–basin

Class	Sub–Basin 1		Sub–Basin 2		Sub–Basin 3	
	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
A1	1,082.28	4.13	1,162.75	14.14	935.36	8.67
A2	1,149.46	4.38	2,174.56	26.44	924.67	8.57
A3	117.12	0.45	222.00	2.70	534.93	4.96
A4	1,909.64	7.28	152.95	1.86	144.22	1.34
A5	137.16	0.52	17.35	0.21	4.64	0.04
A6	1,084.90	4.14	74.41	0.90	39.69	0.37
A7	32.30	0.12	92.63	1.13	16.38	0.15
A8	0.19	0.00	0.01	0.00	0.03	0.00
A9	4.72	0.02	4.24	0.05	2.08	0.02
F1	3,985.08	15.19	364.16	4.43	862.32	7.99
F2	14,808.52	56.45	3,243.09	39.43	6,427.24	59.58
M1	376.66	1.44	70.59	0.86	112.00	1.04

M2	96.65	0.37	66.90	0.81	130.81	1.21
U1	315.58	1.20	135.79	1.65	162.17	1.50
U2	703.00	2.68	268.47	3.26	320.48	2.97
W	431.73	1.65	175.59	2.13	170.58	1.58
Total	26,235	100	8,225	100	10,788	100

Remark: A1= paddy field, A2 = field crop, A3 = perennial crop, A4 = orchard, A5 = horticulture, A6 = shifting cultivation, A7 = pasture and farmhouse, A8 = aquatic plant, A9 = aqua–cultural land, F1 = evergreen forest, F2 = deciduous forest, M1 = rangeland, M2 = marsh and swamp, U1 = city town, U2 = village, and W = water body

(3) Data Entry

The specific point rainfall gathered from 25 rainfall stations in the Ping and Wang River Basins and adjacent area as can be seen in Fig.4, was used and transformed into areal rainfall by Thiessen polygon technique in order to identify the representation of monthly rainfall input of each sub–basin. The monthly reference evapotranspiration (ETo) was estimated using evaporation pan method which requires the evaporation loss data from field observation as shown the list of climate stations in Table 3 and Fig.5. Accordingly, the average monthly evaporation losses for each sub–basin were estimated for the estimation of reference evapotranspiration by multiplying with the pan coefficient (Kp).

Table 3 Rainfall & climate stations considered in this study

Sub–Basin	Rainfall Station	Climate Station
SB1	70391	48326: Mae Jo Agromet.
	70731	
	300201	48327: Chiang Mai
	300202	
	303301	48329: Lamphun
	310201	48377: BB Dam
	327501	
	328301	
	329201	
	376203	
	630181	
SB2	120081	48376: Tak
	120121	48380:Kamphaeng Phet
	120161	
	160221	
	260271	
	260311	
	376201	
	376203	
	376301	
	376401	
	380201	
	400201	
	630181	
SB3	70391	48328: Lampang
	160151	48324: Thoen
	160221	48334: Lampang Agromet.
	303301	
	310201	
	328201	
	328301	
	329201	
	376201	
	376203	
	400111	
	400151	

