Influences of land use and climate changes on hydrologic system in the northeastern river basin of Thailand
Nuanchan Singkran, Jaruporn Tosang, Doungjai Waijaroen, Naree Intharawichian, Ornanong Vannarart, Pitchaya Anantawong, Karika Kunta, Poonsak Wisetsopa, Tanomkwan Tipvong, Naruekamon Janjirawuttikul, Fatah Masthawee, Sanguanpran Amornpatanawat and Sukrit Kirtsaeng

ABSTRACT
This study was a first attempt to portray the effects of land use and climate changes (CCs) on the hydrologic system in the Lamtakhong Basin in northeastern Thailand, which has been disturbed by various human activities, making it difficult to determine these impacts on hydrologic conditions. The hydrologic Soil and Water Assessment Tool model was set up with land use and soil data of 2002 and observed flow and weather data during 1999–2000. After the model was calibrated and validated against observed flow data during 2001–2009, its land use change scenario with input land use data of 2011 and its CC scenario with input weather data during 2010–2065 were simulated. The results showed that changing land use over the 10-year period had trivial influences on the hydrologic system, whereas changing climate over the 56-year period appeared to affect both water yields and flows. Water scarcity will tend to take place across the Lamtakhong Basin in the near future. Longer periods of severe droughts and floods might occasionally occur, particularly downstream. These findings will be useful for land and water resources managers and policy-makers to manage land and water resources in the river basin.

Key words | aquatic, downscale, spatial, temporal, terrestrial, watershed

INTRODUCTION
Population growth, human activities, and other socio-economic changes have put tremendous pressure on ecosystems leading to overexploitation of natural resources (particularly the conversion of natural land covers to various types of land uses), and these have intensified the climate change (CC) phenomenon as the results of energy generation-related emission of greenhouse gases (e.g., Calder 1999; Ficklin et al. 2009; Brookes et al. 2010; Liu et al.)

Nuanchan Singkran (corresponding author)
Faculty of Environment and Resource Studies, Mahidol University, 999 Moo 5, Sai 4 Phuttamonthon Road, Salaya, Phuttamonthon, Nakhon Pathom 73170, Thailand
E-mail: nuanchan.sin@mahidol.ac.th

Jaruporn Tosang
Doungjai Waijaroen
Karika Kunta
Tanomkwan Tipvong
Naruekamon Janjirawuttikul
Land Development Department, 2003/61 Phaholyothin Road, Ladyao, Chatuchak, Bangkok 10900, Thailand

Naree Intharawichian
Poonsak Wisetsopa
Department of Water Resources, 180/3 Soi 34, Rama 6 Road, Samsennai, Phrayahtai, Bangkok 10400, Thailand

Ornanong Vannarart
Mekong River Commission, 576 National Road 2, Sangkat Chak Angre Krom, Khan Menachey, Phnom Penh 12101, Cambodia

Pitchaya Anantawong
Pollution Control Department, 92 Soi Phaholyothin 7, Phaholyothin Road, Samsennai, Phrayahtai, Bangkok 10400, Thailand

Fatah Masthawee
Sanguanpran Amornpatanawat
Sukrit Kirtsaeng
Thai Meteorological Department, 4353 Sukhumvit Road, Bangna, Bangkok 10260, Thailand

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2013; Xu et al. 2013). It has been considered that changing land use and climate might alter both the proportion and types of land cover in an area of interest and influence the hydrologic behavior of catchments (e.g., Hörmann et al. 2005; Wu et al. 2012) in terms of partitioning of rainfall into infiltration, overland flow, groundwater recharge, dry weather stream flow, etc. It is thus important to understand interactions between hydrologic processes and changes in land use and climate at all levels from global to local scales. These are critical for formulating adaptive strategies for an appropriate management of water resources (Southgate et al. 1990; Calder 1999; Gathenya et al. 2011; Palamuleni & Annegarn 2011; Wu et al. 2012).

The relationship between land use change (LUC) and hydrology is complex with linkages existing at a wide variety of spatial and temporal scales (Freniere 2009; Einheuser et al. 2013). LUC directly influences the amount of evaporation, groundwater infiltration, and overland runoff that occurs during and after precipitation events. For example, the conversion of tropical forest or savanna to grassland disrupts the hydrologic cycle through reduced evapotranspiration and increased long-term discharge (Zhang et al. 2001; Costa et al. 2005). Meanwhile, changing global temperature alters potential evapotranspiration by affecting the ability of air to absorb water (Jha et al. 2006). Changing climate related to temperature and precipitation patterns is expected to affect surface runoff and soil erosion (Zhang et al. 2012). Quantifying the impacts of land use and CCs on the hydrologic process and water balance of river basins has been an area of interest to hydrologists and water resource managers (e.g., Potter et al. 2010; Gathenya et al. 2011; Chien et al. 2013). However, most studies have been focused on the changes in the overall water budget rather than the spatial and temporal changes in the variability of water flows (e.g., Hietel et al. 2004; Chien et al. 2013); and several methods have been used for such determinations. Of these, hydrologic modeling is widely applied because it requires fewer resources and provides more flexibility.

