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Hydrological impacts of land use/land cover change in a large river basin in central–northern Thailand†

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ABSTRACT: The purpose of this study is to determine the hydrological impacts of land use/land cover (LULC) change in the Yom watershed in central–northern Thailand over a 15-year period using an integration of remote sensing, Geographic Information System, statistical methods, and hydrological modelling. The LULC changes showed an expansion of urban areas by 132% (from 210 km^2 in 1990 to 488 km^2 in 2006). The Yom River's daily discharge long-term trend significantly increased at most of the measurement stations (p value <0.05), and the rate of increase in discharge at areas downstream of the rapid urbanisation was significantly greater than that at areas upstream. There were no significant long-term trends in precipitation characteristics in the basin, except for one station. The rate of change in discharge after changes in LULC showed a systematic increase over a range from 0.0039 to 0.0180 m^3 s^{-1} day^{-1} over a 15-year period, with the increase in urbanised area spanning a range from 81 to 149% in two flood-prone provinces. A rainfall-runoff model simulated a small increase ($\sim$10%) in peak flows. The coupling of surface observations, remote sensing, and rainfall-runoff modeling demonstrated the impacts of changes in LULC on peak river discharge, hence flooding behaviour, of a major river in central–northern Thailand. Copyright © 2010 Royal Meteorological Society

KEY WORDS remote sensing; land use change; river discharge; rainfall-runoff model

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1. Introduction

Thailand is one of the most flood-prone countries in Southeast Asia. Every year during the rainy season, Thailand is faced with severe flooding in the north, northeast and central parts of the country. For example, the Yom River Basin is typically flooded in August and September during each rainy season (May–October), yet the basin is very dry through the November-to-April dry season (Geo-Informatics and Space Technology Development Agency (GISTDA), 2005). Over-bank flooding inundates the urban and agriculture areas located along the Yom River, especially in the lower portions of the basin. According to the report by the Department of Disaster Prevention and Mitigation, Ministry of Interior, 25% of the villages are severely affected by flooding every year (Ministry of Agriculture and Cooperatives (MOAC) and Ministry of Natural Resource and Environment (MONRE), 2005). To address this problem, the Royal Thai Government has tried to examine potential causes for this flooding. Apart from the pronounced monsoon climate mentioned above, geographical and hydrological features, deforestation, and particularly urbanisation are claimed as major causes. With urban development, impervious surface areas (e.g. roads, sidewalks, driveways, parking areas, rooftops) decrease infiltration and increase the rate and volume of surface runoff (Fitzpatrick *et al.*, 2005). Thus, urbanised areas would become a potentially greater cause of water inundation under conditions of high rainfall intensity. Without research to support these claims, however, conflicts and debate about how to make appropriate decisions to mitigate the flooding problem remains.

Understanding the role and impacts of land use/land cover (LULC) change in flood-prone areas could play a significant role in alleviating the flooding problem. The study of the impacts of LULC change on flood behaviour is a very complex and time-consuming process because the factors that determine river flow and flood intensity vary both spatially and temporally. These problems can be addressed by using a Geographic Information System (GIS) that is efficient for spatial data analysis together with remote-sensing data, which can provide widely, regularly updated, and reliable data. Then, rainfall- runoff models can be used to help further understand and predict changes in river flow behaviour.

In this study, we explore the impacts of LULC change, particularly urbanisation, in the Yom River's discharge behaviour and contribute to discussions regarding the nature of this impact in relation to floods in the basin.

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The specific objectives of this study are to (1) determine how land use has changed in the Yom watershed over a period of 15 years; (2) determine the characteristics and long-term changes in precipitation and discharge in the watershed; (3) investigate the relationship between land cover change and discharge response; and (4) assess the impact of LULC changes on river peak flow behaviours. We first describe the study site, and then assess how LULC has changed in the Yom watershed. Next, we determine the characteristics and long-term changes in precipitation and discharge, followed by a rainfall- runoff model investigation of the relationship between increases in urbanisation and the river discharge response. The last section presents the summary and conclusions.

2. Study area

Yom River Basin is located in the central–northern part of Thailand between longitude 99°13′–100°5′ E and latitude 15°51′–19°24′ N (Figure 1). The basin area is 25 180 km^2, the second largest watershed in the region. The Yom River flows in a north-to-south direction, is 735 km in length, and the elevation of the river ranges from 360 to 20 m above mean sea level at the watershed outlet at Chumsang District

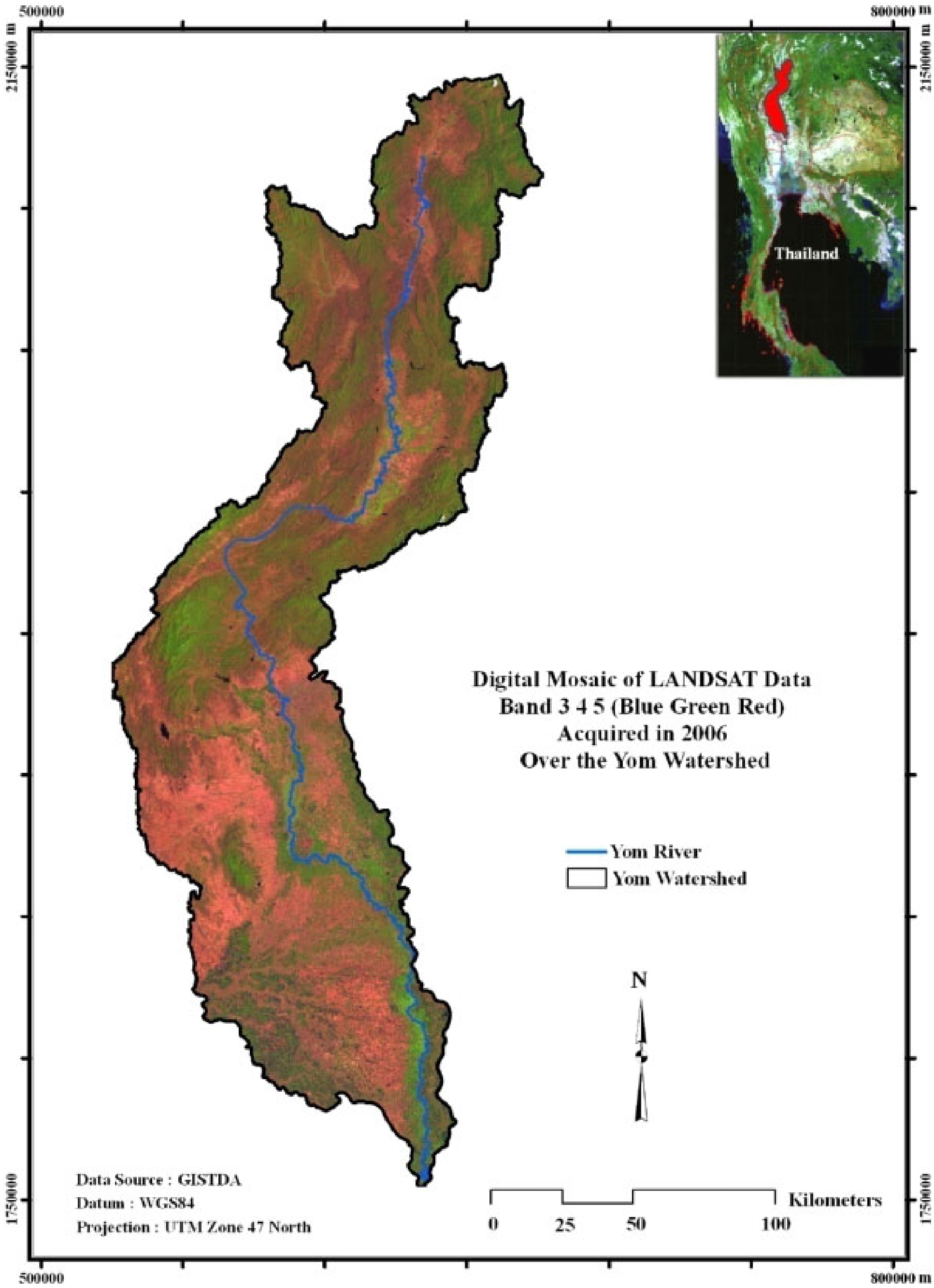

Figure 1. Satellite images from Landsat – 5 TM bands 3, 4, and 5 (BGR) showing the study area. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

