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The responses of river discharge and sediment load to historical land-use/land-cover change in the Mekong River Basin

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Abstract The large river basins throughout the world have undergone land-use/land-cover (LULC)-induced changes in river discharge and sediment load. Evaluating these changes is consequently important for efficient management of soil and water resources. In addition, these changes in the transboundary Mekong River Basin (Mekong RB) are not well-known. The present study aimed to investigate the impacts of LULC changes on river discharge and sediment load in the Mekong RB during the period 1980–2015 using Soil and Water Assessment Tool (SWAT). The SWAT model was calibrated and validated using measured data of daily river discharge and monthly sediment load. Analysis of LULC change showed a 2.35% decrease in forest land and a 2.29% increase in agricultural land during the period of 1997–2010. LULC changes in 1997 and 2010 caused increases in river discharge and sediment load by 0.24 to 0.32% and 1.78 to 2.86%, respectively in the study region. Moreover, the river discharge and sediment load of the Mekong River have significantly positive correlation with agricultural land and negative correlation with forest land. The findings give beneficial insights to implement appropriate strategies of water and soil conservation measures to adapt and mitigate the adverse impacts of LULC in the Mekong RB. Further study will consider the impact of future LULC changes and uncertainties associated with the LULC projections for future management of soil and water conservation in the study region.

Keywords Land-use/land-cover change · River discharge · Sediment load · SWAT model · Mekong River Basin

Introduction

In the last few decades, climate change, anthropogenic activities, population growth, urban extension, and economic development have led to considerable increases in demands for water, energy, and food which put pressures on water and soil resources throughout the world (Aghsaei et al., 2020). Land-use/land-cover (LULC) change is occurring due to impacts of anthropogenic activities on land surface, such as agricultural development, deforestation, industrialization, and urban expansion (Bosmans et al., 2017). Such LULC can alter hydrological components in basins, including evapotranspiration, infiltration, surface runoff, and sub-surface flow

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(Marhaento et al., 2018; Munoth & Goyal, 2020), subsequently influencing the availability of water resources in most regions in the world. Additionally, LULC changes have significant influences on sediment and nutrient loads (Hwang et al., 2016). Deforestation due to intensive agriculture has increased the supply of provisioning ecosystem services (e.g., food, forage, fiber, and bioenergy) (Power, 2010) but has lost regulating ecosystem services, especially hydrological services (e.g., water conservation, flood control, and water purification) (Jin et al., 2015). In the mountainous regions, LULC causes severe soil erosion and water quality degradation through sediments along with large amounts of nutrients due to excess fertilizer use (Kim et al., 2019). Thus, understanding the LULC impacts on water quantity and quality is essential for efficient management of water and soil resources, especially in regions where the socio-economic and ecological systems mainly relied on these resources.

In the past few years, the LULC impacts on soil and water processes have acquired significant attention (e.g., Borrelli et al., 2020; Bosmans et al., 2017). Piao et al. (2007) indicated that the world's river discharge has considerably increased since 1900 and LULC change may contribute to greater than 50% of this increase. Many investigations have examined the impacts of LULC change on river discharge and sediment load in various regions of the world (Aghsaei et al., 2020; Bieger et al., 2015; Pandey et al., 2021; Woldesenbet et al., 2017). For example, Worku et al. (2017) scrutinized the effect of LULC change on runoff and sediment yield in the Baressa watershed in Ethiopia and found that the runoff and sediment yield slightly reduced in the period of 2000–2009. Similarly, Zhao et al. (2017) indicated a considerable decrease in sediment yield under the effect of LULC changes in the period of 1990–2006 in the Huangfuchuan River Basin in China. Chotpantarat and Boonkaewwan (2018) inspected the influence of LULC change on river discharge and sediment yield in the Lower Yom River Basin in Thailand. The results displayed that considerable increases in river discharge and sediment yield were observed during the period of 2000–2013. Munoth and Goyal (2020) also indicated that LULC change caused increases in surface runoff and sediment yield in the Upper Tapi River Basin in India during the period of 1975–2016. Recently, Afonso et al. (2021) estimated the effect of LULC changes on hydrology and sediment yield in the Itacaúnas River Basin in Brazil, and they indicated that the LULC changes caused increases in streamflow and sediment load in the period of 1970–2013. Generally, these studies revealed that the LULC changes can increase or decrease the river discharge and sediment load. However, the contributions of individual LULC changes on hydrological processes were not further investigated. It is of importance to study the specific LULC changes that occurred on the basin to understand the effect of such changes on the hydrological responses. Moreover, quantitative information about the LULC impacts on hydrological processes in tropical basins is still limited (Marhaento et al., 2018).

