# The effect of forest rehabilitation on runoff and hydrological factors in the upstream area of the Ubolratana Reservoir in Thailand

Krit Sriworamas, Haris Prasanchum and Jirawat Supakosol

## ABSTRACT

Thailand's forests in reservoir watershed areas are declining at an alarming rate due to land use demand. Reforestation aiming at maintaining optimum forest areas becomes a top priority in reservoir management planning which needs hydrologic responses as inputs. This study aims at measurable assessment of the changes in hydrologic responses of the Ubolratana Reservoir in northeastern Thailand due to increasing forest areas. The assessment was done in two parts: (i) forest areas by CA Markov model and (ii) rainfall–runoff by Soil and Water Assessment Tool (SWAT) model. Assessment results indicate that increasing forest areas cause a decrease of runoff, peak flow, and hence, inflow volume into the reservoir. The optimum size of forest area was found to be much larger than the existing size, confirming the need for existing reforestation. Additional benefits of pursuing reforestation include less erosion and sedimentation which are required in reservoir management planning.

**Key words** | forest rehabilitation, land use, runoff, SWAT, Ubolratana Reservoir

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## INTRODUCTION

Currently, forest areas are globally destroyed and gradually decrease each year because of the demand for agricultural and residential usage. Due to climate change, hydrological extremes such as frequency distributions of low flow (Hu *et al.* 2017), exceptional magnitudes and frequencies flood peaks, severe storms, etc., increase the likelihood of disaster risk and expensive risk management. Forest management, as a form of preventive risk management, plays a vital role in balancing the hydrological system and the environment. Reforestation is not only community friendly but also a highly manageable tool for responsible agencies. For example, Mueller *et al.* (2011) and Tao *et al.* (2012) found that several communities in Little Colorado River watersheds in the USA and Heshui watershed in China, respectively, benefit from reducing drought frequency, provide a food supply and income after less than a decade of participatory reforestation projects with various agencies. As a result, some hydrological parameters such as runoff, groundwater, evapotranspiration, and evaporation, directly affect reservoir management (Kirby *et al.* 2016). In 2018, forests in Thailand covered 32% of the country (approximately 164,000 km$^2$) compared to 53% in 1961. During the period 2008–2016, government agencies' attempts had successfully increased around 1,000 km$^2$ of forests, but which is far too small compared to the allowable limit of 40%. On this matter, a previous study on the impact of forest area change on the hydrological system indicated that a decreased amount of forest area also decreases the humidity in the basin area (Jia *et al.* 2017). This change can increase the possibility of flash floods. In contrast, after more effort on forest rehabilitation has been performed every year, the humidity seems to be higher (Yao *et al.* 2016) and it helps decrease the velocity of runoff flow into the river (Farley *et al.* 2005).

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At the present, the most common methodology for study and research of the impacts on the changes of soil cover to runoff or hydrology systems is using an empirical model as an analyzing tool. This study chooses the CA Markov model which is one of several spatial–temporal models for predicting changes of land use patterns. The pattern of the changes according to the conditions of the user can be defined by various events in the past in the software using this model. CA Markov has been used to create spatial data for the future trends of forest areas related to environmental conservation (Peterson *et al.* 2009), prevention, and conservation measures for forest areas (Adhikari & Southworth 2012; Vázquez-Quintero *et al.* 2016) for the process of quantitative analysis of runoff in the basin area.

For analysis of the runoff amount in this study, the SWAT (Soil and Water Assessment Tool) hydrological model was implemented (Douglas-Mankin *et al.* 2010) as a model that can analyze the impact of the change in runoff from the land usage transformation in a large complex watershed due to climate change, soil condition, land use. SWAT can be used with GIS data such as digital elevation model (DEM), land use map, soil type map, and river map, including climate data such as maximum–minimum temperature, rainfall, etc. The results from this model also can explain the changes of various factors that respond to the watershed hydrological system reliably and acceptably (Szcześniak & Piniewski 2015).

The aim of this study is to estimate the hydrological response on forest rehabilitation by using two types of numerical models: (1) CA Markov for the prediction on the future forest area change and (2) SWAT for the estimation on the runoff in the basin that further flows into the reservoir. The study area was the headwater area of the Ubolratana Dam, a large multi-purpose reservoir in the northeast of Thailand, where deforestation has been developing in favor of agriculture. Hence, the research results of these simulated situations and circumstances can firmly point out the benefits of forest rehabilitation, which the responsible agencies could apply as a guide to educate local stakeholders to recognize the significance of this activity that further maintains the balance among the hydrological system, forest, water resource, and a sustainable community in the future.

## STUDY AREA

The upstream area of Ubolratana Dam comprises five subbasins of Chi Basin including Lam Phaniang, Nam Phuai, Upper Phong, Nam Choen, and Nam Phrom. Its location is 17°36′N–16°00′N and 102°12′E–102°48′E and covers approximately 11,960 $km^2$, as shown in Figure 1, where the average rainfall is 1,300–1,400 mm and the average temperature is 27 °C. The western-side landscape is a mountainous headwater forest while the middle and the east sides are active agricultural areas. The problems often found in this area are deforestation for agriculture land use, intrusion on the public water resources, insufficient water storage, and farmers changing their land use for traditional crops.