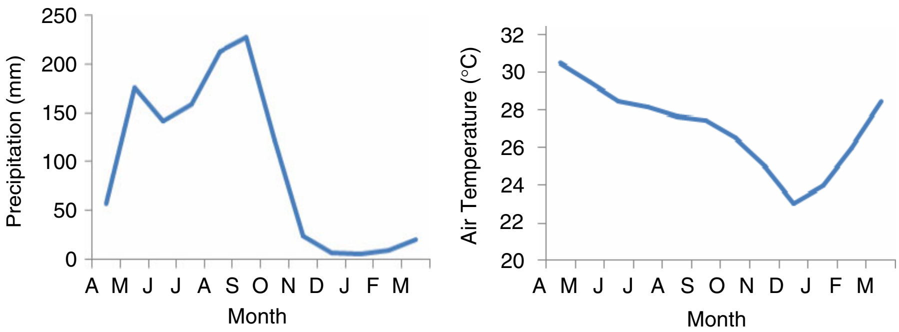

Figure 2. Average monthly air temperature and total monthly precipitation in the study area. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Nakhon Sawan Province (Department of Water Resources (DWR), 2005).

Geographically, the basin is divided into two characteristic parts, the upper and lower river basins. Most of the upper basin is mountainous, with 51% forest cover containing the only large teak forest remaining in the country (GISTDA, 2005), and 49% agriculture (in the river valleys) and urban areas. The lower basin is essentially the river's floodplain, and is well suited for cultivation. Therefore, the land use in the lower basin is mostly agriculture and urban with 26% forest (Srethasirote, 2007). The average annual precipitation in the study area is 1160 mm (ranges from 1000 to 1600 mm) and the average annual air temperature ranges from 25 to 28 °C (Figure 2; Royal Irrigation Department (RID), 2003). The climate is dominated by the tropical southwest monsoon, with over 90% of the annual precipitation occurring between May and October (Figure 2).

3. Methods

3.1. Assessment of LULC change

To investigate the relationship between urbanisation and discharge, urban areas in two flood-prone provinces were delineated from remote-sensing data, and discharge trends for stations along the Yom River were analysed. The interactions of urban growth and discharge were examined within administrative boundaries of the five districts in the two provinces (Figure 3). The discharge trend at each station of the six stations (Y.20 located in Song District, Phrea Province, Y.1C in Muang District, Phrea Province, Y.14 in Si Satchanalai District, Sukhothai Province, Y.6 in Si Satchanalai District, Sukhothai Province, Y.3A in Sawankhalok District, Sukhothai Province, and Y.33 in Si Samrong District, Sukhothai Province) were compared with the increase in urban area from 1990 to 2004 around each station.

Landsat satellite (5 and 7) images of spectral band 3 (0.63–0.69 μm), 4 (0.78–0.90 μm), and 5 (1.55–1.75 μm) of Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) sensors acquired in 1990 (TM), 1994 (TM), 1998 (ETM+), 2002 (ETM+), and 2006 (ETM+), provided by the GISTDA were used to produce a time series of LULC change on a 4-year interval. The selected images were free of signal error from the sensor and were cloud free.

For LULC classification, remote-sensing computer-processing techniques (supervised classification) and visual interpretation (manual interpretation) were applied to classify the images into four land use categories including forests, agriculture, urban and water bodies.

The maximum likelihood method for supervised classification was applied for this study because of its robustness and its easy availability in almost any image-processing software (Lu and Weng, 2007), and the assumption of normally distributed data was met. However, the maximum likelihood method requires more computations per pixel than other techniques like parallelepiped or minimum distance classification algorithms (Jensen, 2005). This classification was based on the standards formulated by the Land Development Department (LDD), Thailand. The classified images were converted to ArcGIS files format for investigating change detection. The Raster Calculation technique in the Spatial Analyst module was applied for calculating LULC changes from 1990 to 2006, for identifying areas where rapid changes occurred, as well as for investigating LULC conversion processes that occurred in the watershed.

3.2. Hydrological and meteorological data and analysis

Daily precipitation and discharge data in the Yom River Basin for 15 water years (1990–2004) were obtained from the RID, Thailand. The study was conducted in two flood-prone provinces; the Phrae and Sukhothai Provinces. The former is located in the upper part of the basin, and the later is located in the central–lower part of the basin (Figure 3). The temporal trends of precipitation and river discharge from each province were spatially and temporally analysed and compared using the procedures described below. Data from six stream gauging stations located along the Yom River, namely, Y. 20, Y.1C, Y.14, Y.6, Y.3A, and Y.33, were used (Figure 3).

The daily observations of discharge from the six gauging stations showed that river discharge was generally low during the dry season (November–April) and high during the wet season (May–October), with the peak discharge generally occurring in July or August. As precipitation can be one of the main causes of changes in river

