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River Runoff under Climate Change Using Dynamic Basin Parameters in Lam Dom Yai River Basin, Thailand

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Abstract

This study aims to study effects of climate change (CC) and land use change (LUC) on future river flows of Lam Dom Yai (LDY) basin covering 5,000 km^2 located in the northeast of Thailand. The study developed a climate hydrologic model (SWAT model) utilizing basin's key spatiotemporal parameters as dynamic parameters comparable to utilizing constant or static parameters. The GIS-based ARC –SWAT model was developed and applied using 78 years of future climatic data from MRI-GCM which are statistically downscaled with observed data. Additionally CA-Markov technique was adopted to simulate temporal and spatial pattern of land use in periodically as the model input taken into account LUC. Results of the study indicated model reliability of both dynamic and static parameters. Dynamic parameters computed better model performance for daily, monthly and annual flow simulation basis than those of applying static parameters, the model with dynamic parameters is consequently recommended. For the case study of LDY basin in the future with the selected CC scenario RCP 4.5, the mean annual flows of LDY for the case of using dynamic and static parameters would be increased respectively 6.1 and 4.9 percent more than the past mean annual flow. Additionally, the future mean monthly flows and extreme daily flows would be significantly increased in September and October, and decreased in February and March respectively. Furthermore, high flows would be deferred from September to October.

Keywords : Dynamic basin parameters; Climate change; Land use change; Climate hydrologic model; Land use change model

Introduction

Global warming and climate change becomes the world's critical phenomenon that challenge all nations' co-operation in greenhouse gas (GHG) reduction to decelerate global warming and essential adaptive measures preparation to alleviate CC impacts respectively. According to the, IPCC, 2021 during 1950-2020 higher global temperature was increased up to 1.09°C on average. Increasing of GHG significantly causes global warming and CC consequently affects hydrologic system comprising surface runoff, groundwater, and evapotranspiration.

Numerous international studies have researched quantitative hydrologic response due to long term future CC by applying different global climate models (GCM) [1, 2] with downscale techniques and various hydrologic models. Results indicated that effects from CC would be uncertain in either increasing or decreasing trends of river flows. Increasing trend of river flows and floods were determined for example in Mekong River [3], Canada [4], Myanmar [5], Brazil [6], Ping River in Thailand [7], and Korea [8]. On the other hand, decreasing trend of runoff was examined in Vietnam [9].

Additionally, some researches [10, 11] considering CC and LUC affecting hydrologic response has been employed. A study of deforestation in Brazil [12] and rapid urbanization only or both of urbanization and CC in Canada would affect increasing mean annual flow and flood flows [4]. On the other hand, LUC due to reforestation in China [13], Kenya [14], and Thailand [15] would result in contrarily decreasing mean annual flow and extreme flood volume.

Most of researches using Soil Water Assessment Tool Model (SWAT) [16] adopted fixed or static basin parameters in the model calibration period and applied for forecasting hydrologic response in future period. Nevertheless, little research on consideration of spatiotemporal parameters under CC and LUC situation has been conducted, therefore a research on comparison of river runoff from the SWAT model between using dynamic basin parameters and using static basin parameters in a particular basin in Thailand should be determined.

Results would be beneficial in selection of dynamic or static parameters approach that suitable for required temporal scale basis and accuracy, as well as time and budget constraints. Additionally, the LDY model could be applied as an essential tool to forecast future hydrologic situation under CC for concerned agencies to prepare CC adaptive measures i.e. land use management by reforestation or perennial planting, redesign or enhance capacity of hydraulic structures, and review of water management operating rule curves of water resources.

Material and Methods

Study area

Lam Dom Yai river basin is one of four main sub basins of the Lower Mun River Basin located in the northeast of Thailand. The basin is located in Ubon Ratchathani province covering 5,000 sq.km or one-third of the catchment area of the lower Mun river basin. At present most of the area is rainfed agriculture approximately 54% of the catchment area is rainfed paddy, 13% of field crops, and 13% of perennial, whereas only 15% of the area is forest. According to past land use maps, changing of forest area was vast decreasing from 34% in year 1985 to 25% in year 2000 and down to 16% in the year 2019, together with global CC effects, consequently more severe droughts and floods have been frequently occurred causing severe losses on environments, social and mainly on economic of agriculture sector in Ubon Ratchathani province, the fifth largest province of Thailand producing the third highest GPP of the northeast region. It is therefore essential to develop a tool to forecast future change of hydrologic response due to CC and LUC and applied for considering appropriate adaptive measures against the adverse effects.