Ubolratana Dam is physically situated in Ubolratana District in Khon Kaen province by an exit of the eastern basin. It is classified as a clay core rock filling type of 885 m in length and 32 m in height. The surface area is 370 $km^2$ to support an average runoff of 2,470 Million Cubic Metres (MCM) per year with a normal storage of 2,431 MCM. This reservoir is managed by the Electricity Generating Authority of Thailand (EGAT) whose main duties are to produce electricity, water supply, irrigation, conserve the ecology, and transportation. In this study, the average monthly rainfall, maximum and minimum temperatures (from the Loei, Chulabhorn Dam, and Ubolrartana Dam climate stations located in the northern, western, and eastern part of the basin, respectively) and average monthly runoff (from the Ubolratana Dam station) during the years 1997–2017 were selected as the baseline period.

## CA MARKOV MODEL

To be able to simulate the forestry situation in the future using the CA Markov model, map data from the years 2007 and 2015 were classified into 12 types of land use, and this information was used as the base map. After data screening, the top three most obvious land use changes were forest, rice, and sugar cane, as shown in Figure 2. Therefore, the hypothesis of the prediction using CA Markov has been set with parameters for the changing area of rice and sugar cane to be forest within the next 30 years. The results were mapped as land usage into three sets for the years 2045, 2075, and 2105 respectively.

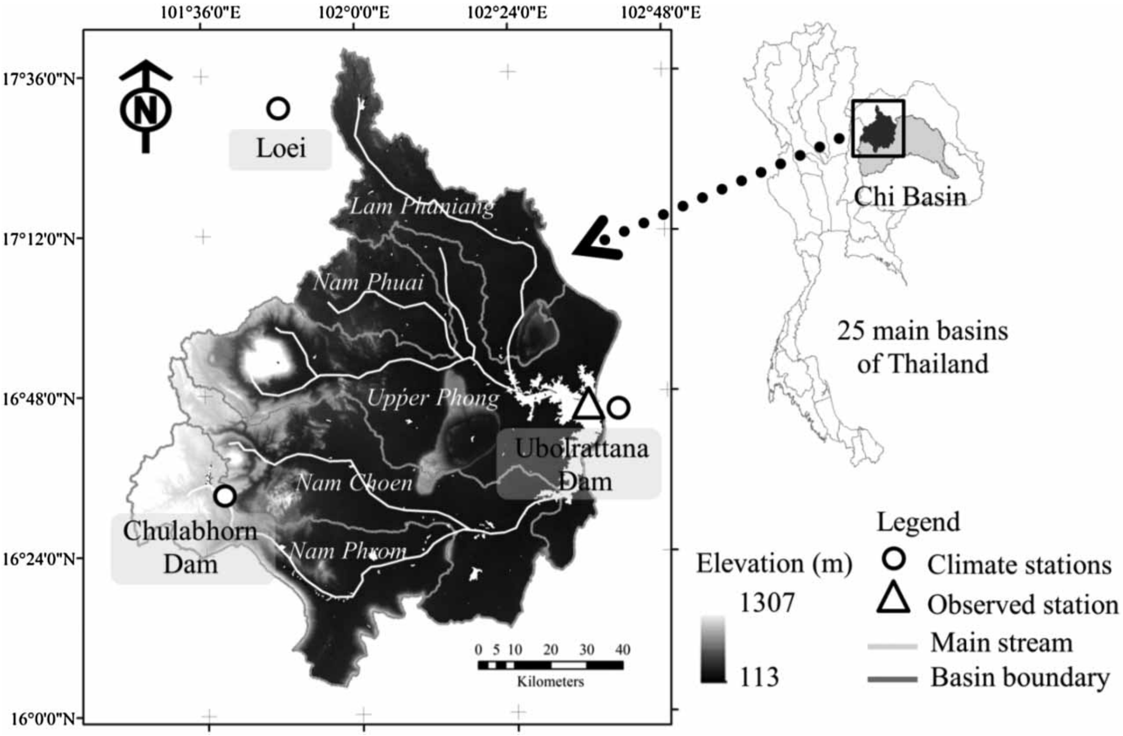

**Figure 1** | Study area and Ubolratana Reservoir.

CA Markov (Sang *et al.* 2011) is a decision-support model working with cellular automata (CA) and Markov chain based on the calculation of transition probability matrix, transition area matrix, and conditional probability image in the past. Basically, the data from the transition area matrix and conditional probability image will be used for