Among the hydrologic modeling tools, a physically based Soil and Water Assessment Tool (SWAT) has been widely used to determine the influences of land use and CCs on hydrologic processes in large complex watersheds with varying soils, land uses, and management conditions (e.g., Neitsch et al. 2002; Chaplot et al. 2004; Arnold & Fohrer 2005; Menzel et al. 2009; Palamuleni & Annegarn 2011; Zang et al. 2012; Chien et al. 2013; Molina-Navarro et al. 2014; Rahman et al. 2014). According to the hydrologic SWAT model, the relationship between input and output variables is described by regression equations. All relevant eco-hydrologic processes, including flow of water, nutrient transport and turnover, vegetation growth, climatic conditions, land use, and water management at a sub-basin scale, can be integrated into the model. The watershed is subdivided into sub-basins based on the number of tributaries. The size and number of sub-basins vary, depending on stream network and size of the entire watershed. Sub-basins are further disaggregated into classes of hydrologic response units (HRUs), whereby each unique combination of the underlying geographical maps (soils, land use, etc.) forms one class. HRUs are the spatial unit where the vertical flows of water and nutrients are calculated and summed for each sub-basin. Soil water processes include evaporation, surface runoff, infiltration, plant uptake, lateral flow, and percolation to lower layers. Detailed features and functions of SWAT can be found in Neitsch et al. (2002).

In this study, ArcSWAT 2012.10 (Winchell et al. 2013) was used to model the hydrologic system in the Lamtakong Basin, located in the northeast of Thailand. The Lamtakong (‘Lam’ is a prefix-local word in the northeast meaning ‘a kind of a river’), one of the five most deteriorated rivers of the country, has been heavily disturbed by human activities from its upstream (originating at the base of KhaoYai Mountain in Pak Chong district of Nakhon Ratchasima province) through its midstream (where the Lamtakong Reservoir and Dam are located) to its downstream that passes the municipality of Nakhon Ratchasima’s Muang district before emptying into the Mun River. The upper river basin, located in KhaoYai National Park, which is one of the most attractive tourist spots in the northeast region of Thailand, has been increasingly encroached on by resorts, hotels, guest houses, golf courses, and residences. These human activities, in varying degrees, tend to affect the natural condition and water quality in the headwaters of the Lamtakong.

The middle portion of the river beneath the Lamtakong Dam acts as the irrigation canal for the Lamtakong Irrigation Project. This river portion was
partly modified, expanded, or excavated to increase irrigation efficiency. The downstream of the Lamtakhong exhibited the worst condition, particularly the river portion that runs through Nakhon Ratchasima’s Muang district and crowded communities. The river shape turns into a wastewater drainage canal with a lot of garbage and strong smells. The most deteriorated water quality has been observed at this river portion (Pollution Control Department, unpublished data). The modified environment of the Lamtakhong by direct (e.g., the dam and the irrigation system) and indirect factors (e.g., land use activities) makes it rather difficult to develop a hydrologic model that is able to best capture both natural and manmade conditions of the Lamtakhong. In fact, there had been no model successfully applied to simulate the hydrologic system in the Lamtakhong Basin.

The objectives of this study were thus to determine the influences of (1) LUC over a 10-year period (2002–2011) and (2) CC over a 56-year period (2010–2065) on the flows and yields of water in the Lamtakhong Basin. This study was the first attempt to quantitatively portray the effects of land use and CCs on the hydrologic system in the Lamtakhong Basin in space and time. These were based on the hypotheses that the changes in climate and land use might alter hydrologic processes in terms of either changing flows of water in the river over time or changing yields of water across the river basin, or both. The results obtained from this study will be useful for water resources managers, environmentalists, and policy-makers (especially the Pollution Control Department and the Royal Irrigation Department of Thailand) in gaining more understanding of how changes in climate and land use affect the long-term conditions of the hydrologic system in the Lamtakhong Basin, so that a holistic approach for managing water resources in the basin can be efficiently conducted.

### MATERIALS AND METHODS

#### Study area

The Lamtakhong Basin is located between 14°20’ N, 101°15’ E and 15°5’ N, 102°16’ E. The basin area is about 3,403.02 km², and it is a sub-basin of the Mun River Basin. The Lamtakhong, 220 km long, is the major river of the basin, and it is one of the five most deteriorated rivers of Thailand (Pollution Control Department, unpublished data). The Lamtakhong runs from a southwestern to northeastern direction passing Pak Chong, Si Khii, Soong Noen, Kham Tale So, and Muang districts of Nakhon Ratchasima province in the northeast of Thailand (Figure 1). There is a population of about 1 million (222 individuals/km²) living in the Lamtakhong Basin. The population is mainly of mixed ethnicity, for example, Thai and Khmer, Laotian, or Chinese. In urban areas, most people speak Thai, while most people in rural areas speak Khorat, a dialect mixture of Thai and Laotian. Currently, many young people and adults move to work in Bangkok and other big cities, whereas children and the elderly are left at home in villages.