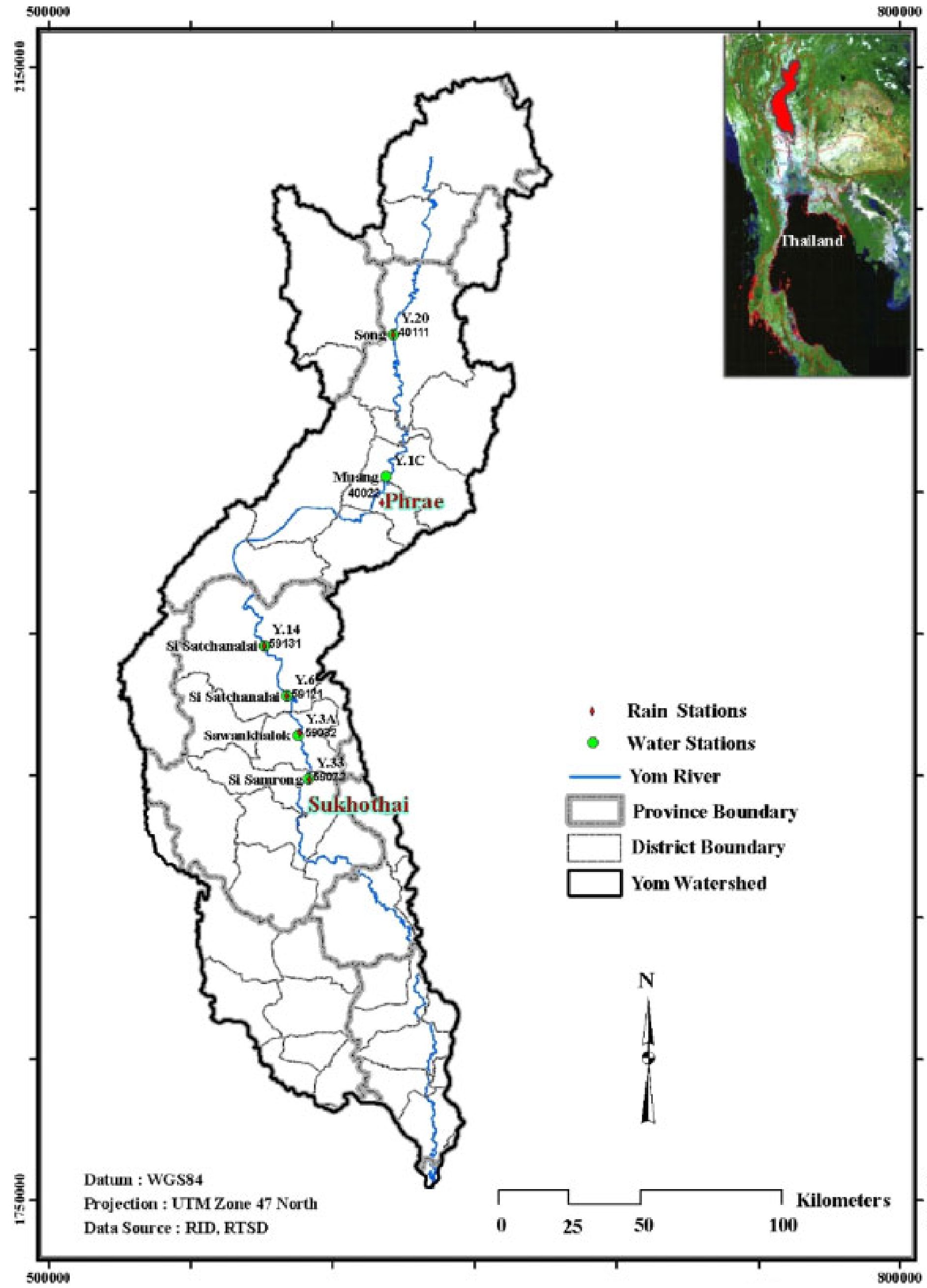

Figure 3. The administrative boundary map showing the locations of water and rain stations. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

discharge characteristics (Dettinger and Diaz, 2000), the daily precipitation from the six meteorological stations co-located with the gauging stations was used to examine the potential influence of precipitation on discharge. The season influence of precipitation on discharge (mean seasonal cycles) was removed by first calculating the mean discharge and precipitation for each day over the course of the measurement period, and then subtracting these values from the discharge and precipitation for each day to effectively remove the influence of precipitation on discharge for time series analysis.

The statistical significance of the time series of discharge and precipitation with the mean annual cycles removed (i.e. anomalies) as described above was determined by linear regression analysis. Statistical tests of the slope (regression coefficient) of the regression lines ($y = \alpha + \beta x$) of the river discharge and precipitation at each station were applied in order to see if the temporal trend was significant using a Student's t-test and the corresponding p value. For all the stations, the length of the discharge and precipitation daily times series was 5479 days ($n = 5479$), from 1 April 1990 through 31 March 2005. Each of the time series for both discharge and precipitation at all stations had lagged autocorrelations, requiring the calculation of effective degrees of freedom (n_{eff}). Therefore, as recommended by Priestley (1981), Bretherton *et al.* (1999), and Santer *et al.* (2000), n_{eff} for each of the discharge and precipitation time series

Table I. Area (km^2) and the overall amount of change (%) in LULC of Yom watershed over the period 1990–2006.

LULC type	1990 (km^2)	Percent of study area	2006 (km^2)	Percent of study area	Amount of change (km^2)	Percentage growth
Forest	11 943	47.42	11 644	46.23	− 299.85	−2.51
Agriculture	12 987	51.57	12 978	51.53	−9.86	−0.08
Urban	210	0.83	488	1.94	277.79	132.20
Water	43	0.17	75	0.30	31.92	74.56
Total	25 184	100	25 184	100	0	

was estimated as $n_{\mathrm{eff}} = n[1 - r/1 + r]$, [Correction made here after initial online publication] where r is the lag-one autocorrelation coefficient calculated from the regression residuals (Tables II and III). Finally, the discharge trends at consecutive upstream versus downstream water stations were compared (two stations in the Phrae Province; four in the Sukhothai Province).

3.3. Modelling the effects of LULC change on discharge

The differences between river discharge response before and after LULC changes were examined under similar precipitation conditions by using the rainfall–runoff model MIKE 11/Nedbør-Afstrømnings-Model (NAM) (DHI Software, 2004). The NAM model is one of the lumped conceptual models similar to simple nonlinear rainfall–runoff model composed of tanks with outlets on the side and bottom of each tank (e.g. Tank Models; Sugawara *et al.*, 1974). Tank models have been used to predict LULC change, for example, in northern Japan, where runoff simulations showed that expanded agricultural development had decreased infiltration resulting in an increase in surface runoff (Nagasaki and Nakamura, 1999). The NAM and tank models have been found to give results similar to ours in Thailand river basins (Tingsanchali and Gautam, 2000), and given that the NAM model requires fewer parameters with a simpler calibration procedure, the NAM model was used in this study. The lumped model has been successfully applied to evaluate the effects of LULC changes on watershed hydrology around the world (Lorup *et al.*, 1998; Nagasaka and Nakamura, 1999).

The NAM hydrologic model is characterised as a deterministic, lumped, and conceptual model that simulates the rainfall–runoff processes at the catchment scale. The model operates by continuously accounting for the soil moisture content in three different and commonly interrelated storages that represent overland flow, interflow, and base flow. As NAM is a lumped model, it treats each sub-basin as one unit, therefore the parameters and variables are considered to represent average values for all the sub-basins. Irrigation or groundwater pumping of water can also be accounted for in this model. This study combined statistical methods with the hydrological model to discriminate between the effects of climate variability and land use change.

As changes in runoff are difficult to measure in the field, these were calculated using the model in order to explore how the changes in land use affect the hydrologic regime of the upper Yom River Basin. The Phrae Province, located in the upper part of the basin, is one of the areas that experienced rapid LULC change, particularly urbanisation; therefore, this area was selected to compare the discharge between before urbanisation. The watershed area (7624 km^2) of the Y1C river gauging station was selected as the terminus of river flow from the study area. The model's parameters were derived objectively by an automatic calibration application routine based on a multi-objective optimisation strategy, in which three calibration objectives were satisfied, namely, (1) agreement between the daily average simulated and observed discharge; (2) agreement of the shape of the hydrograph; and (3) agreement of the peak and low flows with respect to timing and rate (Madsen, 2000).

To capture the potential effects of LULC changes on discharge, the model was run for a period of one water year at the beginning and end of the 15-year study period (1 April 1990–31 March 1991; 1 April 2004–31 March 2005). As precipitation was different in each of these years, and changes in precipitation can compound the influence of LULC changes on discharge (Tomer and Schilling, 2009); the same precipitation data were used for each model run to determine if changes in discharge were indeed due to changes in LULC. Differences in discharge, and the associated changes in model parameters, were therefore associated with changes in LULC.

4. Results

4.1. LULC change

Through the interpretation of satellite images, the Yom watershed was mostly occupied by agriculture followed by forest areas, urban areas, and water bodies throughout the study period (Table I; Figure 4). Between 1990 and 1994, agricultural and urban areas exhibited progressive increases, whereas the forest areas were declining. Between 1994 and 2006, there was a notable increase in urban areas, with forest and agricultural areas both decreasing slightly. The area of open water slightly increased (by ∼30 km^2) due to the construction of reservoirs for agriculture, but the percentage of change is not comparable to that of urbanisation (by ∼278 km^2,