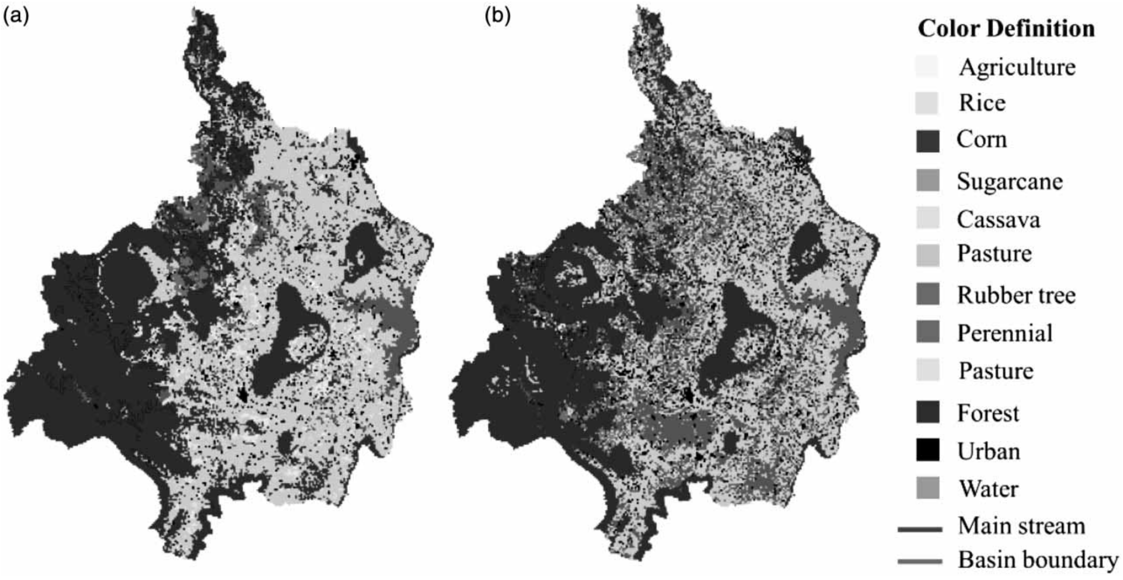

**Figure 2** | Land use changes during 2007 to 2015.

the prediction on the future land use. Later, transition area files were created, processed, and the data were linked from the land use map in 'Time + 1' (present time) to 'Time + 2' (predicted time). CA Markov has been applied to water resource engineering works, such as the projected impacts of increased annual runoff and urban areas to flood events (Du *et al.* 2012), runoff variability due to climate and land use changes in the future (Pan *et al.* 2017). The projection of land use change can be represented in the following equations:

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

$$P_{ij} = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1m} \\ P_{21} & P_{22} & \cdots & P_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ P_{m1} & P_{m2} & \cdots & P_{mm} \end{bmatrix} \tag{2}$$

$$\left(0 \le P_{ij} < 1 \text{ and } \sum\nolimits_{j=1}^{m} P_{ij} = 1, \quad (i, j = 1, 2, \ldots, m)\right) \tag{3}$$

where $L_{(t+1)}$ and $L_{(t)}$ are the land use status at the times of t or t + 1 and $P_{ij}$ is the transition probability matrix of the state.

## SWAT AND DATA COLLECTION

SWAT (Douglas-Mankin *et al.* 2010) is a hydrological model for estimation on the runoff and an analysis on the impact of land use change or climate change on the runoff change with a large, complex watershed zone. The model calculation is based on the water balance equation as illustrated in Equation (4). SWAT can analyze the daily runoff, predict the future runoff, and connect with the spatial data from a GIS model, e.g., climate data, land uses, types of soil, geographical features, and land management for the target basin area. These physical processes are concerned with the water movement required for the runoff estimation. In this regard, the spatial data and general data for the SWAT model evaluation are given in Table 1. Additionally, the SWAT model is used for reservoir management analysis (Wang *et al.* 2014) and water resource management in a basin (Welde & Gebremariam 2017):

$$SW_t = SW_0 + \sum\nolimits_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{qw}) \tag{4}$$

where $SW_t$ is final soil water content (mm), $SW_0$ is the initial groundwater content on day $i$ (mm), $t$ is time (day), $R_{day}$ is rainfall on day $i$ (mm), $Q_{surf}$ is surface water content on day $i$ (mm). $E_a$ is evapotranspiration content on day $i$ (mm), $W_{seep}$ is the water entering the unsaturated zone of soil profile on day $i$ (mm), and $Q_{gw}$ is the total flow of underground water on day $i$ (mm).

### Sensitivity analysis and performance evaluation for SWAT

SWAT simulates physical processes that occur in a watershed area that is divided into sub-basins based on DEM. Each sub-basin comprises physical data, such as land use types, soil profile classifications and slope, called the hydrologic response units (HRUs). The nine sensitivity parameters of the model that were most sensitive were selected for the sensitivity analysis and result calibration according to recent research on the sensitivity analysis of SWAT parameters. This study tested the parameters applied from a

**Table 1** | SWAT model data input and performance evaluation

| Data type | Period | Scale | Data source |
|---|---|---|---|
| Digital elevation model | 2011 | 30 × 30 m | Land Development Department |
| Land use map | 2015 | 30 × 30 m | |
| Soil series map | 2011 | 1:50,000 | |
| Stream line | 2011 | 1:50,000 | |
| Climate data | 1997–2017 | Daily | Thai Meteorological Department |
| Observed runoff at Ubolratana Dam | 1997–2017 | Daily | Electricity Generating Authority of Thailand |

study on streamflow using SWAT in nearby basin areas in northeast Thailand (Prasanchum & Kangrang 2018). These were the baseflow alpha factor (Alpha_BF), threshold water depth in the shallow aquifer for flow (Qwqmn), water uptake directly from the shallow aquifer by deep tree (GW_Revap), groundwater delay time (GW_Delay), available water capacity (Sol_Awc), initial curve number (CN2), plant uptake compensation factor (Epco), soil evaporation compensation factor (Esco), and channel Manning's coefficient (Cn_N2). The assessment on the SWAT performance can be performed by comparing the runoff from the observed station with the SWAT monthly results during 1997–2017 for Ubolratana Dam Station, and were chosen for calibration and validation: 13 years (1997–2009) were used for calibration and 8 years (2010–2017) for validation, where the two parameters that were the key indicators of data accuracy included the following:

1. Coefficient of determination ($R^2$), as shown in Equation (5):

$$R^2 = \frac{[(O_{obs} - O_{avr})(S_{sim} - S_{avr})]^2}{\sum (O_{obs} - O_{avr})^2 \sum (S_{sim} - S_{avr})^2} \tag{5}$$

2. Relative error (RE), as shown in Equation (6):

$$RE = \frac{S_{sim} - O_{obs}}{O_{obs}} \times 100\% \tag{6}$$

where $O_{obs}$ is a result from the observed station, $O_{avr}$ is an average from the observed stations, $S_{sim}$ is the SWAT result, and $S_{avr}$ is an average from the SWAT result.