Based on the basin’s varied altitudes, the elevations above mean sea level (MSL), five zones were categorized as follows. Zone 1 covers sub-basins 63 and 64 located in the upper portion of the Lamtakhong Basin (i.e., in Pak Chong district). There is about 221.73 km² of highland area with altitudes of 515.62–827.10 m in this zone. Zone 2 covers sub-basins 16, 30, 41–43, 45, 49, 53–56, and 58–62 located in Pak Chong, Si Khii, and Soong Noen districts. This zone comprises about 925.60 km² of area with altitudes of 367.65–515.61 m. Zone 3 covers sub-basins 4, 14, 15, 33, 35, 37, 44, 47, 48, 50–52, and 57 located in Pak Chong and Si Khii districts with about 685.79 km² of area with altitudes of 277.20–367.64 m. The Lamtakhong Dam was built across the Lamtakhong at sub-basin 44 with a reservoir water storage volume of about 310 million m³. Zone 4 covers sub-basins 1, 5, 11, 12, 17, 20, 21, 23, 25, 27–29, 31, 32, 34, 36, 38–40, and 46 located in Si Khii, Soong Noen, Kham Tale So, and Muang districts. There is about 1,015.48 km² of area with altitudes of 216.92–277.19 m in this zone. Finally, Zone 5 covers sub-basins 2, 3, 6, 8–10, 18, 19, 22, 24, and 26 located at the central-lower portion of the basin (i.e., in Soong Noen, Kham Tale So, and Muang districts) before emptying into the Mun River. This zone is mainly covered by floodplains and low-lying areas of about 554.42 km² with altitudes of 166.46–216.91 m (Figure 1).

The climate in the Lamtakhong Basin is influenced by two seasonal monsoons (i.e., the southwest and northeast
monsoons), the inter-tropical convergence zone, and tropical cyclones. These generate three typical seasons (i.e., summer, rainy, and winter). The summer starts with the cessation of the northeast monsoon and begins around the middle of February and ends around the middle of May. The weather in this season is quite warm and humid with high temperatures and low precipitation. The rainy season starts in the middle of May and ends around the middle of October. In this season, there is frequent high precipitation, humidity, cloudiness, and tropical temperatures. The heaviest rainfall generally occurs in August and September. The winter, caused by the northeast monsoon, generally starts from the middle of October and lasts to the middle of February. In this season, there is relatively little rainfall, low humidity, little cloudiness, and lower temperatures. The weather data, including temperature, relative humidity, solar radiation, wind speed, and precipitation in the river basin, observed over a 19-year period (1991–2009) by various Thai governmental agencies including the Royal Irrigation Department (RID), Thai Meteorological Department (TMD) and Department of Water Resources (DWR), are summarized in Table 1.

In the Lamtakhong Basin, major soil compositions, including loam soil, sandy loam, clayey loam and clayey sandy loam/clayey gravelly loam, have been found in relation to the basin topography. The two main groups of soil are (1) agricultural soil in the downstream and (2) forest soil in the upstream. According to the soil classification of the Land Development Department (LDD, unpublished data), Pak Chong (Pc) and Muak Lek (Ml) are major soil series of the agricultural soil in the downstream. Surface runoff and soil permeability are moderate whereas soil drainage is good. These characteristics can lead to water shortage in the dry season. Furthermore, soil fertility is slightly low. It is therefore necessary to improve the soil before crop cultivation. Four major types of land
use in the Lamtakhong Basin are agricultural land-row crop areas, paddy fields, forest-evergreen areas, and urban areas, respectively. Major cultivations in the basin are cassava, rice, maize, sugarcane, and fruits, in that order.

The total runoff in the Lamtakhong Basin is approximately 599.50 million m$^3$ with an annual rate of 5.60 liters/second (s)/km$^2$ whereas the Lamtakhong Reservoir is a major source of water for the irrigation project in Nakhon Ratchasima province. The reservoir has a water storage volume of about 370.00 m$^3$ for allocations (e.g., consumption, industrial, and irrigation purposes) covering a total irrigation area of about 262.70 km$^2$. However, the rapid increase in water demand because of population growth, the expansion of human activities, drought, etc., has brought about water scarcity in the Lamtakhong Basin, particularly in the dry season. For instance, in 2008, water storage in the Lamtakhong Reservoir was critically insufficient for people’s use. Heavy floods in the rainy season (e.g., in 2010 and 2013) and the low quality of water are also serious problems in the Lamtakhong Basin. Additionally, it has been observed that modern agricultural practices with overuse of chemicals and fertilizers have substantially polluted both surface and groundwater systems in the basin.