Based on the aforementioned studies, the prevailing approaches for investigating the LULC impacts on the hydrology and sediment yield are paired catchments, multivariate statistics, and hydrological modeling. In the midst of these approaches, the hydrological modeling has the advantageousness for scenario analysis (Woldesenbet et al., 2018). There are many hydrological models, such as the Agricultural Nonpoint Source Pollution Model (AGNPS), Hydrologic Simulation Program FORTRAN (HSPF), and Soil and Water Assessment Tool (SWAT). Among these hydrological models, the SWAT model has been popularly utilized to analyze the LULC impacts on hydrological processes (Chotpantarat & Boonkaewwan, 2018; Sok et al., 2020; Tan et al., 2020).

Changes in river discharge and sediment yield might be crucial for large river basins, including the transboundary Mekong River Basin (Mekong RB) in East Asia and Southeast Asia, which ranks as the 21st largest river basin in the world. The Mekong RB is a nutrient-rich sediment river, which has abundant aquatic biodiversity and a large capture fishery in the world (Meynell, 2017). Agriculture is a keystone of economic development, providing livelihoods for more than 70% of the population living in this basin (FAO, 2011). Agriculture in the basin depends on abundant water resources and soils fertilized by nutrient-rich sediments provided by the wet-seasonal flow. Nevertheless, this is altering because of extensive LULC changes. In addition, the Intergovernmental Panel on Climate Change (IPCC) report showed that the tropical and sub-tropical regions, including the Mekong RB, are one of the most vulnerable regions for water scarcity and soil degradation owing to intensified LULC change (IPCC, 2019). Pokhrel et al. (2018) indicated that the LULC impacts on hydrology are yet to be clearly understood. The existing literature in the Mekong RB has mainly focused on investigating hydrological impacts of climate change and hydropower dams.

The main aim of the present study is to investigate how the LULC change alters the river discharge and sediment load of the Mekong RB. The findings of the present study are expected to have important implications for the policymakers in efficient management of soil and water resources in the transboundary Mekong RB, one of the largest drainage basins of the world. Additionally, the employed approach of hydrological modeling based on the SWAT model and scenario analysis could be applied to examine the LULC impacts in other basins.

Materials and methods

Study area

The present study focused on the Mekong RB (Fig. 1), consisting of the Upper Mekong RB (known in China as the Lancang RB) and the Lower Mekong RB (approximately 76% of Mekong RB's area). The Mekong River is the 12th longest river length (around 4350 km) in the world, with a total drainage area of 795,000 km^2 (MRC, 2010). The river starts from the Tibetan Plateau, flows into the mainstream Mekong River through six countries (i.e., China, Myanmar, Laos, Thailand, Cambodia, and Vietnam), and finally drains into the South China Sea (known in Vietnam as the East Sea). The Upper Mekong RB is highly mountainous regions and deep valleys, while the Lower Mekong RB is mainly lower and flatter regions and floodplains (Eastham et al., 2008). The basin has a diverse climate varying from temperature zone in the Upper Mekong RB to sub-tropical and tropical zones in the Lower Mekong RB (MRC, 2005). The annual rainfall in the basin varies from 400 to 2500 mm (Lauri et al., 2014), with high rainfall in the eastern highlands of Laos and central highlands of Vietnam. The Mekong River has a total river discharge of approximately 475 km^3/year, of which approximately 70–80% of the total discharge is in the flood season (June to November) (MRC, 2005). Regarding the total suspended sediment load, it is estimated to be approximately 160 Mt/year (Walling, 2008).