### Runoff response to forest rehabilitation

The response of the forest rehabilitation towards the hydrological system in the study area is described step by step in Figure 3. That is, the SWAT model gave the closest result to the observed station (using the adjusted hydrological sensitivity parameters) so this model was ultimately effective. After that, the estimated forest map from CA Markov in three future situations in every 30 years (2045, 2075, and 2105) was imported into the SWAT model to estimate the runoff by not mentioning the same climate change or spatial data as in the base year; finally, the result allowed us to see the difference between the runoff in the base year and those after more forest areas were restored in the headwater area. This result was derived from the comparison between the SWAT result and the data during the base years (1997–2017), respectively.

## LAND USE CHANGE SCENARIO RESULTS

The future land use map using CA Markov is to use the model to calculate the change from five types of land use including rice, sugar cane, corn, and pasture to the forest areas (since the baseline year data indicated the highest tendency of change) in which the change tendency was calculated every 30 years including 2045, 2075, and 2105. Eventually, the future forest estimation suggested a high tendency that forest areas would replace the rice and sugar cane fields, mostly on the east, especially around the reservoir. This was apparently confirmed in 2105 as presented

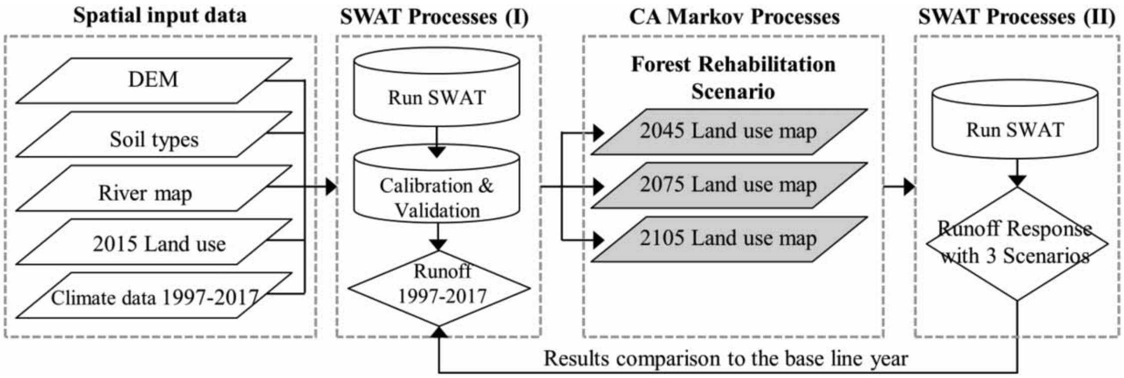

**Figure 3** | Conceptual and model set-up processes.

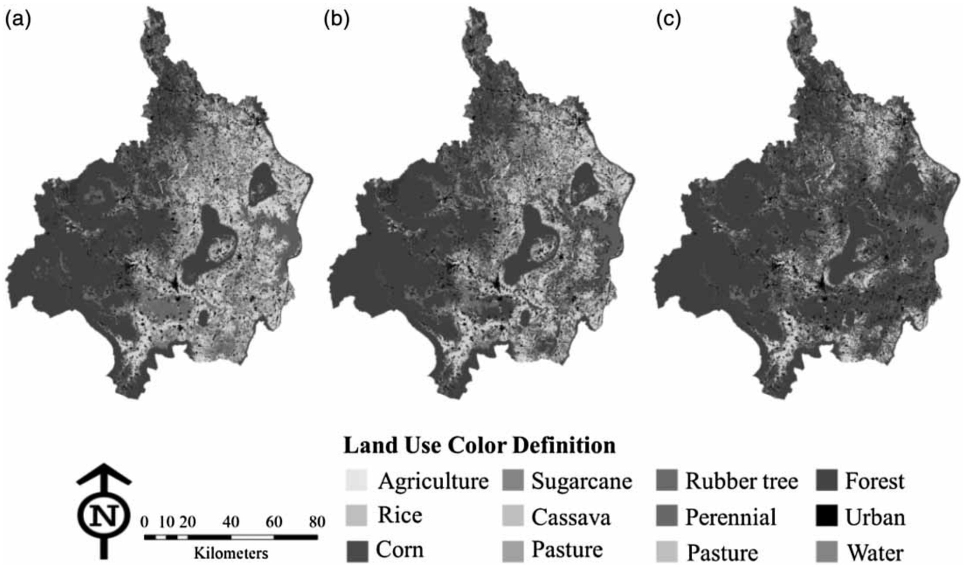

**Figure 4** | Projected spatial land use map for forest rehabilitation scenarios.

in Figure 4. The spatial area of land use changes during 2007–2105 are shown in Figure 5 in which the forest was 27.9%, 60.4%, and 93.7% increased, respectively, compared to 2015 (baseline year) whereas other types of land use were decreased, particularly for sugar cane and rice fields.