### Hydrologic model setup

ArcSWAT 2012.10 (Winchell et al. 2013) was used to model the hydrologic system in the Lamtakhong Basin using the input data obtained from Thai governmental agencies as follows:

- The 30 m resolution digital elevation model (DEM) of the Lamtakhong Basin acquired from a 5 m resolution DEM in 2004 of LDD (unpublished data).
- Land use data with a scale of 1:50,000 for the Lamtakhong Basin in 2002 and 2011 (LDD, unpublished data).
- Soil data with a scale of 1:25,000 for the Lamtakhong Basin in 2002 (LDD, unpublished data).
- Daily precipitation (rainfall, mm/d) data observed over a 19-year period (1991–2009) selected from the 10 monitoring stations located in the study area of RID (unpublished data), TMD (unpublished data), and DWR (unpublished data).
- Daily temperature (°C), relative humidity (%), solar radiation (MJ/m$^2$), and wind speed (m/s) observed over a 19-year period (1991–2009) at the two meteorological stations of TMD located in the proximity of the study area.
- Daily water flow (m$^3$/s) in the Lamtakhong of RID (unpublished data) during 1999–2007 at upstream (Station M.89) and midstream stations, and the other during 2007–2009 at the downstream station (Station M.164) of the river.

According to the model setting, the Lamtakhong Basin was delineated into 64 sub-basins (Figure 1). This enabled the model to capture the hydrologic conditions for various classes of land use, crops, and soils. The layers of land use and soil data in 2002 were overlaid; the distribution of HRUs within the river basin was then determined according to 5, 20, and 20% of threshold settings for land use, soil, and slope classes in each sub-basin, respectively. This percentage proportion of the threshold settings were assigned to cover the common types of land use, soil, and slope classes existing in most of the 64 sub-basins. As a result, 916 HRUs were classified across the river basin. After the HRUs were defined, the time-series weather data (i.e., precipitation, temperature, relative humidity, solar radiation, and wind speed) in the study area were imported into the model. For each type of weather data loaded, each sub-basin is linked to the nearest associated weather station in the study area. The initial values of the watershed variables were written to the nearest associated weather station in the study area. However, the soil moisture condition data were rarely available in the study basin and across Thailand.

Model calibration and validation

The hydrologic SWAT model for the Lamtakhong Basin was calibrated to: (1) achieve mass balance over the calibration period; (2) obtain good fit patterns between the observed and predicted flows at each calibrated station in the Lamtakhong; and (3) increase the model efficiency for further applications in this study (i.e., simulating the land use and CC scenarios). The monthly observed outflows of water during the 5-year period (2001–2005) at the RID’s station M.89 located at the downstream of sub-basin 54, namely Station 1 (ST1, Figure 1) were used to calibrate the monthly predicted outflows in the same time period at this station. The important model parameters for sub-basins 54 and above (i.e., sub-basins 57–64) were adjusted to provide the best fit between the monthly observed and predicted outflows at ST1.

Over the same period of time (i.e., 2001–2005), the monthly observed inflows of water into the Lamtakhong Reservoir located at the upstream of sub-basin 44, namely Station 2 (ST2, Figure 1) were used to calibrate the monthly predicted inflows into this station. The important model parameters for sub-basins 43, 44, 47–53, 55, and 56 were adjusted to provide the best fit between the monthly observed and predicted inflows at ST2. Only the monthly observed outflows during the 2-year period (2008–2009) were available for calibrating the monthly predicted outflows in the same time period at the RID’s station M.164 located at the downstream of sub-basin 13, namely Station 3 (ST3, Figure 1). The important model parameters for sub-basins 1, 4, 5, 11–24, 26–42, 45, and 46 were adjusted...
to provide the best fit between the monthly observed and predicted outflows at ST3.

Both manual and automated procedures were used to calibrate the predicted flows against the observed flows at the three stations. SWAT-CUP version 4.3.7.1 (Abbaspour & Srinivasan 2011) was used for the initial auto-calibrations to obtain the approximate ranges of the parameter values that might provide the goodness-of-fit. More details about the calibration process using SWAT-CUP can be found in Arnold et al. (2012). Afterwards, the manual calibrations were performed by investigating and adjusting values for each of the model parameters (Table 2) one at a time for each round of the model simulation until its best calibrated value was obtained. To assess the calibrated performance after each round of the model simulation, the monthly observed and predicted flows at each station were compared using Nash–Sutcliffe Efficiency (NSE) (Nash & Sutcliffe 1970).