Objectives

The objectives of the study aim to firstly developing a reliable hydrologic rainfall-runoff model of Lam Dom Yai River Basin, considering dynamic basin parameters comparing to static basin parameters, and secondly studying how CC affecting river runoff i.e. average annual flows, monthly flows, and extreme daily flows in near future period (2022-2047), mid future period (2048-2073), and far future period (2074-2099).

Methodology

A mathematical hydrologic (Rainfall – Runoff) model named Arc SWAT (version 2012.10) was developed for the study basin on the principle of soil water balance equation as follow;

$$SW_t = SW_0 + \sum_{i=0}^{n}\left(P_{day} - Q_{surf} - E_a - W_{seep} - Q_{qw}\right)$$

where SW_t is the soil moisture (mm) at the time i, P_{day} is the precipitation (mm), Q_{surf} is the streamflow (mm), E_a is evapotranspiration (mm), W_{seep} is the water flow to the unsaturated zone (mm), and Q_{qw} is the ground water flow (mm).

Study Approach is depicted in Figure 2 comprising two main procedures i.e. (1) SWAT Model development consisting of input data, calibration and verification by static and dynamic parameters (2) Simulation of future river runoff.

1. Model Development

1.1 Model Input Data

Three key physical data are basically required by the Arc SWAT model, i.e. 1) topographic map or digital elevation model (DEM) of 1:50,000 scale, 2) soil series map of 1:250,000 scale, and 3) land use maps of 1:50,000 scale of four different years, i.e., year 2000, year 2008, year 2017, and year 2019 as shown in Figures 1, 3 and 4, respectively.

The other type of data is meteo-hydrologic data comprising (1) daily maximum and minimum temperatures of the meteorologic station at Amphoe Muang Ubon Ratchathani and data set of six rain gauge stations were selected basing on well - spreaded locations and valid observed data availability (2) daily streamflow data set of six selected discharge stations were used for model calibration namely M152, M153 and M154 in the upstream reach, M170 in the middle reach, and TS7 and LDY at Lam Dom Yai Regulator in the downstream reach, respectively, (Figure 1).

1.2 Model Calibration

Calibration of the SWAT model's groups of parameters mainly comprising surface runoff, groundwater, river channel, soil type, land cover, were accomplished by upstream, middle, and downstream reaches with the past recorded data of climate, hydrology and land use maps during the period of 2001-2017. Four consecutive periods of 4-5 years were calibrated to obtain dynamic parameters of each period whereas the static parameters were calibrated by only one best set of parameters through 17 years of calibration period.

To obtain more accurate results, three more land use maps of the year 2005, 2012 and 2015 which were simulated by CA Markov's model using following equation of transition probabilities matrix were added.

$$S(t+1) = P_{ij} \times S(t) \tag{1}$$

Where $S(t), S(t+1)$are the system status at the time of t or $t+1$; P_{ij} is the transition probability matrix in a state which is calculated as follows;

$$P_{ij} = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ P_{n1} & P_{n2} & \ldots & P_{nn} \end{bmatrix} \tag{2}$$

$$\left(0 \le P_{ij} < 1 \; and \; \sum_{j=1}^{N} P_{ij} = 1 \, . \, (i.j = 1,2,\ldots,n)\right)$$

1.3 Model Verification

According to no available observed data in the upper basin since 2010, verification with the observed stations at middle reach (M170) and downstream reach (TS7 and LDY) during 2018 to 2021 were applied.

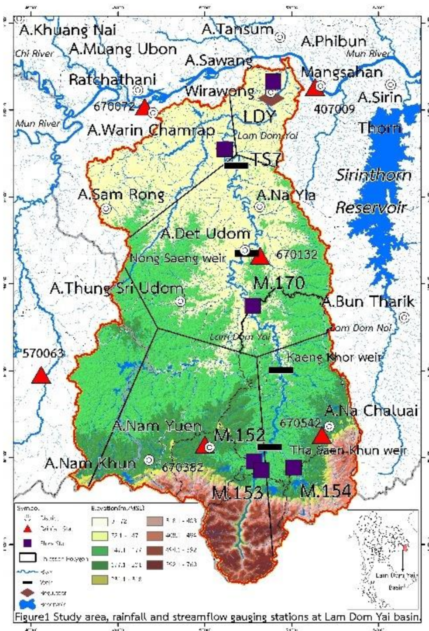

Figure 1 Study area, rainfall and streamflow gauging stations at Lam Dom Yai basin