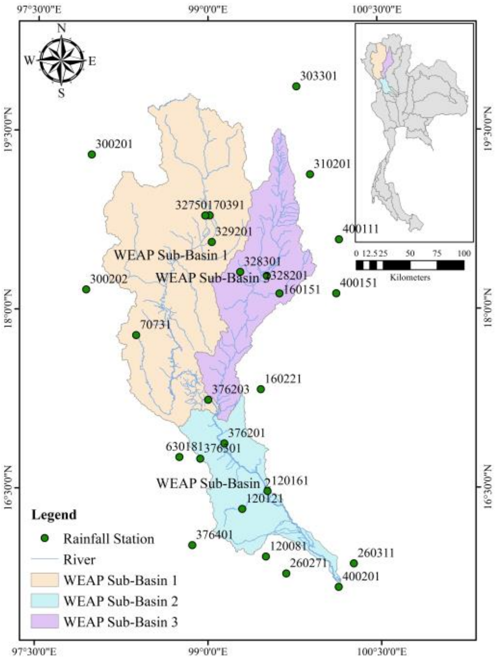

Figure 4 Location of rainfall stations

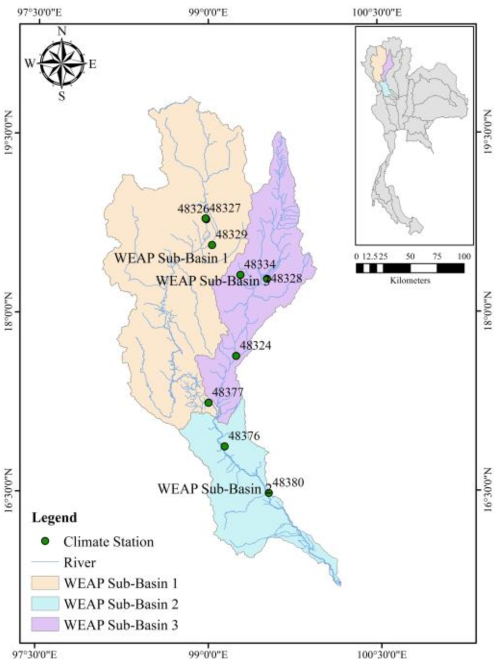

Figure 5 Location of climate stations

Table 4 Summary of average monthly rainfall and ETo identified in each sub–basin

Month	SB1		SB2		SB3	
	Rain* (mm)	ETo (mm)	Rain* (mm)	ETo (mm)	Rain* (mm)	ETo (mm)
Jan	280.4	100.9	225.8	106.1	337.1	102.5
Feb	98.1	122.2	206.3	128.5	131.4	126.4
Mar	433.7	162.7	705.0	171.5	608.5	170.5
Apr	1,176.9	179.8	1,223.3	187.4	1,372.8	181.5
May	3,599.3	158.6	3,524.7	164.3	3,973.4	157.2
Jun	2,801.0	138.4	2,978.1	129.4	2,376.4	131.8
Jul	2,932.4	125.2	2,865.8	121.9	2,681.3	119.6
Aug	3,912.7	121.5	3,381.7	118.5	3,924.0	115.2
Sep	4,153.9	107.6	5,232.7	110.5	4,249.0	112.1
Oct	2,658.8	111.5	3,904.3	98.9	2,674.4	102.7
Nov	759.9	97.4	652.7	92.2	570.4	93.4
Dec	216.2	95.7	144.6	94.9	207.0	91.5

Remark: * Areal rainfall

The values of crop coefficient (Kc) for each land use class were determined to estimate the crop evapotranspiration (ETc) as summarized in Table 5.

Table 5 Crop coefficient values identified for each land use class

Land Use Class	Kc Value
A1	1.30
A2	1.01
A3	1.10
A4	1.20
A5	1.13
A6	0.88
A7	0.49
A8	1.00
A9	0.90
F1	0.35
F2	0.38
M1	0.90
M2	0.90
U1	0.77
U2	0.80
W	1.00

Source: [6]

Interactions between surface water (Sub_Basin_1, Sub_Basin_2, Sub_Basin_3) and groundwater (GW_SB_1, GW_SB2, GW_SB3) in each sub–basin were specified and hydraulically connected in WEAP model. For the demand data, two branches of demand site for agricultural water use (WD_LPWDZ) and non–agricultural water use (WS_LPWDS) were identified downstream of Bhumibol Dam to supply irrigation water to the Lower Ping Irrigation Scheme and non–irrigation water use to the downstream region as shown in Fig.6. The demand priority was then set up on the transmission link equally for both irrigation water and non–irrigation water uses to avoid water scarcity for all demand sectors.

The model calibration was conducted by adjusting key parameters of rainfall–runoff processes namely runoff coefficient, infiltration coefficient, and effective rainfall to match the real behavior of hydrologic system. The model accuracy was verified by the validation procedure using the past data. In this study, the model calibration and validation were implemented through comparison between monthly observed and simulated streamflow measured at 3 gauging stations; P.12C, P.17, W.4A on the Ping and Wang Rivers as well as the monthly inflow of Bhumibol Dam during 2000–2020.