The NSE value indicates how well the plot of observed versus predicted values fits the 1:1 line (Santhi et al. 2001; Van Liew et al. 2005). It is used to measure the goodness-of-fit between the predicted and the observed flows. The closer the efficiency value is to 1, the better the agreement between the observed and predicted values. The

<table>
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<th>Name</th>
<th>Description</th>
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<th>Station 2</th>
<th>Station 3</th>
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⁵NA – not available.
⁶OV_N and CN₂ values varied across the calibrated sub-basins within a certain range at each station.
satisfactions of the model performance based on the NSE value are varied. Santhi et al. (2001) concluded that a calibrated model is acceptable when it obtains the NSE value \( \geq 0.50 \) and the coefficient of determination \( (R^2) \geq 0.60 \). The \( R^2 \) is an indicator of the strength of the relationship between the observed and predicted values. In other words, the \( R^2 \) describes the proportion of the variance in predicted data explained by the model, ranging from 0 to 1, where higher values indicate less error variance.

Saleh et al. (2000) stated that the model performance was adequate and very good when the calibrated model obtained the NSE value of 0.54–0.65 and >0.65, respectively. The NSE equation is expressed as

\[
\text{NSE} = 1 - \frac{\sum_{i=1}^{n} (Y_{i,\text{pred}} - Y_{i,\text{obs}})^2}{\sum_{i=1}^{n} (Y_{i,\text{obs}} - \bar{Y}_{\text{obs}})^2}
\]

where \( Y_{i,\text{pred}} \) and \( Y_{i,\text{obs}} \) represent the predicted and observed values for \( n \) of water flow in this study, respectively. \( \bar{Y}_{\text{obs}} \) represents the average value for \( n \) of the observed flow. In this study, the model calibration at each of the three stations was ended when the best agreement between the predicted and the observed flows at that station was obtained with the NSE \( \geq 0.54 \).

To evaluate if the calibrated hydrologic SWAT model for the Lamtakhong Basin is robust and efficient for applying to simulate the land use and CC scenarios, the model was validated against another set of the monthly observed flows. In the validation process, the model with its calibrated parameters was used to predict flows at ST1 and ST2 during 2006–2007 without further adjustment of the model parameters. However, because of insufficient observed flow data available at ST3, the model validation was not performed for this station. The model prediction performance at ST1 and ST2 was determined using the NSE method described above.

**LUC scenario**

To determine the influences of LUC over a 10-year period (2002–2011) on the hydrologic system in the Lamtakhong Basin, the change in percentage area of each land use type between the land use data of 2002 (that were used to build the hydrologic SWAT model previously described) and the land use data of 2011 was initially compared at a basin scale. Afterwards, the percentage area for each land use type in the year 2011 at each sub-basin of the river was used to estimate a new set of fractions of total watershed area contained in HRU (HRU_FR) in the land use update (.lup) file in SWAT. The calibrated hydrologic SWAT model with the new .lup file of 2011 (whereas the remaining input files were the same) was then simulated to predict water yields across the river basin during 2001–2009. The annual predicted water yield for each sub-basin averaged over the 9-year period obtained from the LUC scenario was compared with those obtained from the baseline hydrologic SWAT model (which was set up based on the land use data of 2002 and was calibrated and validated against the observed flow data).

**CC scenario**

To determine the influences of CC on the hydrologic system in the Lamtakhong Basin, the daily weather data (i.e., precipitation, temperatures, relative humidity, solar radiation, and wind speed) in the basin during 2010–2065 extracted from the CC scenario for Thailand (Chinvanno et al. 2010) were used to simulate the CC scenario for the Lamtakhong Basin. The CC scenario for Thailand of Chinvanno et al. (2010) projected the future climate for Thailand and surrounding countries until the end of the 21st century based on dynamic scaling of the Providing REgional Climate Models for Impacts Studies (PRECIS) Regional Climate Model (RCM) of the Hadley Centre for Climate Prediction and Research, United Kingdom. The downscaling process was generated by ECHAM5 Global Climate Model of the Max Planck Institute for Meteorology and German Climate Computing Center, Germany. In general, RCM is a downscaling tool that adds fine-scale (high-resolution) information to the large-scale projections of a global general circulation model (GCM). GCMs are typically simulated with horizontal scales of 200–300 km and they can resolve features down to 25–50 km (Jones et al. 2004; Chinvanno et al. 2010).

According to the CC scenario for Thailand (Chinvanno et al. 2010), the downscaling process was set up with a resolution of 0.22°. The topography, coastlines, land use data, etc. were included in the PRECIS RCM to produce a more...
accurate presentation of surface features for the country. The model was simulated with a daily time step over the 91-year period (2010–2100). The projected results were rescaled to 20-km grid resolution and they were adjusted for better fitting the observed data. The projected results obtained from the PRECIS RCM during the time period of the 1980s were verified against the observed data from 130 weather stations in Thailand and adjacent countries for the same time period. The projected results revealed that the climate in the Southeast Asia region will tend to be slightly warmer, but the warm period duration will extend much longer in the future, especially in the latter half of the century. Precipitation will fluctuate in the first half of the century with an increasing trend which is clearly seen in the latter half of the century (Chinvanno et al. 2010). The detailed information about PRECIS, GCM, and general downscaling and rescaling techniques can be found in, for example, Chinvanno et al. (2010) and Västilä et al. (2010).