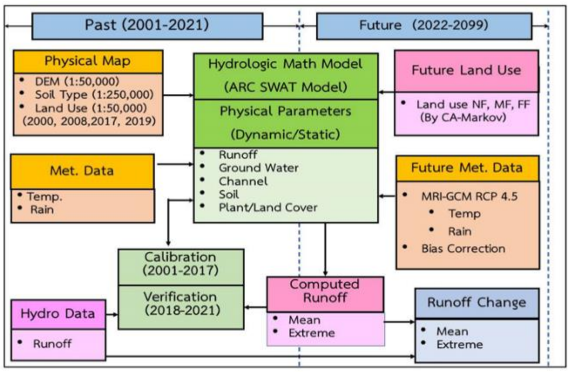

Figure 2 Conceptual approach of the study

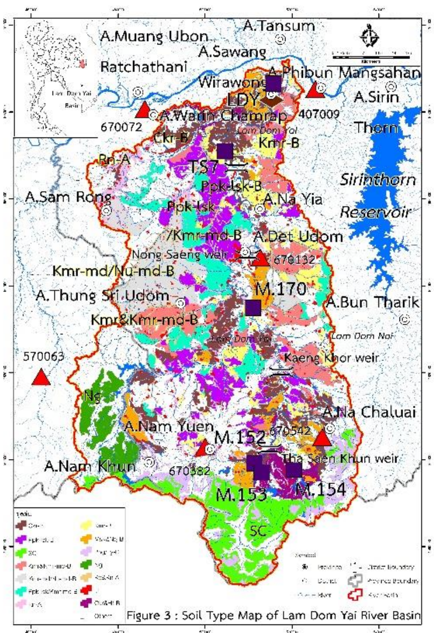

Figure 3 Soil type map of Lam Dom Yai river basin

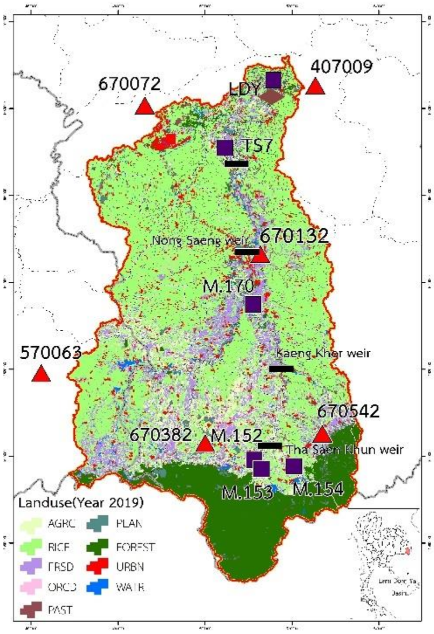

Figure 4 Land use map of year 2019

1.4 Comparison of Model's Parameters

Reliability of the model applying dynamic parameters and static parameters were compared by utilizing three indicators at good performance rating i.e. 1) Correlation coefficient (R^2) ranging 0.75-0.85, 2) Nash–Sutcliffe Coefficient of Effective (NSCOE) ranging 0.7-0.8, and 3) Bias factor (BIAS) ranging ±5-10% [17].

2. Simulation of Future River Runoff.

The calibrated model was then adopted as the tool for simulation of the river runoff under future CC condition from 2022 to 2099. Three future time periods were defined as near future (NF) for years 2022-2047, mid future (MF) for years 2048-2073, and far future (FF) for years 2074-2099, respectively. Following data were prepared,

2.1 Future Climate Data

Future daily climate data set of temperature and rainfall during 2001-2099 were obtained from the GCM model. The Hydro – Informatics Institute (HII) of Thailand has manipulated various GCM data for Thailand by statistical downscaling technique. Rainfall data of MRI –GCM model were selected since the MRI-GCM model utilized finer grid resolution and the resulted R^2 and S.D. of the downscale data compared to observed data were more preferable both temporal and space to those of other six GCM models [18].

The downscaled MRI-GCM rainfall data of RCP 4.5 were manipulated bias correction using the Standard Deviation Ratio (SDR) method [19]. The SDR method presented good results of R^2 and SD in term of temporal and space in wet season and especially in dry period comparable to the other methods, [18].

2.2 Future Land Use Map

Future land use maps were periodically generated for three future periods interval from 2022 to 2099 by CA-Markov method [20, 15] based on past land use changing rate during 2010 – 2019.