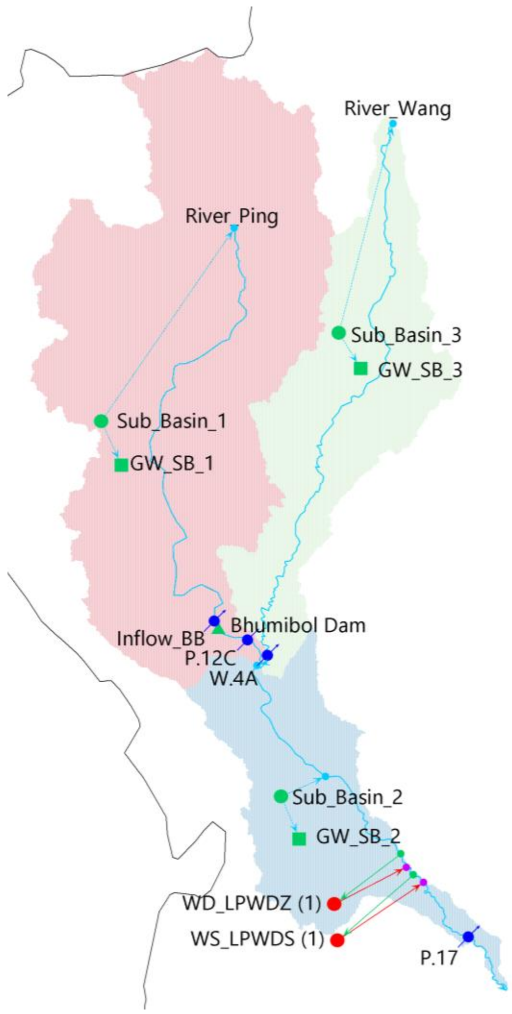

Figure 6 Development of WEAP model for rainfall–runoff simulation in the Ping and Wang River Basin

2.3 Assessment of WEAP Model Performance

To assess the WEAP model performance for rainfall–runoff simulation, statistical indices namely; Percent Bias (PBIAS), Nash–Sutcliffe Efficiency (NSE), Index of Agreement (d), RMSE–Observations Standard Deviation Ratio (RSR), and Volumetric Efficiency (VE) were evaluated as described below;

2.3.1 Percent Bias (PBIAS)

Percent bias (PBIAS) measures the average tendency of the simulated values to be larger or smaller than their observed ones. The optimal value of PBIAS is 0. The small values of PBIAS indicate high accuracy of the model simulation. However, the positive values of PBIAS reflect overestimation bias, whereas negative values express underestimation bias of the model simulation. The model performance is in general satisfactory if PBAIS is ± 25% [6].

$$PBIAS=100\left(\frac{\sum_{i=1}^{N}(O_i-S_i)}{\sum_{i=1}^{N}O_i}\right) \qquad (1)$$

2.3.2 Nash–Sutcliffe Efficiency (NSE)

The Nash–Sutcliffe Efficiency (NSE) is a normalized statistic to measure the relative magnitude of the residual variance compared to the measured data variance. It is absolutely similar to the coefficient of determination (R^2).

$$NSE=1-\left(\frac{\sum_{i=1}^{N}(O_i-S_i)^2}{\sum_{i=1}^{N}(O_i-\bar{O})^2}\right) \qquad (2)$$

For monthly hydrographical data, NSE values range between −∞ and 1.0. NSE = 1.0 is the perfect fit, NSE > 0.75 is a very good fit, NSE = 0.65 to 0.75 is a good fit, NSE = 0.5 to 0.65 is a satisfactory fit and NSE < 0.5 is an unsatisfactory fit [9].

2.3.3 Index of Agreement (d)

Index of Agreement (d) is a standard measure to explain the degree of model error. Values of agreement index varies between 0–1. Higher values indicate better agreement between the model outputs and observations.

$$d=1-\left(\frac{\sum_{i=1}^{N}(O_i-S_i)^2}{\sum_{i=1}^{N}(|S_i-\bar{O}|+|O_i-\bar{O}|)^2}\right) \qquad (3)$$

2.3.4 Ratio of RMSE to the Standard Deviation of the Observations (RSR)

RMSE–Observations Standard Deviation Ratio (RSR) is the standardized form of RMSE. Ratio of RMSE to the standard deviation of the observations is expressed in the following equation. The model performance is satisfactory when RSR ≤ 0.70. RSR > 0.70 is rated as unsatisfactory for monthly data [9].