For the Lamtakhong Basin, the weather data in the basin during 2010–2065 extracted from the CC scenario for Thailand (Chinvanno et al. 2010) were converted from grid cell to point format (Table 3) required by SWAT before simulating the CC scenario over the 56-year period (2010–2065). The monthly projected flows and yields of water in the river basin averaged over the 56-year period obtained from the CC scenario were derived and analyzed.

RESULTS AND DISCUSSION

Modeling performance

The monthly observed flows during 2001–2007 were in the range of 0.81–27.83 m³/s at ST1 and in the range of 1.06–38.67 m³/s at ST2 (Figures 2(a) and 2(b)). In general, flows of water in most rivers are usually higher at the lower ends of the rivers or at the river mouths than those observed in the upper portions of the associated rivers. However, unlike those, the flows of water at the lower portion (ST3) of the Lamtakhong were in the range of 1.03–15.66 m³/s and lower than those at ST2 (Figure 2(c)). These might be due to heavily modified aquatic conditions as a result of the rapid expansion of the urban communities of Nakhon Ratrasim’s Muang district located in this portion of the basin. The river profile that runs through the communities turns into a wastewater drainage canal. Some parts of the river channel were empty, especially in the summer, with a lot of garbage and strong smells.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Monthly and annual values of the weather parameters in the Lamtakhong Basin averaged over a 56-year period (2010-2065)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td>Temperature*</td>
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<tr>
<td></td>
<td>Mean</td>
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<tr>
<td>January</td>
<td>25</td>
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<td>February</td>
<td>28</td>
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<td>March</td>
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<td>June</td>
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<td>July</td>
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<td>August</td>
<td>29</td>
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<td>September</td>
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<td>October</td>
<td>28</td>
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<td>November</td>
<td>26</td>
</tr>
<tr>
<td>December</td>
<td>23</td>
</tr>
<tr>
<td>Annual</td>
<td>28</td>
</tr>
</tbody>
</table>

*Mean, maximum (Max.), and minimum (Min.) values of temperature (°C), relative humidity (%), wind speed (m/s), and solar radiation (MJ/m²) were obtained from the TMD (unpublished data), whereas those of precipitation (PCP, millimeters) were obtained from the Department of Water Resources, Royal Irrigation Department, and TMD (unpublished data).
The best values of the model parameters for calibrating the monthly predicted flows against the monthly observed flows at ST1–ST3 are summarized in Table 2. Sufficient sizes of the observed flow data were necessary for calibrating the model. In this study, the large observed flow data were available to calibrate the model for ST1 and ST2; and there were not many side flows from tributary streams discharging into the river above these stations. These made it easier to calibrate the model for the two stations. Consequently, the monthly observed and predicted flows during...
the 5-year period (2001–2005) showed good agreement with each other at ST1 (NSE = 0.92, \( R^2 = 0.93 \)) and ST2 (NSE = 0.86, \( R^2 = 0.88 \); Figures 2(a) and 2(b)).

It was rather difficult to calibrate the model for ST3, which is located in the lower portion of the Lamtakhong. This was due to a number of reasons, for example: (1) many tributary streams flow into ST3, but these flow data were not available; (2) only the observed flow data during 2008–2009 were available at a few water gauges above or around ST3 for calibrating the model for this station; and (3) many small dykes had been constructed in the tributary streams or across the lower portion of the Lamtakhong for diverting water from the river, thus making it difficult for the model to capture the influences of these man-made structures. Consequently, the monthly observed and predicted flows during the 2-year period (2008–2009) showed lower magnitude of agreement with each other at ST3, but it was still acceptable with regard to its NSE ≥ 0.54 (Figure 2(c); Saleh et al. 2000).

According to the model validation, the monthly observed and predicted flows during the 2-year period (2006–2007) still showed good agreement with each other at ST1 (NSE = 0.93, \( R^2 = 0.93 \)) and ST2 (NSE = 0.73, \( R^2 = 0.75 \); Figures 2(a) and 2(b)). Although the model validation was not performed at ST3 because of insufficient data at this station, the calibrated hydrologic model was apparently rigorous for simulating the LUC and CC scenarios for the Lamtakhong Basin according to the good validation results obtained at ST1 and ST2.