2.3 Future Parameters

Model parameters were applied using both the resulted static and dynamic parameters changing rate obtained from the calibration.

Results

Calibration and Verification Results

Figures 5 to 7 show results of daily simulated flows compared to observed flows and correlation coefficients of upper to downstream reaches. The calibrated results using static parameters showed significant reliability ranges of R^2 (0.75-0.94), NSCOE (0.75-0.93), and BIAS (4.84-13.13). The verified results showed good compatibility with observed data both in hydrograph pattern and magnitude. The resulted indicators of R^2, NSCOE, and BIAS were in the ranges of 0.65-0.95, 0.60-0.93, and 3.6-16.65%, respectively.

The calibrated results using dynamic parameters showed better significant reliability ranges of R^2 (0.80-0.96), NSCOE (0.75-0.96), and BIAS (4.8-12.0%). The verified results indicated good compatibility with observed data. The resulted ranges of R^2, NSCOE, and BIAS were 0.76-0.98, 0.70-0.94, and 1.37-7.7%, respectively. The daily, monthly, and annual flows resulted from using static parameters showed small less significance test of R^2, NSCOE, and BIAS than those using dynamic parameters.

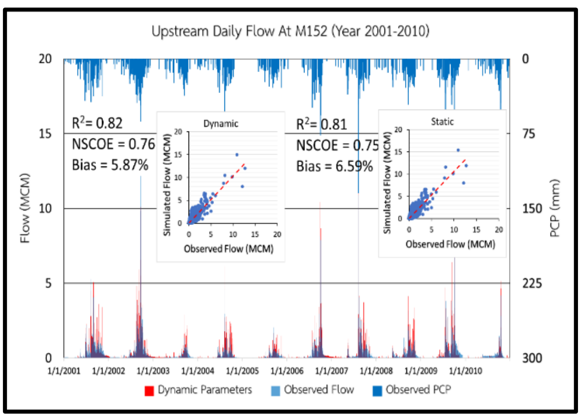

Figure 5 Calibrated results of daily flows at M152 (upstream reach) by dynamic and static parameters

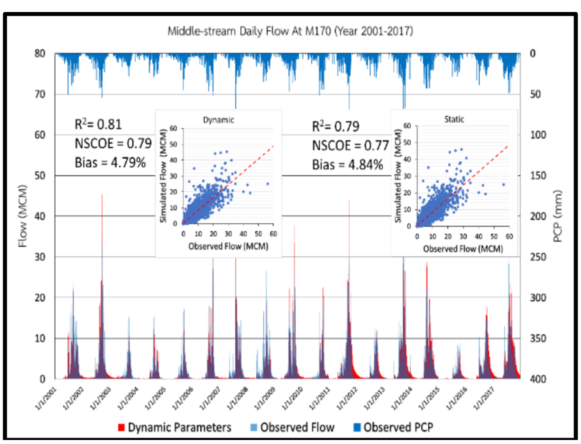

Figure 6 Calibrated results of daily flows at M170 (Middle reach) by dynamic and static parameters

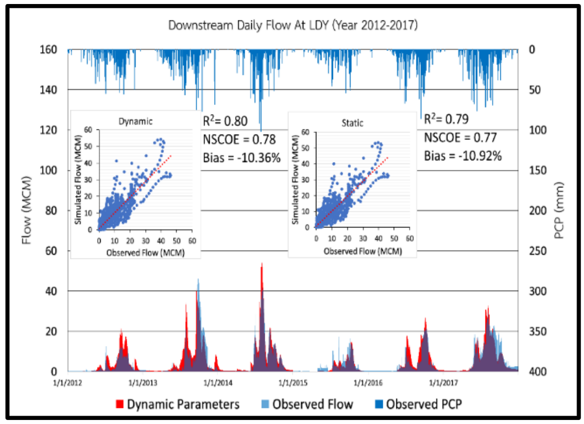

Figure 7 Calibrated results of daily flows at LDY (downstream reach) by dynamic and static parameters

Results of Model Parameters

Key parameters concerned were adopted referring to previous studies on main parameters significantly affecting runoff calculation [21, 22].

1. Static Parameters

In case of static parameters, the calibrated parameters were assumed constant upon calibration period of which parameters summarized in Figure 8.

2. Dynamic Parameters

Following results of 8 selected key parameters values and their changing trends for future are presented in Figure 8,

1) Groundwater : Decreasing of AIPHA-BF(Baseflow alpha factor) and GWQMN (Threshold depth of water in the shallow aquifer required for return flow). Increasing of GW_DELAY (Groundwater delay) and REVAPMN (Threshold depth of water in shallow aquifer for revaporation).