$$RSR=\frac{RMSE}{STDEV_{obs}}=\frac{\sqrt{\sum_{i=1}^{N}(O_i-S_i)^2}}{\sqrt{\sum_{i=1}^{N}(O_i-\bar{O})^2}} \qquad (4)$$

3.4.5 Volumetric Efficiency (VE)

Volumetric Efficiency (VE) is the statistical measure to describe the model efficiency in term of volumetric residual between the model outputs and observations. The values of VE vary between 0–1. The perfect agreement between observed and simulated values is found when VE is equal to 1.

$$VE=1-\frac{\sum_{i=1}^{N}|S_i-O_i|}{\sum_{i=1}^{N}O_i} \qquad (5)$$

where O_i is observed values at time i, S_i is modeled/simulated values at time i, N is the number of observed values, $\bar{O}$ is the average value of the observed values, and $\bar{S}$ is the average value of the modeled values.

3. RESULTS AND DISCUSSIONS

3.1 Model Calibration and Validation

In this study, model calibration was conducted using the dataset from 2000–2015 by aiming at receiving the suitable model parameters reasonably to represent the hydrologic behavior of the Ping and Wang River Basins. Table 6 shows the estimated values of model parameters in each sub-basin including runoff coefficient, infiltration coefficient, and percent of effective rainfall. Estimating model parameters in WEAP was made by manual adjustment to minimize the difference between the observed and simulated flows at key gauging stations; P.12C, P.17, W.4A and reservoir inflow of Bhumibol Dam. Validation procedure was also conducted using dataset during 2016–2020 to assess the model validity for the simulation of hydrologic response.

It is found that the estimated values of runoff coefficient for 3 sub–basins varies from 0.10–0.25 describing surface runoff potential in the Ping and Wang Basins where the large portion of total land area is vastly forestland and agricultural areas. The infiltration coefficient in WEAP model is inversely correlated with the runoff coefficient to describe capability of water penetrating into soils. It is exhibited that the infiltration coefficient ranges from 0.75–0.90 for these 3 sub–basins. In addition, the effective rainfall explaining the net amount of rainfall potentially consumed by crops, varies greatly subject to the specific land use classes and hydro–geological conditions for each sub–basins as can be seen in Table 6.

Table 6 Estimation of model parameters by the simplified rainfall–runoff method in WEAP

WEAP Parameters		Sub–Basin		
		1	2	3
Runoff Coefficient		0.25	0.10	0.18
Infiltration Coefficient		0.75	0.90	0.82
Effective Rainfall (%)	A1	85	99	64
	A2	42	16	67
	A3	92	24	88
	A4	22	84	34
	A5	43	46	3
	A6	92	91	88

	A7	29	91	12
	A8	42	100	88
	A9	41	68	96
	F1	63	79	97
	F2	69	17	61
	M1	46	55	28
	M2	4	65	90
	U1	80	63	97
	U2	36	69	92
	W	100	100	100

3.2 Assessment of Model Performance

The efficiency of model performance was considerably investigated using the statistics assessed from the simulated outputs performed by WEAP model and observed flow data at key gauging stations; P.12C, P.17, W.4A and reservoir inflow of Bhumibol Dam. The model performance statistics for rainfall–runoff simulation during calibration and validation periods and long–term simulation periods are presented in form of PBIAS, NSE, R^2, RSR, d, and VE as summarized in Table 4.

It exhibits the similar pattern of the simulated and observed monthly flows at P.12C, P.17, W.4A stations and reservoir inflow of Bhumibol Dam when long–term simulation during 2000–2020 is implemented as qualitatively displayed in Fig.7–Fig.10.

For the calibration period during 2000–2015, the model performance shows good agreement of R^2 index of 0.80 and 0.76 at P.17 and W.4A gauging stations. Moreover, the model performance could be achieved in simulating the monthly reservoir inflow of BB Dam with R^2 of 0.82. Moreover, a normalized statistic measured in form of NSE value shows good fit of 0.72–0.80 at P.17 and W.4A gauging stations, and BB inflow.

However, the model performances are slightly decreased when the model validation during 2016–2020 is performed for P.17 and W.4A stations and BB inflow with R^2 of 0.63–0.75 and NSE of 0.44–0.65. For the long–term simulation during 2000–2020, it provides the reasonably good agreement of R^2 of 0.72–0.81 and NSE of 0.71–0.78 at all gauging stations except P.12C station. It is investigated that the streamflow data at P.12C station located downstream of BB Dam, is strongly associated with the regulated dam release. Therefore, further study in setting up related parameters for reservoir operation of BB Dam corresponding to the current operational practices should be reconsidered to improve the model performance particularly at P.12C station.