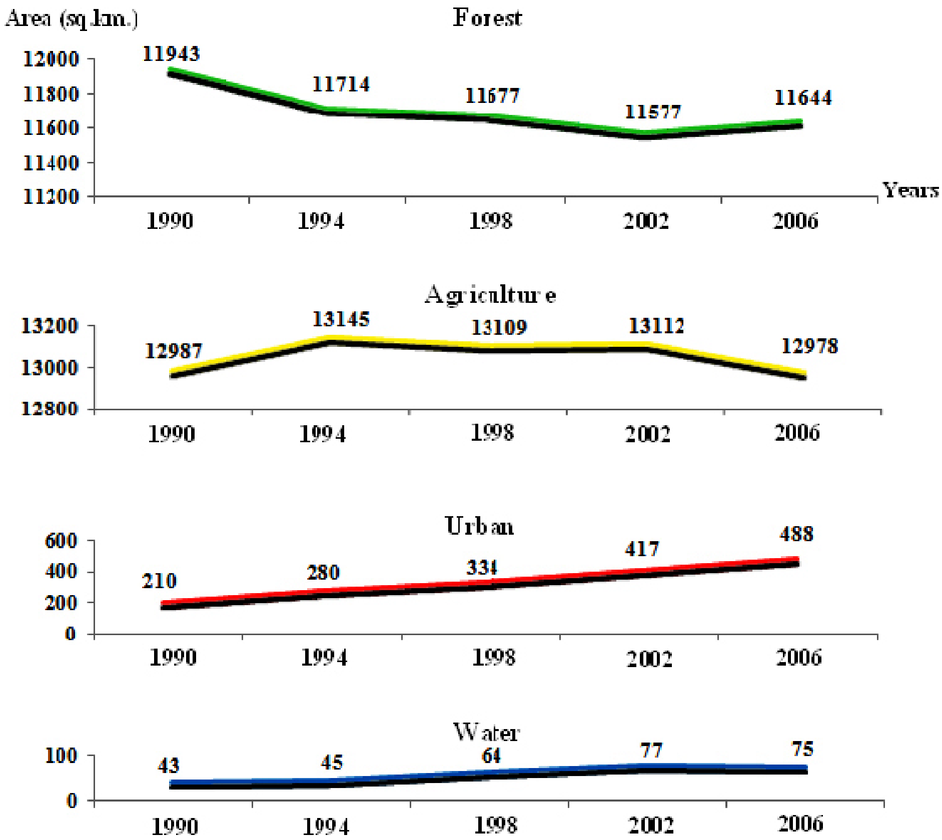

Figure 4. Changes in the area of each LULC class from 1990 to 2006. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

an increase of 132% compared the initial 210 km^2; Figure 4).

On the basis of the change detection analysis from the LULC data, the urban area in the basin increased from 210 km^2 in 1990 to 488 km^2 in 2006, with a trend to increase over time. The main land conversion process was from agriculture to urban land. In addition, agriculture areas had expanded into steep terrain, which, as a result, accelerated the removal of forest cover on the slopes. Figure 5 shows the change detection map, which indicates major land use conversion processes. Each colour represents a characteristic activity, e.g. red indicates the conversion of agricultural area into urban land, blue indicates the conversion of forest areas to water bodies, and green indicates the reforestation areas etc.

4.2. Characteristics and long-term change of discharge and precipitation

Regression analyses and trend lines of daily discharge at the six main river stations along the Yom River are shown in Table II and Figure 6. The regression coefficients (or slope indicating the long-term trend in discharge or precipitation) for discharge were positive and statistically significant ($p < 0.05$) at all stations, except at stations Y.14 and Y.6, which were statistically significant at lower confidence levels (p value 0.10 and 0.06, respectively). In the Phrae Province, the daily discharge trends of Y.20 and Y.1C were compared (the former is located upstream and the later downstream). The slope for discharge at Y.20 was 0.0039 m^3 s^{-1} day^{-1}, which is significantly lower than that at Y.1C (0.0065 m^3 s^{-1} day^{-1}). According to these results, the discharge at the downstream location increased at a higher rate than that at the upstream area during the same time period. The same patterns were found in the Sukhothai Province; the slopes of the long-term discharge trends (all in m^3 s^{-1} day^{-1}) moving progressively from upstream to downstream stations were 0.0180 (Y.33), 0.0130 (Y.3A), 0.0076 (Y.6), and 0.0059 (Y.14), with each increase being statistically significant.

The regression analysis of daily precipitation time series revealed that there were both increases and decreases in the regression slopes, with only one being statistically significant (station 59 121; $p = 0.05$) over

Table II. Regression analysis results for daily discharge time series over the time period from 1 April 1990 through 31 March 2005.

Station ID	Province	Effective degrees of freedom	Slope (m^3 s^{-1} day^{-1})	p value
Y.20	Phrae	722	0.0039	0.0159
Y.1C	Phrae	398	0.0065	0.0216
Y.14	Sukhothai	282	0.0059	0.1094
Y.6	Sukhothai	268	0.0076	0.0681
Y.3A	Sukhothai	214	0.0130	0.0115
Y.33	Sukhothai	215	0.0180	0.0001

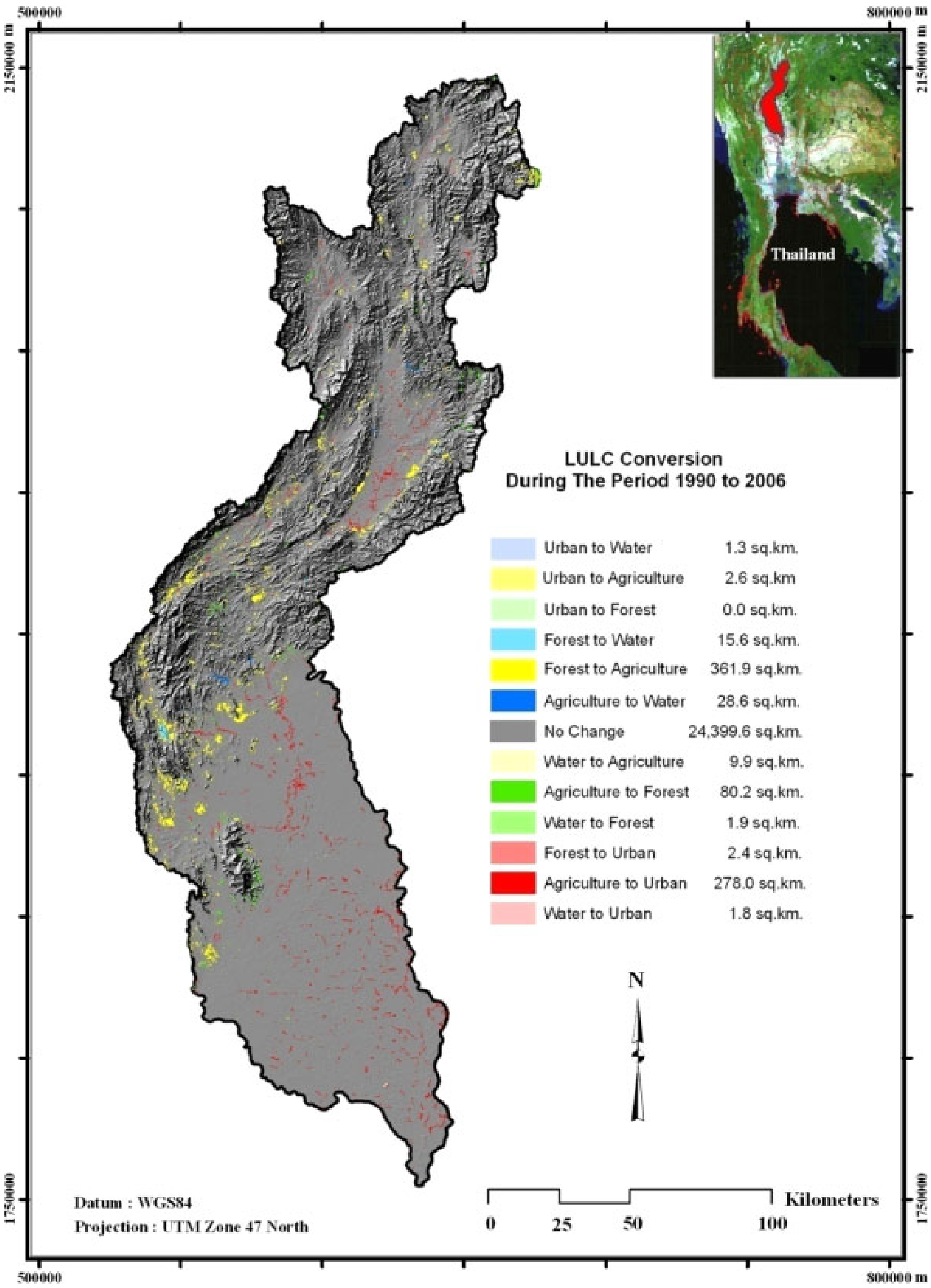

Figure 5. Change detection map of the Yom watershed from 1990 to 2006. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

the 15-year study period (Table III; Figure 6). For example, stations 40 111 and 40 022 (Phrae Province) had a slight decrease in precipitation, as did stations 59 131 and 590 032 (Sukhothai Province). In contrast, stations 59 121 and 59 072 (Sukhothai) showed a small positive slope in the long-term precipitation trend. These results indicated that, except for one station, there were no significant changes in precipitation, similar to the results of Cook and Buckley (2009) that found no significant trend in the onset, withdrawal, or monsoon season length ($p < 0.05$) in central Thailand from 1951 to 2005. Generally if precipitation changed, the river discharge should also have changed proportionally if there was no change in LULC