2) Surface–runoff : Increasing of CN2.Mgt (Initial SCS CNII Value). Decreasing of OV_N (Overland N Value).

3) Channel : Increasing of CH-K2 (Effective hydraulic conductivity). Decreasing of CH-N2 (Manning N value for main channel).

4) Land cover : Decreasing of EPCO (Plant uptake compensation factor).

5) Soil : Increasing of ESCO (Soil evaporation compensation factor), SOL_AWC (Available water capacity of the soil layer), and SOL_K (Saturated hydraulic conductivity).

3. Future Conditions

3.1 Future Climates

Future rainfall data from the MRI–GCM scenario RCP 4.5 at six stations were bias corrected with observed rainfall data during past period as summarized in Table 1. All stations' data indicated increasing of future rainfall approximately 5-10% or equivalent to 6.7% in term of basin rainfall more than those of past period, whereas the average maximum and minimum daily temperature would be increased by approximately 1.0°C and 2.0 °C respectively in the far future period.

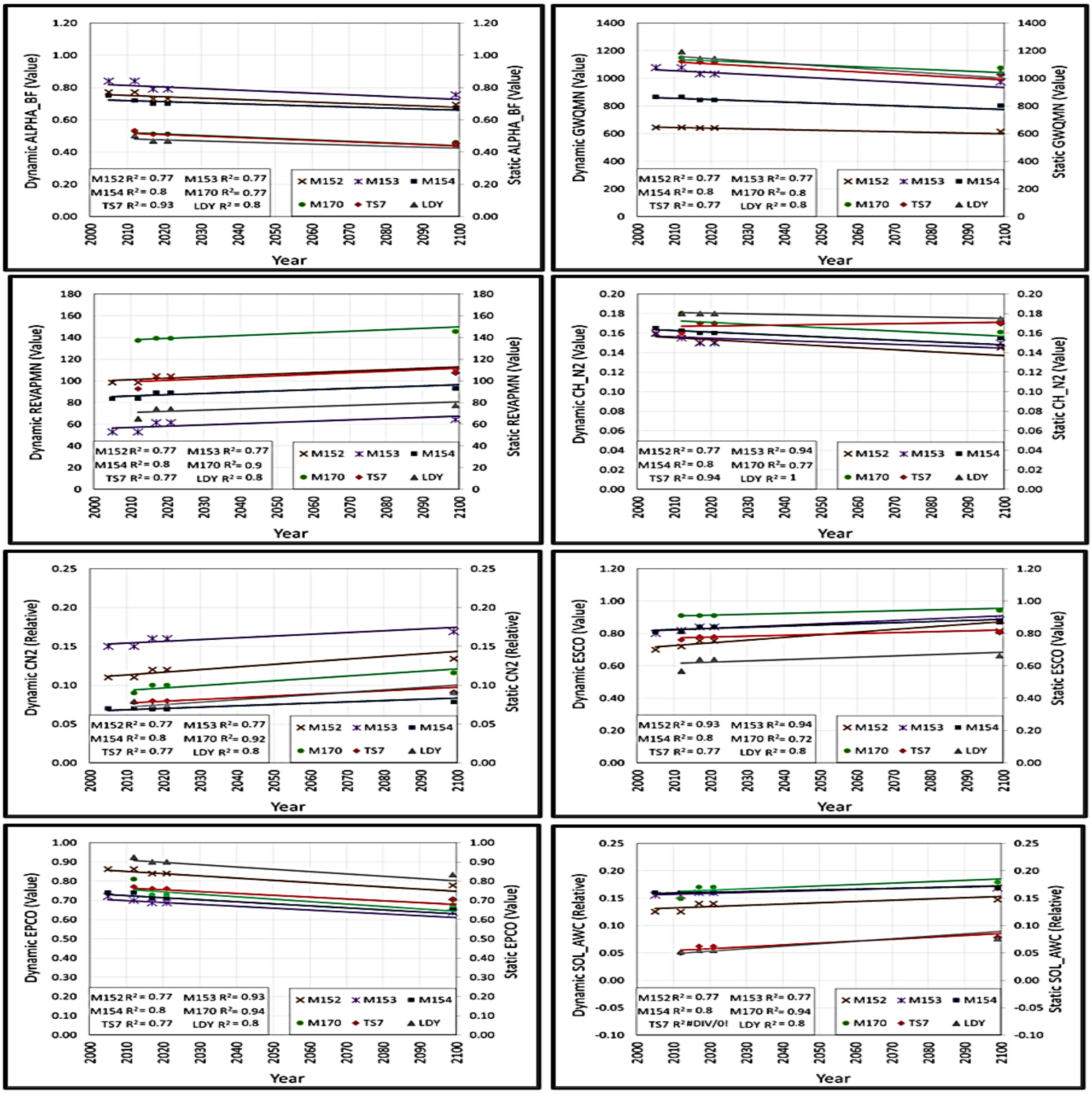

Figure 8 Adapted future SWAT's key dynamic and static parameters of Lam Dom Yai sub – basins

Table 1 MRI-GCM future rainfall and temperature, under CC scenario RCP 4.5

Stations	Average RCM Annual Rainfall (After Bias Correction), mm								
	2001-2021	2022-2047	Diff (%)	2048-2073	Diff (%)	2074-2099	Diff (%)	2022-2099	Diff (%)
Rainfall	PAST	RCM NF	fr. Past	RCM MF	fr. Past	RCM FF	fr. Past	Av. NF-FF	fr. Past
1.1) A. Na Chaluai STA. 670542	1431	1562	9.20	1569	9.63	1573	9.93	1568	9.58
1.2) A. Nam Yuen STA. 670382	1151	1202	4.49	1221	6.10	1252	8.81	1225	6.47
1.3) A. Det Udom STA. 670132	1371	1431	4.37	1465	6.91	1480	7.99	1459	6.42
1.4) A. Phibun Mangsahan STA. 670022	1432	1481	3.42	1594	11.34	1591	11.11	1555	8.62
1.5) A. Warin Chamrap STA. 670072	1292	1296	0.34	1409	9.10	1390	7.62	1365	5.68
1.6) A. Kantharalak STA. 570063	1333	1357	1.80	1490	11.76	1488	11.62	1445	8.39