Table 7 Summary of model performance statistics for rainfall–runoff simulation in the Ping and Wang River Basins

Statistics	Streamflow Gauging Stations			
	BB Inflow	P.12C	P.17	W.4A
Calibration Periods (2000–2015)				
PBIAS	16.67	18.44	12.70	28.47
NSE	0.80	-0.27	0.77	0.72
R^2	0.82	0.29	0.80	0.76
RSR	0.45	1.13	0.48	0.53
d	0.80	-0.26	0.77	0.73
VE	0.62	0.63	0.77	0.47
Validation Periods (2016–2020)				
PBIAS	35.10	34.39	57.77	28.27
NSE	0.65	-0.53	0.44	0.59
R^2	0.74	0.14	0.75	0.63
RSR	0.59	1.24	0.75	0.64
d	0.65	-0.53	0.44	0.60
VE	0.51	0.66	0.42	0.43
Long–Term Simulation (2000–2020)				
PBIAS	20.05	20.70	18.24	28.44
NSE	0.78	-0.30	0.73	0.71
R^2	0.81	0.29	0.79	0.75
RSR	0.47	1.14	0.52	0.54
d	0.78	-0.29	0.73	0.71
VE	0.60	0.64	0.73	0.46

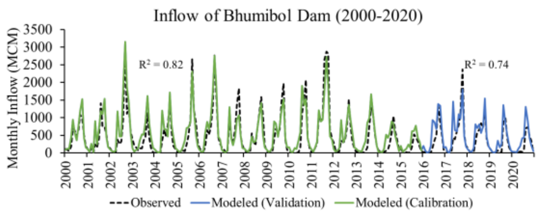

Figure 7 Comparison of simulated and observed monthly inflows of BB Dam

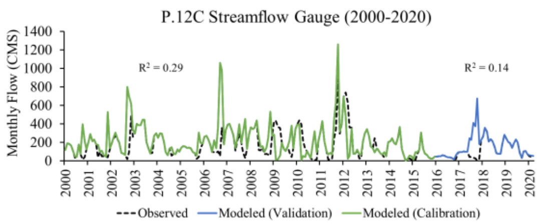

Figure 8 Comparison of simulated and observed monthly flows at P.12C station

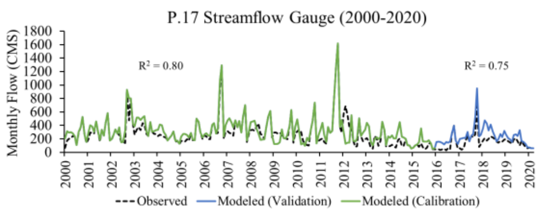

Figure 9 Comparison of simulated and observed monthly flows at P.17 station

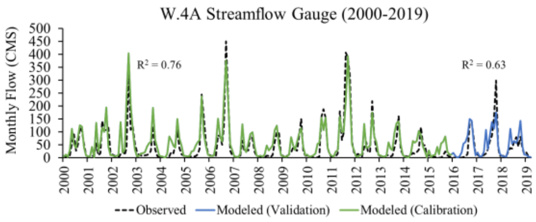

Figure 10 Comparison of simulated and observed monthly flows at W.4A station

4. CONCLUSIONS

WEAP hydrologic model was developed for the Ping and Wang River Basins in the northern region of Thailand by aiming to assess the model efficiency in simulating the rainfall–runoff relation to explain the hydrologic dynamics and responses of the implemented watershed system over long–term periods. The long–term simulation results showed that WEAP model could provide the reasonably good agreement of R^2 of 0.75–0.81 at key gauging stations; P.17, W.4A and reservoir inflow of Bhumibol Dam except P.12C station where the hydrologic response has been strongly affected by the influence of regulated dam release. Based on the overall model performance statistics, predominant capability of WEAP model to simulate behavior of hydrologic responses was found particularly at the outlet of sub–basin (P.17 and W.4A gauging stations) and outflow point (reservoir inflow of BB Dam) where the impact of regulated flow on the model performance has been diminished.

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