Table III. Regression analysis results for daily rainfall time series over the time period from 1 April 1990 through 31 March 2005.

Station ID	Province	Effective degrees of freedom	Slope (mm day^{-1})	p value
40 111	Phrae	4232	0.000029	0.3692
40 022	Phrae	3711	0.000120	0.1197
59 131	Sukhothai	4052	−0.000020	0.4168
59 121	Sukhothai	3840	0.000150	0.0500
59 032	Sukhothai	3918	−0.000003	0.4865
59 072	Sukhothai	4046	0.000045	0.3206

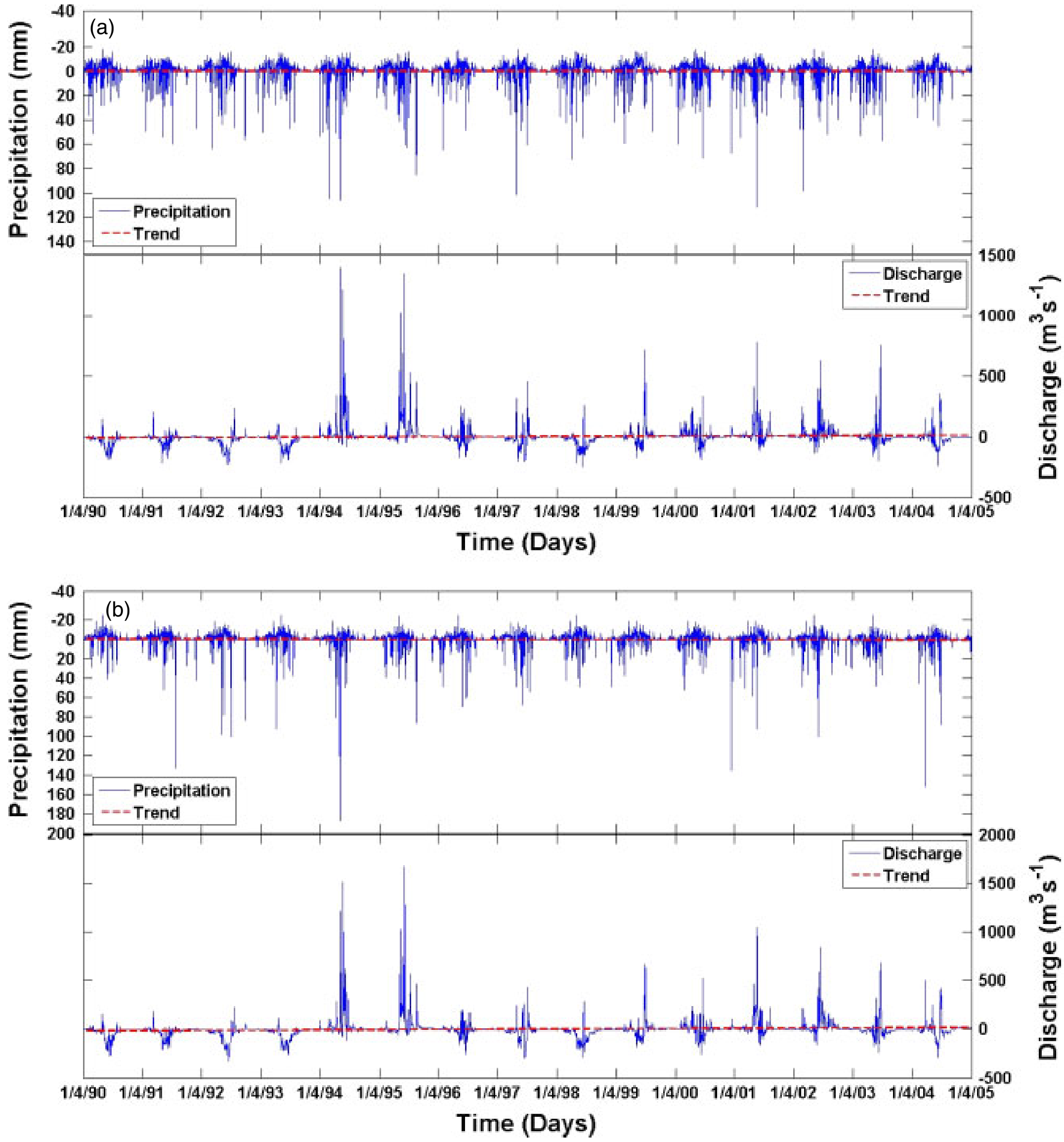

Figure 6. Precipitation (upper panel) and discharge (bottom panel) anomalies at stations Y.20, 40 111 (a) and Y1C, 40 022 (b) in the Yom River at Phrea Province during the period 1 April 1990–31 March 2005 with their trends imposed. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

characteristics in the watershed. As described previously, however, the discharge significantly increased without significant changes in precipitation in the basin (Figures 6 and 7), except for the one station where the cause(s) of the increase in precipitation are unknown. This suggests that overall there was a change in discharge due to changes in LULC of the watershed.

4.3. Effects of urbanisation on discharge

The changes in urbanised areas and river discharge of the five districts in two provinces that experienced rapid urbanisation are shown in Table IV. The river discharge changes exhibited positive temporal trends in relation to the urban expansion. These results support the idea that the increasing discharge was directly related to the increase in urbanised areas in the watershed. The range in the slopes of the river discharge temporal trends increased between 0.0039 and 0.0180 m^3 s^{-1} day^{-1} over the 15-year period, corresponding to a range in the increase in urban areas from 6 to 16 km^2, or 80–149% growth (only 0.02–0.08% of the total catchment area). The district with the greatest increase in urban area (Si Satchanalai 20 km^2; 282% growth), however, had the least statically significant increase in discharge and the slope (0.0076 m^3 s^{-1} day^{-1}) ranked third amongst the five stations due to the type of LULC change within the urban class (see Section 5).