## SWAT model calibration and validation results

The runoff data from Ubolratana Dam Station during 1997–2017 was compared with the SWAT result with the adjusted sensitivity parameters for the closest result to those gained from the gauge stations as presented in Table 2. According to the comparative study, the annual average runoff, $R^2$, and RE during the calibration period of 1997–2009 were 2,776.1 MCM, 0.80, and −5.32%, respectively. For validation (2010–2017), the values are 3,038.3 MCM, 0.87, and 4.07%, respectively. Overall, SWAT calculates the annual average runoff volume of 2,876 MCM, which is close to the value obtained from the observed station (2,831.7 MCM). This provides overall $R^2$ and RE values as 0.83 and −1.54%, respectively. This indicates the accuracy of the model with good criteria (as shown in Table 3). The goodness-of-fit between SWAT results and the data from the observed station are shown in Figure 6.

## Runoff scenarios affected by forest rehabilitation and climate variability

Estimation of the runoff response change on the increased forest rehabilitation during 2045–2105 created by the CA Markov model for the runoff estimation by the SWAT model was compared with the 2015 land use map and the

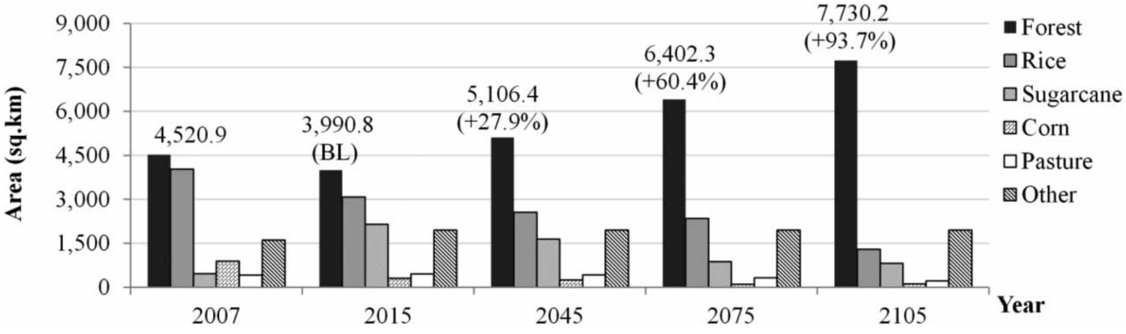

**Figure 5** | Area of land use changes.

**Table 2** | Final value of SWAT sensitivity parameters

| No. | Parameters | Range | Final value |
|---|---|---|---|
| 1 | Alpha_BF | 0–1 | 0.05 |
| 2 | Qwqmn | 0–500 | 0.01 |
| 3 | Gw_Revap | 0–500 | 1.25 |
| 4 | Gw_Delay | 0–500 | 15 |
| 5 | Sol_Awc | 0–1 | 0.27 |
| 6 | CN2 | −20–20 (%) | 0.10% |
| 7 | Epco | 0–1 | 0.55 |
| 8 | Esco | 0–1 | 0.40 |
| 9 | Ch_N2 | 0.014–0.3 | 0.036 |

**Table 3** | SWAT performance evaluation index

| | | Average annual runoff (MCM) | | Assessment index | |
|---|---|---|---|---|---|
| **Periods** | **Years** | **Observed** | **Simulation** | **$R^2$** | **RE** |
| Calibration | 1997–2009 | 2,776.1 | 2,628.5 | 0.80 | −5.32% |
| Validation | 2010–2017 | 3,038.3 | 3,161.8 | 0.87 | 4.07% |
| Summary | 1997–2017 | 2,831.7 | 2,876.0 | 0.83 | −1.54% |

climate data found during 1997–2017 as baseline year. The volume of annual average runoff of the reservoir calculated from SWAT in 2007, 2045, 2075, and 2105 shows the value of 2,606, 2,571, 2,509.9, and 2,394.8 MCM, respectively. These clearly show results lower than the average annual runoff (2,877 MCM) as −9.42%, −10.61%, −12.76%, and −16.76%, respectively, as shown in Figure 7(a). However, when the results were compared to the average runoff in a normal year (2,470 MCM), it was found that the results from 2007, 2015, 2045, and 2075 show values higher than the normal average. These results obtained from the amount of runoff of 8 years from the total of 21 years are close to 3,000 MCM (except in the year 2105, which shows a value lower than the normal average). This agrees with the research of Buendia *et al.* (2016), the study of effects of the increase in forest areas on the volume of decreasing runoff trend in an area of the Mediterranean basin of the Iberian Peninsula. The difference in the annual average runoff from SWAT based on forecasts for forest area changes compared to the baseline year and the comparison of the volume of runoff each year are shown in Table 4 and Figure 7(a), respectively.

The rainfall volume is the most important variable (Jahandideh-Tehrani *et al.* 2015) that mainly affects the runoff. The annual rainfall data during 1997–2017 were in between 874 and 1,499 mm (average 1,130 mm), as shown in Figure 8. The annual runoff has shown values close to or higher than 3,000 MCM corresponding to the rainfall above 1,100 mm (up to 10 years). On the other hand, the rainfall below 1,100 mm will give runoff lower than the normal average (there are 11 years). Similarly, the comparison of peak flow values considering the total and annual volume of the baseline year with the results from SWAT clearly shows that the peak flow volume decreases when the forest area increases in the future. This can be obtained as the percentage difference with the baseline year (2015) in the range of 28.1–35.9%, as shown in Table 4, Figures 7(b) and 9, respectively.