### Influences of land use change

Ten types of land use in the Lamtakhong Basin in the years 2002 and 2011 were categorized, including agricultural land-generic, agricultural land-row crops, forest-deciduous, forest-evergreen, forest-mixed, orchard, pasture, paddy field, urban area, and water (Table 4). The percentage areas of four land use types in the river basin obviously changed over the 10-year period. That is, from the total area of 3,403.02 km², the agricultural land-row crop area decreased from 44.10% (of the total area) in 2002 to 33.77% (–10.33%), and the forest-evergreen area decreased from 13.18% in 2002 to 6.12% (–7.06%). Meanwhile, the forest-deciduous area increased from 2.72% in 2002 to 13.15% in 2011 (10.43%) and the urban area increased from 8.98% in 2002 to 15.46% in 2011 (6.48%). Noticeably, the decreased proportions of total agricultural land (–10.35%) and forest-evergreen areas (–7.06%) were close to the increased proportions of the forest-deciduous (10.43%) and urban areas (6.48%), respectively. In addition, the decreased proportion of paddy field was the same as the increased proportion of pasture (i.e., 2.98%; Table 4).

Whereas some previous studies (e.g., Costa et al. 2003; Dadhich & Nadaoka 2012) detected the influences of land

<table>
<thead>
<tr>
<th>Land use type</th>
<th>Area in 2002 (km²)</th>
<th>Area in 2011 (km²)</th>
<th>Land use code</th>
<th>Land use code</th>
<th>Land use code</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(km²) (%)</td>
<td>(km²) (%)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Agricultural land-generic</td>
<td>AGRL 1.87 0.05 1.00 0.03</td>
<td>– 0.02</td>
<td>AGRR 1,500.74 44.10 1,149.12 33.77</td>
<td>– 10.33</td>
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</tr>
<tr>
<td>Agricultural land-row crops</td>
<td>FRS 92.60 2.72 447.37 13.15 10.43</td>
<td></td>
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</tr>
<tr>
<td>Forest-deciduous</td>
<td>FRSE 448.66 13.18 208.20 6.12 7.06</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Forest-evergreen</td>
<td>FRST 166.00 4.88 202.49 5.95 1.07</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest-mixed</td>
<td>ORCD 209.44 6.15 148.81 4.37 1.78</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Orchard</td>
<td>PAST 38.16 1.12 139.63 4.10 2.98</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Pasture</td>
<td>RICE 604.14 17.75 502.64 14.77 2.98</td>
<td></td>
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</tr>
<tr>
<td>Rice</td>
<td>URBN 305.74 8.98 526.14 15.46 6.48</td>
<td></td>
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</tr>
<tr>
<td>Urban</td>
<td>WATR 35.67 1.05 77.62 2.28 1.23</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>Total 3,403.02 100 3,403.02 100.00</td>
<td></td>
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</tr>
</tbody>
</table>
use changes on the runoff in the study areas, the changing land use over the 10-year period (2002–2011) in the Lamtakhong Basin showed trivial influences on the hydrologic system in the river basin. The annual predicted water yields obtained from the baseline hydrologic SWAT model and those obtained from the LUC scenario averaged by sub-basin over the 9-year period (2001–2009) were not significantly different (t-test, $\alpha = 0.92$, i.e., $\alpha > 0.05$; Figures 3(a) and 3(b)). The minimum, mean, and maximum yields of water across the 64 sub-basins obtained from the baseline hydrologic SWAT model were 0, 184, and 328 mm/y, respectively; and the ones obtained from the LUC scenario were 0, 183, and 327, respectively (Figures 3(a) and 3(b)). The zero predicted yield of water was detected at sub-basins 63 and 64 located in the headwater where there have been severe water shortages across the years and the encroachment of human activities, such as tourism business, hotel and residential developments. The Lamtakhong Irrigation Project is thus a very important water source for most land use activities in the river basin, especially agricultural areas where the amount of water needed is dependent on the cropping pattern (Menzel et al. 2009).

Overall, the complex hydrologic process linkage with land use change (Freniere 2009) might lead to the ambiguous influences of land use changes on both flows and yields of water in the Lamtakhong Basin. Additionally, there were no lucid results to indicate the changing direction (increase or decrease) for certain types of land use that affected the flows of water in the Lamtakhong. In other words, it is rather difficult to clearly define quantitative relationships between land use types and runoff mechanisms (Singkran & Meixler 2008; Wang & Kalin 2011). Some reasons are because: (1) the types of land use, rates of conversion, and spatial distribution of land use vary noticeably across different ecological transitions (Strayer et al. 2003); (2) changes in land use can drive channel morphology and hydrology into a state of flux that may take many decades to stabilize (Fitzpatrick & Knox 2000); and (3) ecological responses may lag behind physical habitat modification (e.g., Harding et al. 1998), and the duration of such lag effects is not always known (Strayer et al. 2003). Thus, a longer period of time to study the influences of changing land use on the hydrologic system in the Lamtakhong Basin should be further considered.