The Mekong RB plays an important role in providing an abundant environment for agriculture, aquaculture, and fisheries, which is a foundation of socio-economic development. This basin is recognized as the second richest region of aquatic biodiversity, with more than 850 fish species (Meynell, 2017). More than 80% of people living in the Lower Mekong RB are dependent on the river system and its natural resources for their basic food and livelihood. Moreover, more than 40% of the land in the Mekong RB is utilized for agriculture, and this basin is one of the most productive agricultural regions in the world.

Data collection

In the present study, spatial and temporal data, including Digital Elevation Model (DEM), LULC, soil, and meteorology, were utilized. Data description is listed in Table 1. This study utilized DEM data with a spatial resolution of 90 m from the Shuttle Radar Topography Mission (STRM). The LULC data in 1997, 2003, and 2010 with a spatial resolution of 300 m were obtained from the Climate Change Initiative (CCI) of the European Space Agency (ESA). The soil data with a spatial resolution of 10 km were collected from the Food and Agriculture Organization of the United Nations (FAO). Additionally, the daily rainfall and temperature data from 70 weather stations within and around the Mekong RB were collected from the Mekong River Commission (MRC) for the period of 1980–2015 (Fig. 1). Furthermore, daily discharge data in the period of 1983–2010 recorded from seven hydrological stations (i.e., Chiang Sean, Luang Phrabang, Nakhon Phanom, Mukdahan, Pakse, Stung Treng, and Kratie) and monthly sediment data in the period of 1985–2008 recorded from 3 hydrological stations (i.e., Chiang Sean, Luang Phrabang, and Nakhon Phanom) were collected. In the present study, the hydro-meteorological data were checked to remove anomalous values and to fill any temporal gaps to ensure data quality before translating them to the SWAT model. The missing data were automatically filled using the WXGEN weather generator, a component model of SWAT.