Climate	Average Max and Min Daily Temperature, °C								
2.1) A. Meung Ubon	33	34	1.11	34	1.53	35	3.20	34	1.94
Ratchathani	23	24	7.71	25	12.39	26	14.58	25	11.56

3.2 Future River Runoff (RCP 4.5)

Figure 9 shows the results of the simulated daily runoff of future 78-years (2022-2099). The mean annual flows, using dynamic parameters would be higher than observed data in the past period at 22.8% for upstream reach (M152), 16.7% for middle reach (M170), and 6.1% for downstream reach (LDY), respectively as summarized in Table 2. Whereas mean annual flows using static parameters would also be higher than observed data in the past period at 9.8% for upstream reach (M152), 23% for middle reach (M170), and 4.9% for downstream reach (LDY), respectively. In summary, mean annual flows from the dynamic parameters would be greater than those from the static parameters for 1.2-13%.

In term of monthly basis, the model (dynamic parameters) indicated that future wet season flows would be greater than the past especially in October approximately 33% for M152, 24% for M170, and 6% for LDY. Whereas mean daily peak flows would be greater than those of the past at 18%, 31%, and 10%, respectively (Figure 10). In addition, the future higher flow hydrographs would be shifted later from September to October.

Future dry season flows would overall be greater than the past due to more rainfall but some months be drier than the past especially in the upstream and downstream river reaches during February and March in the range of 2-50%. Mean daily minimum discharges would be decreased at 0.7% for M152, increased at 33% for M170, and increased at 8% for LDY, respectively.

This implies future CC would affect LDY runoff on more volume, greater extreme flood flows, drier minimum flows in the upper reach, and deferred high flow occurrence period.

Table 2 Summary of future average annual flows by dynamic and static parameters. unit : (MCM/yr)