Influences of CC

A changing climate brings many changes in water availability and demand management (e.g., Vorösmarty et al. 2000) as detected from the CC scenario in this study. The speculated impacts of CC with respect to water resources are, for instance, higher evaporation and change in the regional patterns of precipitation (National Research Council 2007). The dramatic increase of solar radiation averaged over the 56-year period apparently affected the relative humidity and temperature over the same time period.

![Figure 3](https://iwaponline.com/jwccc/article-pdf/6/2/325/375735/jwc0060325.pdf)

**Figure 3** | The annual predicted water yields in millimeters per year (mm/y) obtained from the baseline flow model (a) and the land use change scenario (b) were averaged by sub-basin over a 9-year period (2001–2009), whereas those obtained from the CC scenario (c) were averaged by sub-basin over a 56-year period (2010–2065).
(Table 3). Although the annual and minimum temperatures were the same as those obtained during the 19-year period (1991–2009), the maximum value had obviously increased from 38 to 43°C (Tables 1 and 3). These parameters appeared to influence the changing patterns of evaporation, precipitation, and yields and flows of water in the Lamtakhong Basin. The increased temperature could change the rate of evapotranspiration and the form of precipitation, subsequently influencing stream flow patterns (Mehta et al. 2011; Chien et al. 2013). The monthly precipitations between the first 19-year period (Table 1) and the latter 56-year period (Table 3) in the river basin were significantly different ($t$-test, $α$ ≤ 0.05). The monthly precipitations of the latter period were lower than those in February–April, but higher than those in the remaining months of the first period.

Similar to the studies of, for example, Zhan et al. (2011) and Chien et al. (2013), the influences of CC on the hydrologic process in the river basin were noticeable. The annual projected water yields obtained from the CC scenario averaged by sub-basin over the 56-year period (2010–2065) were significantly different from those obtained from the baseline hydrologic SWAT model ($t$-test, $α$ = 0.00, i.e., $α$ < 0.05; Figures 3(a) and 3(c)). Additionally, the annual projected yields of water across the 64 sub-basins averaged over the 56-year period were decreased by 63.27% compared to those obtained from the baseline hydrologic SWAT model. The annual projected yields ranged from 0 to 182 mm/y with a mean of 68 mm/y (Figures 3(a) and 3(c)). The monthly projected flows in the Lamtakhong averaged over the 56-year period considerably decreased with broad ranges of variations. The projected flows ranged from 0.17 to 5.11 m$^3$/s with a mean of 0.92 m$^3$/s at ST1, from 0.13 to 14.29 m$^3$/s with a mean of 1.17 m$^3$/s at ST2, and from 0.00 to 35.20 m$^3$/s with a mean of 0.20 m$^3$/s at ST3. The projected flows of the three stations are graphically portrayed using a logarithmic scale base 10 (i.e., log$_{10}$ scale) in Figure 4 for better comparing their differences in details. The future climate in the river basin is likely to be drier in relation to decreased monthly relative humidity and increased solar radiation (Tables 1 and 3).

The CCs appear to affect the availability of water resources (e.g., Gosain et al. 2006; Ficklin et al. 2013; Xu et al. 2013; Zeng et al. 2013). For this study, the projected yields and flows of water in the Lamtakhong Basin indicated that crisis situations of the river basin might occur within the next 50 years. Water scarcity will tend to take place across the river basin in the future. Longer periods of severe droughts and floods might occasionally occur, particularly at the lower portion of the river basin according to the annual peak flows detected at ST3 in certain time periods (Figure 4). These findings are consistent with the projected results obtained from the CC scenario for Thailand indicating that the climate in the Southeast Asia region will tend to be slightly warmer and the duration of the warm period will extend much longer in the future (Chinvanno et al. 2010). Additionally, the field observations during the study period showed that the lower Lamtakhong might be changed into a wastewater drainage canal in the near future with a low amount of water of very poor quality (Pollution Control Department, unpublished data). Thus, contingency plans with CC adaptations (Keskinen et al. 2010; Nuorteva et al. 2010) for the river basin should be integrally conducted to restore both water resources and good socio-economic conditions for people living in the river basin.

**CONCLUSIONS**

SWAT was efficient for modeling the hydrologic system in the Lamtakhong Basin and portraying the varied influences of land use and CCs on the hydrologic regime in the river basin. The study results revealed that the changing land use over the 10-year period (2002–2011) showed trivial influences on the hydrologic system in the Lamtakhong Basin, whereas the influence of CC appeared to noticeably affect both yields and flows of water in the river basin. The projected flows of water over the 56-year period (2010–2065) obtained from the CC scenario indicated that water scarcity will tend to take place across the river basin in the near future. Longer periods of severe droughts and floods might occasionally occur, particularly at the lower portion of the river basin. These insightful findings are useful for stakeholders to integrally prepare contingency plans with CC adaptations to restore both water resources and good socio-economic conditions for people living in the river basin.
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