The results of the calibrated NAM rainfall–runoff model at the Phrea Province run during the start (water year 1990–1991) and end (water year 2004–2005) of the measurement period are shown in Figure 8(a) and (b) respectively, and the resulting model parameters for each period are shown in Table V. In general, the low flows and the peak flows were simulated well, with occasional underestimation and overestimation of the medium high peak flows. To simulate the differences

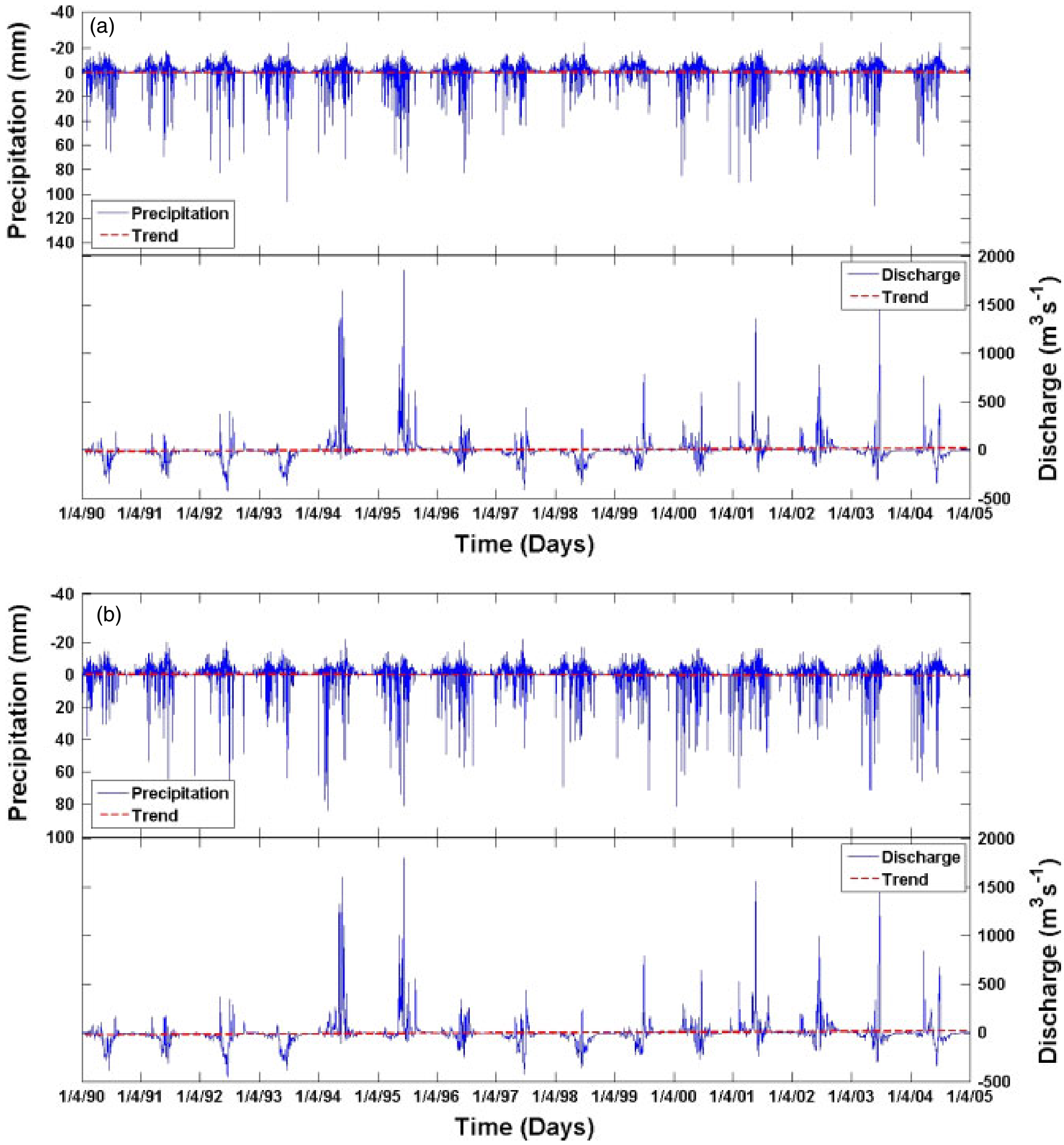

Figure 7. Precipitation (upper panel) and discharge (bottom panel) anomalies at stations Y.14, 59 131 (a), Y6, 59 121 (b), Y3A,59 032 (c), and Y33, 59 072 (d) in the Yom River at Sukhothai Province during the precipitation period 1 April 1990–31 March 2005 with their trends imposed. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

between river discharge (especially peak flows) before and after LULC changes including the increase in urban area, the model parameters derived during the start of the study period were compared with those derived at the end of the study period to simulate discharge under the same precipitation regimes (Figure 9(a) and (b)). An increase in peak discharge for both of the simulated years using the model parameters to reflect the change in LULC was apparent (an average increase in peak flow of ∼10%), even when the model was run using the same precipitation data.

5. Discussion

The largest LULC changes over the study period in terms of actual area were a decrease in forest cover (300 km^2) and nearly an equal increase in urban cover (278 km^2). More land was converted into urban areas at the expense of agriculture, and this was mainly due to commercial and industrial growth (Department of Environmental Quality Promotion (DEQP), 2007). Navanukgraha (1997) also stated that agriculturally productive land and forests in Thailand have been converted into residential and other uses. For example, in the northern part of Thailand, the urban area of Chiang Mai increased from 15 km^2 in 1952 to 339 km^2 in 2000 due to the economic and population growth (Sangawongse *et al.*, 2005).

On the basis of the results presented in this study (both observations and simulations), LULC changes can affect river discharge, implying changes in the hydrological characteristics of the watershed. With less storage available for water in urban areas and more rapid runoff, the water level of rivers in urban areas rises more quickly during storms and has a higher peak discharge

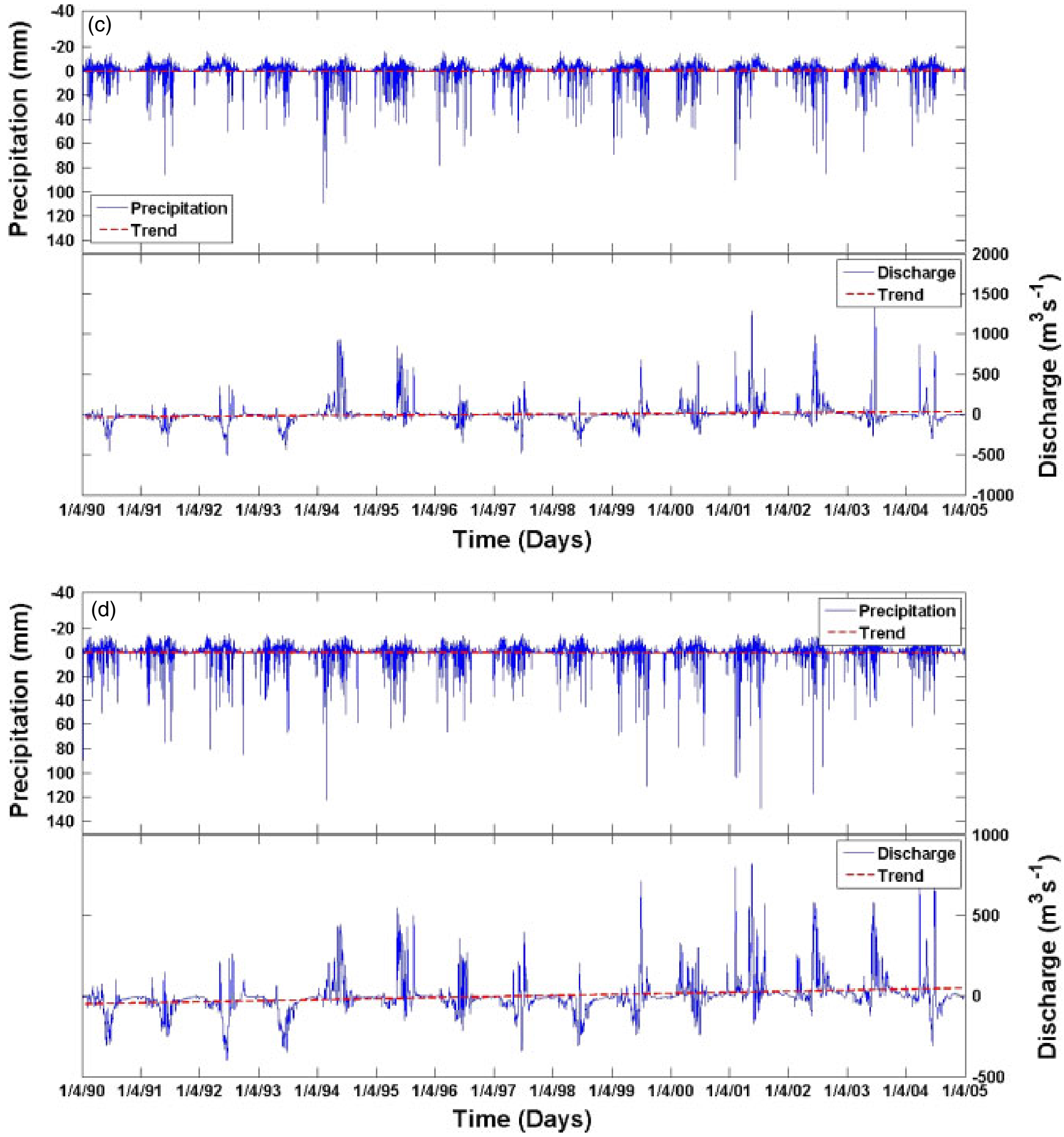

Figure 7. (*Continued*).