Stations	PAST (2001-2021)			NF (2022-2047)						MF (2048-2073)						FF (2074-2099)						Total (2022-2099)					
	Bs.PCP	$\bar{Q}$ (MCM/yr)		Bs.PCP		$\bar{Q}$ (MCM/yr)		$\bar{Q}$Diff (%)		Bs.PCP		$\bar{Q}$ (MCM/yr)		$\bar{Q}$Diff (%)		Bs.PCP		$\bar{Q}$ (MCM/yr)		$\bar{Q}$Diff (%)		Bs.PCP		$\bar{Q}$ (MCM/yr)		$\bar{Q}$Diff (%)	
	mm/yr	Dynamic	Static	mm/yr	Diif %	Dynamic	Static	Dynamic	Static	mm/yr	Diif %	Dynamic	Static	Dynamic	Static	mm/yr	Diif %	Dynamic	Static	Dynamic	Static	mm/yr	Diif %	Dynamic	Static	Dynamic	Static
M152 Upstream Reach	1151	101	98	1202	4.5%	124	100	23.4%	20.4%	1221	6.1%	133	108	31.7%	28.4%	1252	8.8%	137	115	36.2%	32.8%	1225	6.5%	124	108	22.8%	9.8%
M170 Midstream Reach	1368	962	944	1468	7.4%	1114	1088	15.9%	13.1%	1483	8.5%	1205	1196	25.3%	24.4%	1495	9.3%	1207	1198	25.5%	24.6%	1482	8.4%	1122	1161	16.7%	23%
Lamdomyai Downstream Reach	1309	1824	1787	1368	4.5%	1908	1818	4.6%	0.3%	1415	8.1%	1934	1879	6%	3.1%	1427	9%	1964	1928	7.7%	5.7%	1403	7.2%	1935	1875	6.1%	4.9%

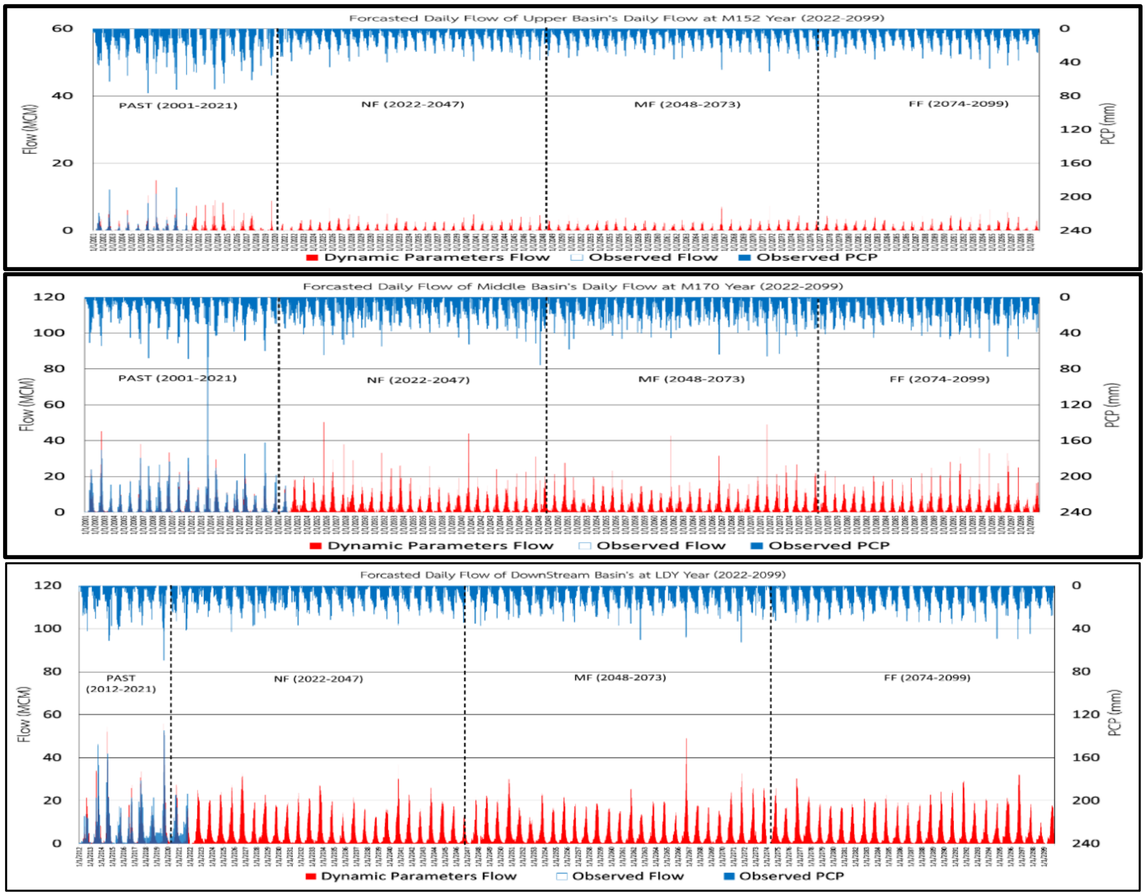

Figure 9 Forecasted future daily flows at M152, M170, and LDY (Year 2022-2099)