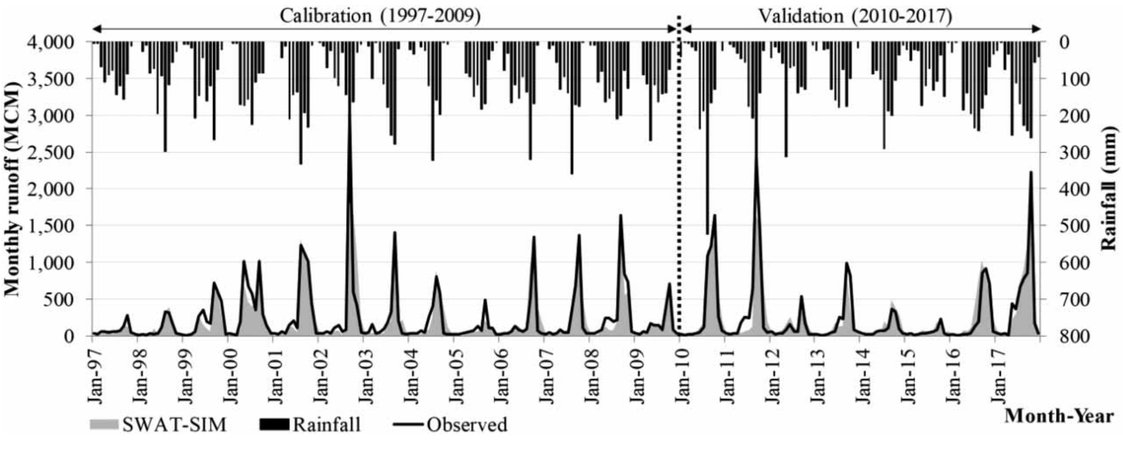

**Figure 6** | Calibration and validation results at Ubolratana Observed Station.

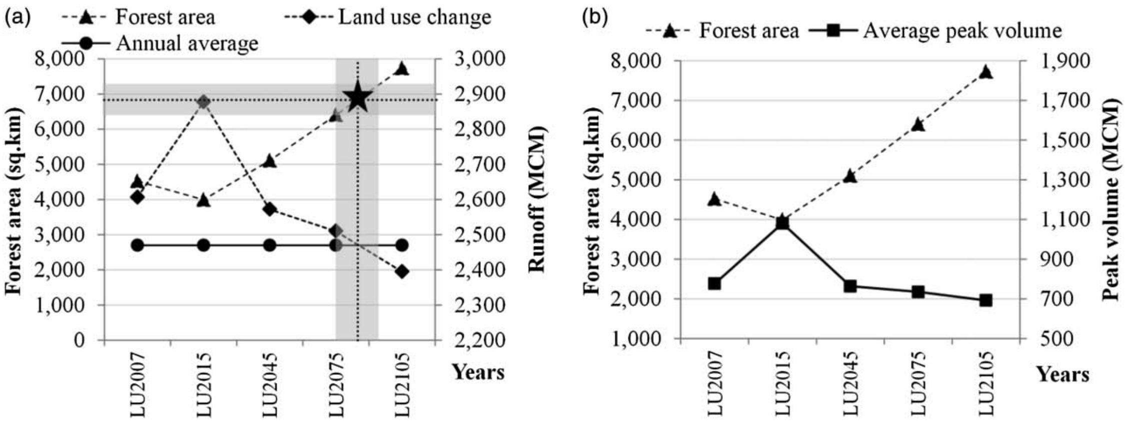

**Figure 7** | Comparison of forest area changes between (a) average annual runoff and (b) average peak volume.

The average annual rainfall during the period of 21 years, as shown in Figure 8, used in this study, shows high variation due to global climate change. This affects the variation of the volume of water flows into the reservoir, as shown in 2002, 2010, and 2011, the volume of water is higher than the average value. On the other hand, for the events in the next consecutive years (2003–2005 and 2012–2015), the rainfall shows a lower average than the average, causing the flow of water to decrease and adversely affecting the management of the reservoir. However, considering the overall results from the model, increasing forest areas will reduce the runoff and the peak flow values. This is confirmed by Qi *et al.* (2007), who found that runoff and peak flow in the watershed area of the Three Gorges Reservoir were reduced by 20% and 18.9%, respectively. In addition, Xu *et al.* (2019) reported significant reductions in peak flow magnitudes and days of occurrence in Jiujushui Watershed, China, especially in the case of the rainfall in the upstream area higher than the average, to prevent high risk of flooding.

## Optimal forest area for the average annual runoff

Figure 7(a) shows the relationship between the increased forest area and the annual average runoff in the future period. When the annual normal average runoff (2,470 MCM) is taken into consideration, it is found that the trending line of the runoff decreases due to the changes in forest areas during the forecast years 2045 to 2105 at the intersection point on the line of the annual normal average runoff. At this point, when the vertical line is crossing the trend line of the forest area (the star symbol in Figure 7(a)), this point provides the suitable forest area for the runoff to be close to the average normal runoff (creating a horizontal dotted line from the position of the star symbol, moving to the left to cross the quantity of the forest area). At this point, the forest area between 6,500 and 7,200 $km^2$ is the optimum range for potentially restoring the upstream forest. However, the results from the CA Markov model show an increase in forest as defined, i.e., 30, 60, and 90 years respectively. Runoff and maximum flow tend to