Table IV. The urbanisation and river discharge trends for the five districts.

Urbanisation						Discharge		
District	1990 (km^2)	2006 (km^2)	Area Change (km^2)	Growth %	% Change of catchment to urban	Station	Slope (m^3 s^{-1} day^{-1})	Trend (at 95 significance levels)
Song	7.39	13.36	5.97	80.86	0.02	Y.1C	0.0039	Upwards
Muang	16.89	31.76	14.86	88.00	0.06	Y.20	0.0065	Upwards
Si Satchanalai	7.11	27.18	20.07	282.44	0.08	Y.6	0.0076	Upwards
Sawankhalok	12.96	28.11	15.16	117.00	0.06	Y.3A	0.0130	Upwards
Si Samrong	10.92	27.18	16.26	148.81	0.06	Y.33	0.0180	Upwards

rate than rural rivers (Illinois Association for Floodplain and Stormwater Management (IAFSM), 2004), thus increasing the watershed's flood potential (Liu *et al.*, 2004). Several others have reported changes in watershed characteristics (e.g. discharge) associated with changes in LULC. For example, Cowden *et al.* (2006) stated that the urbanisation of the Clinton River watershed in Southeastern Michigan strongly impacted the hydrology because of changes in channel alteration, impervious surface, and soil characteristics. Noorazuan *et al.* (2003) also found that urban extent and changes in urban-related LULC could affect river discharge behaviour by increasing the

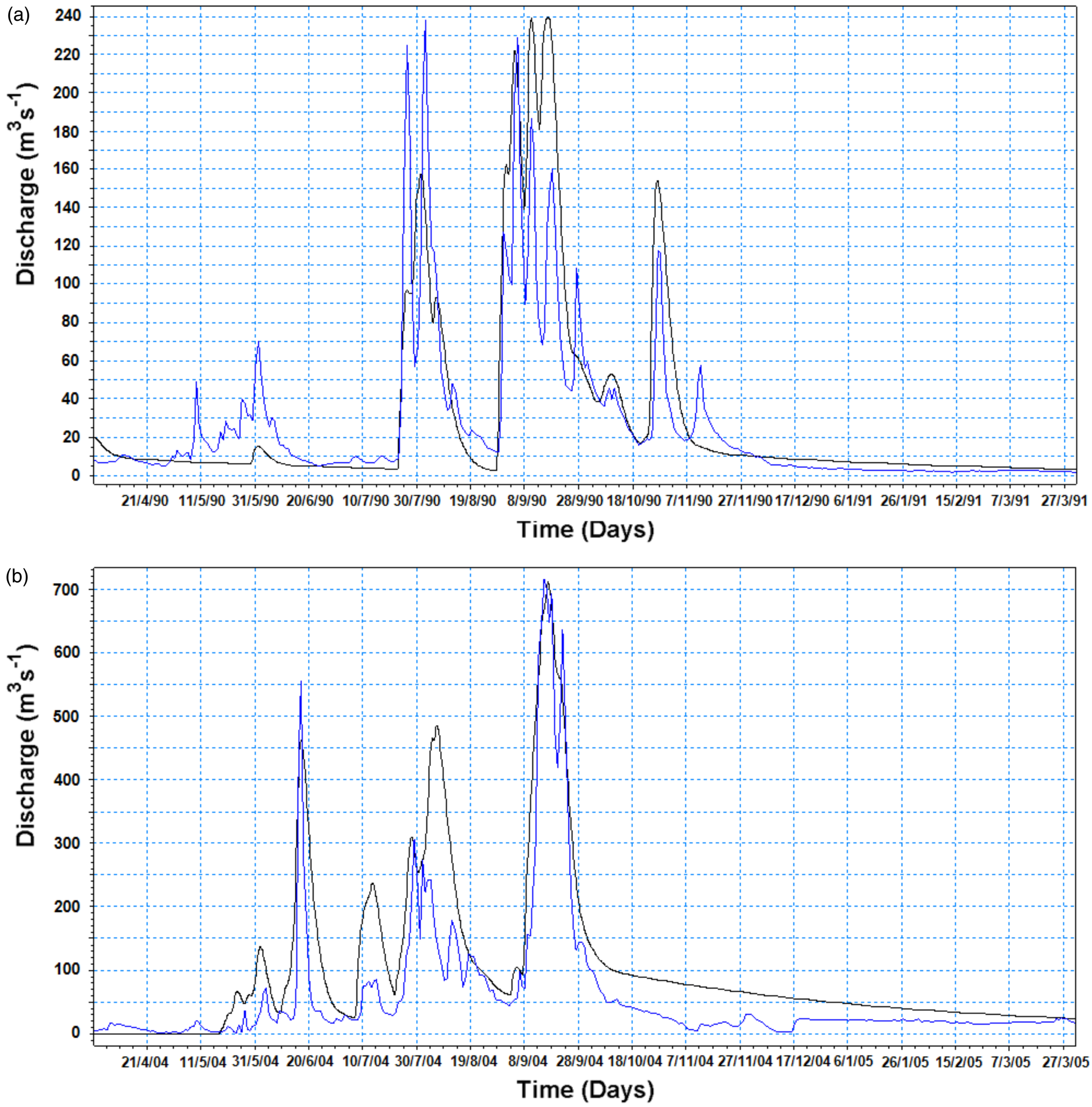

Figure 8. (a). Simulated (black line) and observed (blue line) river discharge in the Yom River at Phrea Province during the precipitation period 1 April 1990–31 March 1991. (b) Simulated (black line) and observed (blue line) river discharge in the Yom River at Phrea Province during the precipitation period 1 April 2004–31 March 2005. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Table V. Model parameters for Y1C (Phrae Province) in 1990–1991 and 2004–2005. See DHI software (2004) for a complete description on model parameters.

Parameter	Period	
	1990–1991	2004–2005
U_{max}: Surface water storage (mm)	19	18
L_{max}: root zone water storage (mm)	130	100
CQOF: Overland flow runoff coefficient (–)	0.50	0.456
CKIF: Time constant for interflow (h)	804.7	845.6
CK_{12}: Runoff routing constant (h)	55.6	53.5
TOF: Root zone threshold (–)	0.369	0.338
TIF: Root zone threshold for interflow (–)	0.812	0.936
TG: Root zone threshold for overland flow (–)	0.925	0.828
CK_{BF}: baseflow time constant (h)	2558	2897
C_{area}: Ratio of groundwater catchment to topographic catchment area (–)	1	1

Table V. (*Continued*).