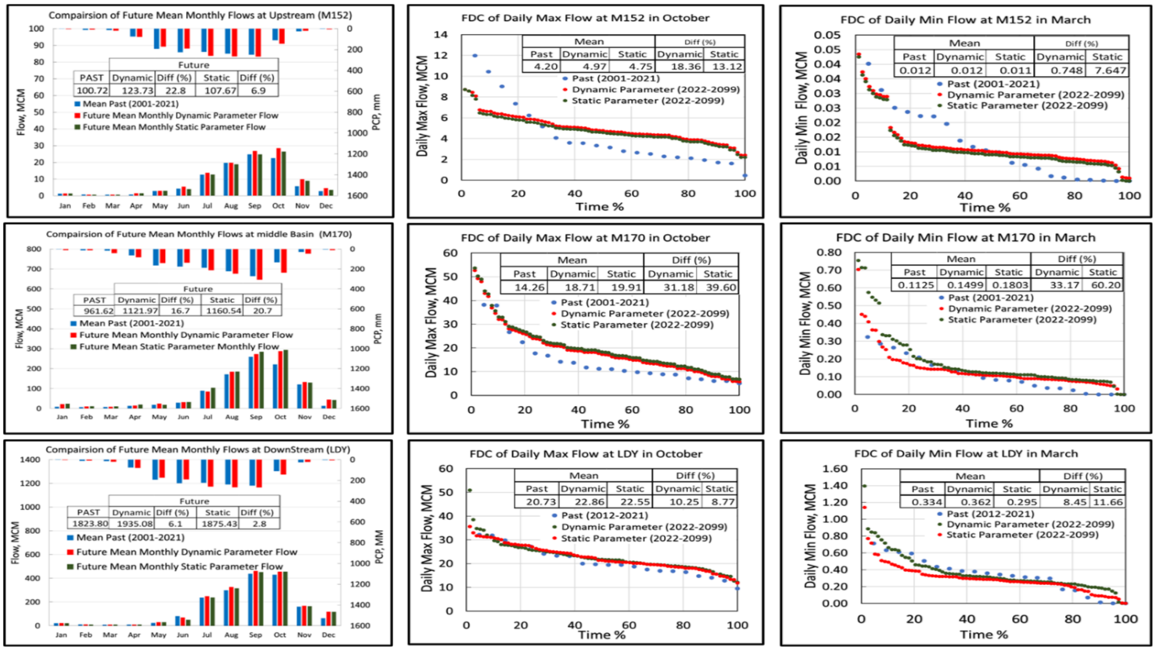

Figure 10 Future mean monthly flows, Flow Duration Curves (FDC) of daily maximum flow in October, and FDC of daily minimum flow in March

Conclusion and Recommendation

Conclusions

The developed SWAT model shows good correlation between computed flows and the observed flows in daily, monthly and annual basis. The results indicated that dynamic parameters give better correlation to the observed data. Consequently, forecasting future hydrologic response using dynamic basin parameters is recommended.

The future mean annual flows of the basin over 78 years using dynamic parameters would be increasing trend at 22.8%, 16.7%, and 6.1%, for upstream, middle, and downstream reaches, respectively which were more than those of applying static parameters by 13.0%, 6% and 1.2%, respectively.

Recommendations

1. The study has not taken into account irrigation water usage along the river and tributaries. The existing irrigation areas of 30,000 rai utilized water from the river approximately average flow volume of 40-50 mcm per year. Consequently, the calibrated flows especially in dry reason would be calculated more volume than observed flows. Further studies on the irrigation water demand and other main demands should be considered.

2. LDY' s overbank flood flows could not be actually field measured, instead, responsible agencies calculated the floods by applied rating curve extrapolation technique of which results might be deviated from the actual flows. A hydrodynamic model calibrated with floodplain flow velocity should be additionally developed in parallel to rectify overbank flows for further study.

3. Monitoring and review of model's parameters of LDY should be manipulated in the future to improve the changing trend and rates of the parameters. Other adjacent river basin models are suggested to be developed and comparison study of applying dynamic parameters and static parameters should be prepared. Sufficient results of model parameters could be analyzed and summarized as regional basin parameters that could be applied for modeling other ungauged river basins.

4. Further researches on quantitative effects of LUC on the river flow regime comparable to effects of CC should be examined.

5. Further applications on feasible land use management measures (e.g. reforestation, crop planning), design revision of existing and future hydraulic structures' capacities, and review of operating rule curves of water resources, should be carried out to alleviate CC problems.

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