**Table 4** | Comparison of forest area changes between average annual runoff and average peak volume

| | **Baseline years** | | **Scenario years** | | |
|---|---|---|---|---|---|
| **Comparative quantity** | **2007** | **2015** | **2045** | **2075** | **2105** |
| Forest area changes ($km^2$) | 4,520.9 | 3,990.8 | 5,106.4 | 6,402.2 | 7,730.2 |
| Average annual runoff (MCM) | 2,606.2 (−9.4%) | 2,877.0 (BL) | 2,571.8 (−10.6%) | 2,509.9 (−12.8%) | 2,394.8 (−16.8%) |
| Average peak volume (MCM) | 777.1 (−28.1%) | 1,080.4 (BL) | 764.0 (−29.3%) | 735.1 (−31.9%) | 692.3 (−35.9%) |

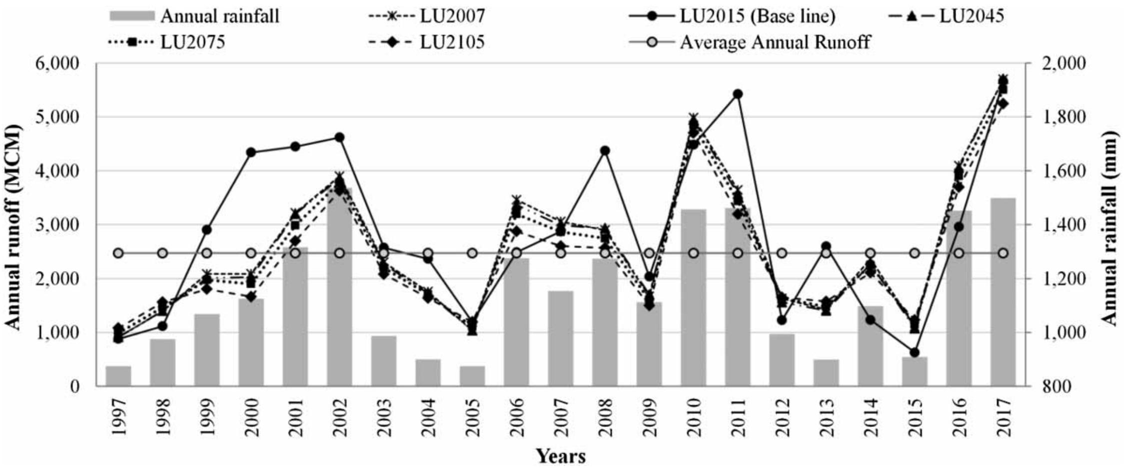

**Figure 8** | Annual runoff variation under three scenarios and baseline land use map.

decrease clearly, which is similar to the study of Suryatmojo (2015) that found that 37 years of forest age decreased peak flow lower than the forest area of 7 and 15 years, respectively. The suitable amount of forest areas in headwaters of the reservoir are considered within appropriate inflow quantities into the reservoir. This can maintain the runoff into the reservoir close to the normal average runoff without water shortage in the reservoir operation.

## HYDROLOGICAL RESPONSES TO FOREST AREA CHANGES

In the analysis of hydrological responses, the increase of forest can be evaluated from SWAT by considering four parameters: evapotranspiration, base flow, surface runoff, and return flow. The evapotranspiration and base flow show increasing trends as the forest area increases, referring to the base year in the range of 990.8–1,006.0 mm and 131.0–155.6 mm, respectively, as shown in (Figure 10(a) and 10(b)). The surface runoff and return flow show trends of decreasing in the range of 11.0–2.36 mm and 76.5–47.1 mm, respectively, as shown in Figure 10(c) and 10(d). This explains the increasing forest areas' interception in the coverage area. The humidity increases when the trees transpire, including the volume of evaporated water raising the moisture in the air, and the interception process provides higher soil moisture. The water trapped by the leaves on the stem and coverage on the ground will increase evaporation and soil moisture content. Then, when the moisture has evaporated into the atmosphere, it may cause rain in the watershed area. Similarly, the leaves on the trees can delay