Parameter	Period	
	1990–1991	2004–2005
Sy: Specific yield (–)	0.1	0.1
GWL_{BF0}: Maximum groundwater depth causing baseflow (m)	10	10
GWL_{BF1}: Groundwater depth for unit capillary flow (m)	0	0
CQ_{low}: Proportion of recharge to lower groundwater storage (–)	79	98.8
CK_{low}: Time constant for routing lower baseflow (h)	27902.7	27003.6

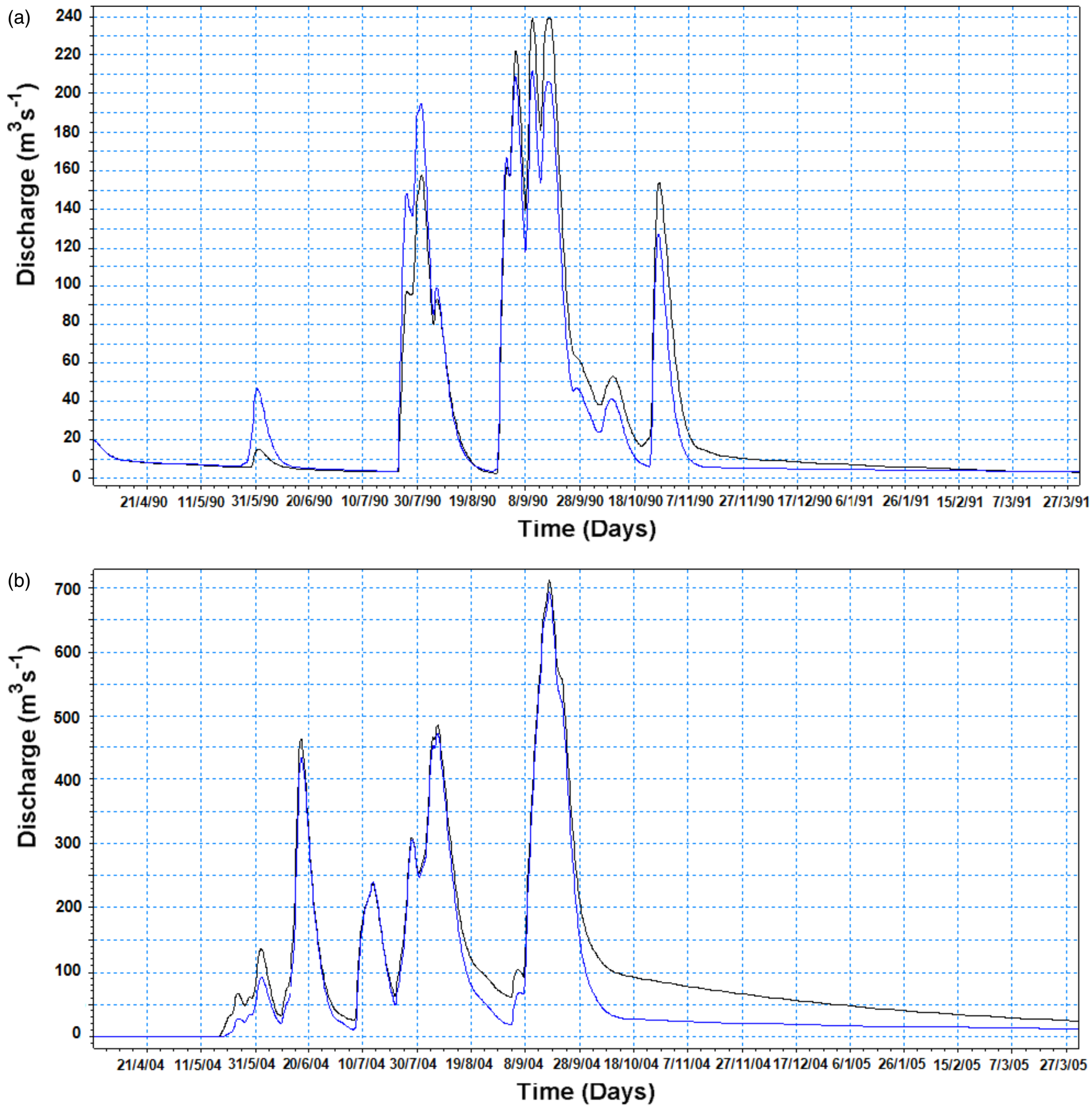

Figure 9. (a) Comparison simulated hydrograph before (blue line) and after (black line) urbanisation in the Yom River at Phrae Province under the same the precipitation period 1 April 1990–31 March 1991. (b) Comparison simulated hydrograph before (blue line) and after (black line) urbanisation in the Yom River at Phrae Province under the same precipitation period 1 April 2004–31 March 2005. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

surface runoff in the Langat river basin, Malaysia, South-east Asia. Shi *et al*. (2007) studied the effect of LULC change on surface runoff in the Shenzhen region, China, and concluded that urbanisation led to increases in the maximum flood discharge. Lastly, Sebastian (2005) found that the increase in the impervious surface area from urbanisation in the Mapocho basin, Santiago de Chile, South America caused an increase in winter mean and peak discharge flows, as well as an increase in the stream levels.

Our results are similar to these other studies, in that a relatively small change in LULC relative to the size of the entire watershed had a small but detectable hydrological basin impact. Four of the five districts showed a small increase in the long-term (15-year) discharge corresponding to an increase in urban land area. The Si Satchanalai District, however, which had the largest increase in urban area (20 km^2; 282% increase), did not have the largest increase in long-term discharge (0.0076 m^3 s^{-1} day^{-1}). This may be attributed to the fact that urban areas of Si Satchanalai District have different characteristics compared to the other districts, e.g. the district had a lower coverage of commercial and industrial areas. As we have used first-level categories to classify LULC, the commercial and industrial areas are represented by one category in the urban LULC class, thus preventing us from identifying these potentially important subclasses of LULC.

Our results indicated a small but statistically significant (p 0.0001–0.1094) increase in discharge and small ($\sim$10%) increases in peak discharge corresponding to relatively small changes in the absolute areal coverage of urban and forested areas of the watershed. Whereas Hurkmans *et al*. (2009) found small impacts on discharge in the Rhine River Basin from simulated projected increases in urbanisation due to compensatory decreases in other vegetated LULC, the changes we report here may be due to the location of the land use change within the watershed. In addition to factors such as compensatory changes in other LULC, changes in river dimensions (e.g. width and depth), and the changes in hydrological parameters such as surface and root zone water storage before and after LULC changes, the location of the LULC change may be important in interpreting our results. For example, in our study, the conversion from agricultural to urban land use occurred directly along the banks of the Yom River, thus resulting in a faster peak-flow discharge response compared to urbanisation occurring further away for the river. Water storage capacity with LULC changes located further from the river should also buffer the peak-flow discharge response, but such a decrease in discharge, however, was unlikely due to the small net increase in reservoir area ($\sim$30 km^2) and large distance of the reservoirs from the Yom River ($\sim$50 km).

6. Conclusions

From the results of the study, the following conclusions can be drawn:

- Satellite remote sensing is useful in classifying and studying LULC and detection of change in the Yom watershed. The area was subjected to urbanisation and this was mainly at the expense of agricultural area. Higher resolution satellite imagery would be helpful in identifying subclasses on LULC, especially in urban areas.
- A slight increase occurred concurrently in the long-term discharge with changes in LULC, especially an increase in urban areas and a decrease in forested areas. The relatively small increase in the areal coverage of urban areas may have had a disproportionally large impact on discharged behaviour (mean and extreme flows) due to the location of these LULC changes adjacent to the banks of the Yom River.
- As the Yom watershed has been characterised by urbanisation along the river over the last decade and may continue to experience extensive landscape change in the future, the potential for increased discharge and urban flooding is probable. The information provided in this study can be useful in planning for emergency urban floods, disaster announcement measures, and evacuation of the people living in flood-risk area. In addition, this type of analysis can support relevant organisations in public sectors for future land use and flood management plans in order to protect and reduce the impact on life and the assets of government and local people in the northern central watershed of Thailand.

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