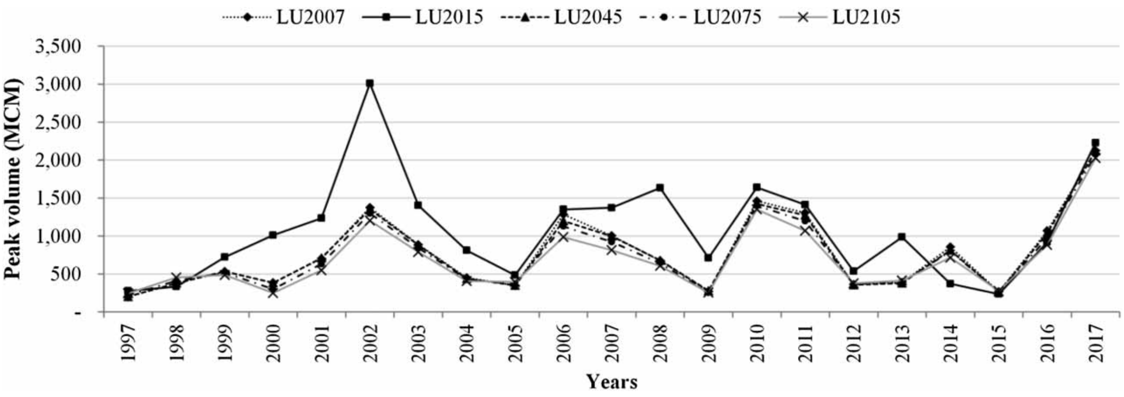

**Figure 9** | Peak flow volume under three scenarios and baseline land use map.

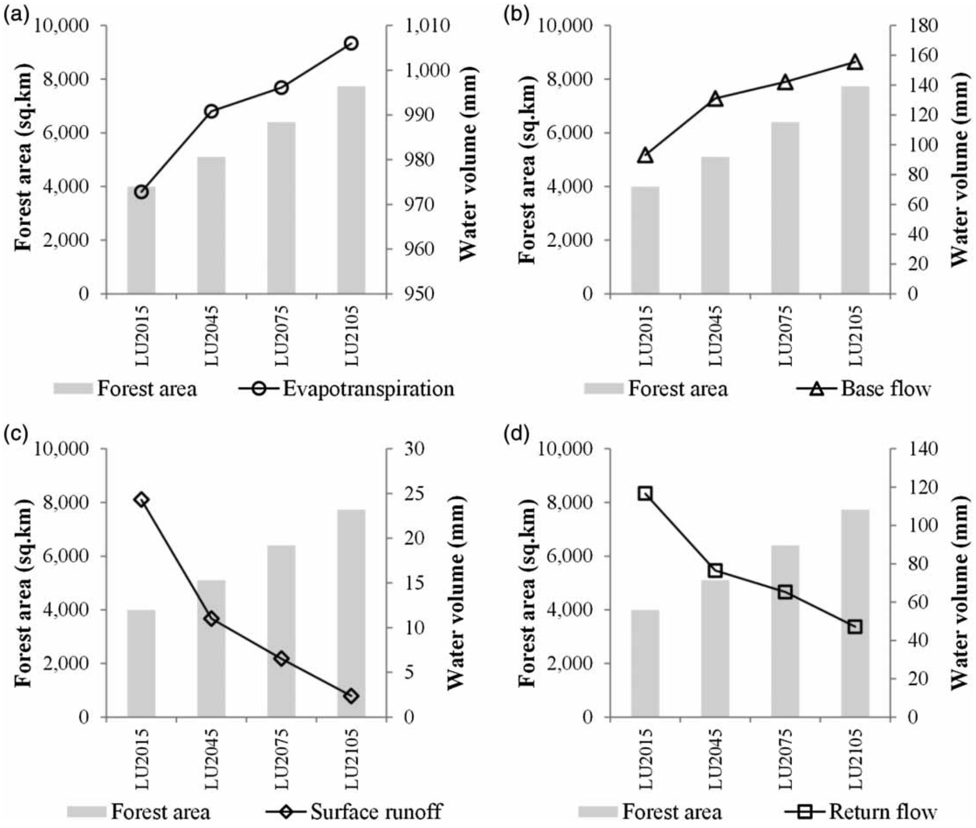

**Figure 10** | Hydrologic parameter responses to forest area rehabilitation.

water falling to the ground, the direct runoff, and then, flow velocity will be slower. These also reduce waterway erosion, prevent flooding events, and sedimentation into the reservoir. In addition, the root zone part of trees can hold the soil firmly and absorb the amount of water and thus the amount of groundwater increases. Therefore, the volume of water in the shallow depth soil surface will increase and infiltration into the deep level will also increase the base flow or the volume of groundwater. The continuous decrease of surface runoff trend illustrates the significant point that the increased forest area will retard the flow of water into the reservoir.

## CONCLUSION

The study presents the runoff and hydrological response in the watershed area above the Ubolratana Reservoir for forest rehabilitation by using prediction of the future situation between the years 2045 and 2105 with CA Markov and using the base year climate data from 1997 to 2017. SWAT was selected to assess the changes of hydrological processes. This study indicates that SWAT can assess reliable runoff based on the precision index of the values $R^2$ and RE of 0.83 and 1.54%, respectively. CA Markov simulated the increasing forest area by changing agricultural areas such as rice, sugar cane, and cassava. This provides results between 27.9% and 93.7% compared to the baseline year and they are imported into SWAT to calculate the runoff. The results are lower than the baseline year average between 9.4% and 16.8% and the peak flow has decreased between 28.1% and 35.9%. The significant hydrological variables that affected the runoff and the peak flow changes during the study period are variations of rainfall due to the influence of global climate change. In addition, the forecast of suitable forest areas with respect to the quantity of runoff into the Ubolratana Reservoir is in the range of 6,500–7,200 $km^2$. The benefits of this study aim to provide an appropriate restoration plan for the management of Ubolratana Reservoir for proper runoff related to the capacity of the reservoir. This must eliminate the risks in the reservoir management.

For analysis of the hydrological variables that affect the changes of the runoff, it is found that evapotranspiration and base flow volume continuously increase according to the rise in the forest area. On the other hand, the surface runoff and return flow tend to decrease. The water volume of these changes causes the runoff to change from the original because the water from the rainfall and surface flow has been intercepted by the trees. However, the results of the study indicated that the increase of forest areas will decrease the peak flow and runoff into the reservoir, which may affect water allocation and reservoir management. Since the forest area of headwaters is controlled in proportion to the amount of runoff, as proposed in this research, benefits would be significant for all stakeholders, especially in forest conservation and water resource engineering. The purpose of this conceptual research has shown how to evaluate the optimal forest quantity related to hydrological responses, and the results of this study will be a powerful procedure in sustainable water management in the future. There are still more related factors, not only technical but also social and community concerns, that need to be taken into consideration for implementation into the site. The knock-on effects need to be researched for more confidence.

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