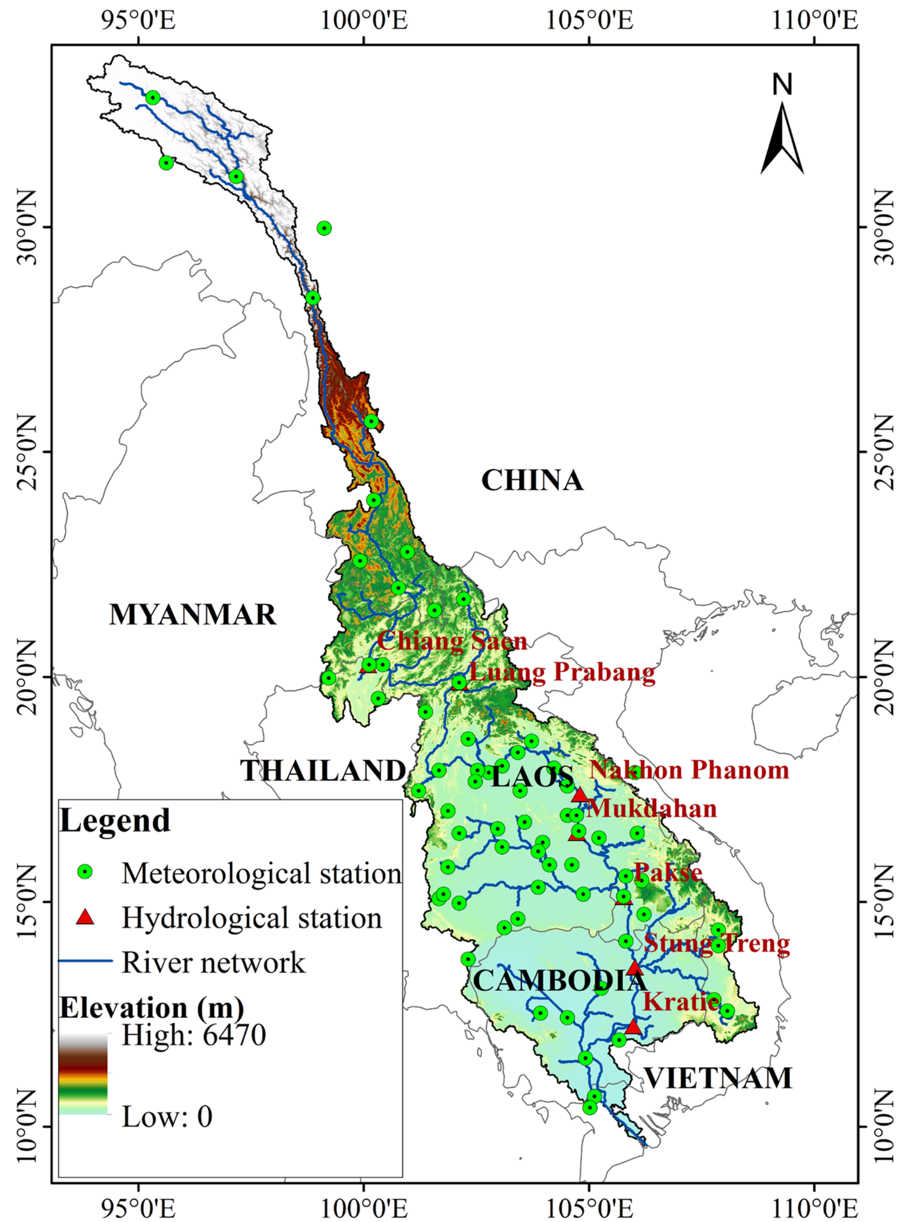

Fig. 1 Map of the Mekong RB

Theoretical description of Soil and Water Assessment Tool

The SWAT model was utilized to analyze the LULC impact on responses of river discharge and sediment load in the Mekong RB. This model is designed to simulate the impact of climate change, human activities, and land management practices on hydrological components, nutrient and sediment transport at a small to large basin scale (Neitsch et al., 2011). In SWAT, a basin is separated into sub-basins where each sub-basin includes one or more Hydrological Response Units (HRUs). HRU is defined as an individual mixture of LULC, slope, and soil features. The number of HRUs is determined by the variety of LULC, soil, and slope classes. These varieties are determined based on the spatial resolution of LULC, soil, and DEM data. The soil and water processes of the SWAT model are estimated at the HRU level and then combined at the sub-basin

Table 1 Details of data input used in the present study

Data type	Source	Description
Topography	Shuttle Radar Topography Mission (STRM)	Spatial resolution of 250 m
Land-use/land-cover (LUCC)	Climate Change Initiative (CCI) of the European Space Agency (ESA)	Spatial resolution of 300 m, LULC in 1997, 2003, and 2010
Soil	Food and Agriculture Organization of the United Nations (FAO)	Spatial resolution of 10 km
Meteorology	Mekong River Commission (MRC)	70 meteorological stations, daily data in the period 1980–2015
River discharge	Mekong River Commission (MRC)	7 hydrological stations, daily data in the period of 1983–2010
Sediment load	Mekong River Commission (MRC)	3 hydrological stations, monthly data in the period of 1985–2008

level. The hydrological processes are simulated using the balance equation of soil water content, and the sediment load is calculated using the Modified Universal Soil Loss Equation (MUSLE). More details on the SWAT model can be found in Neitsch et al. (2011).

SWAT model setup, calibration, and validation

In order to set up the SWAT model for the Mekong RB, the present study utilized the DEM data to delineate basin and 166 sub-basins, and estimate topographical characteristics in the study area. The LULC and soil data were used to provide the physical and chemical properties of soils in the study area. In reliance on the features of slope, LULC, and soil, the SWAT model further separated 166 sub-basins into 3546 HRUs. The daily meteorological data (i.e., rainfall and temperature) in the period 1980–2015 were used as input climate data for the SWAT model. Furthermore, the remaining meteorological data (relative humidity, solar radiation, and wind speed) were automatically filled by a WXGEN weather generator within SWAT based on the monthly statistical parameters from existing meteorological data. Additionally, daily discharge data and monthly sediment data were utilized in order to calibrate and validate the SWAT performance.

The SWAT model of the Mekong RB was calibrated and validated for the hydrological simulation using daily discharge data from 1983 to 2010 at seven hydrological stations, namely Chiang Sean, Luang Phrabang, Nakhon Phanom, Mukdahan, Pakse, Stung Treng, and Kratie along the mainstream Mekong River (Fig. 1). After that, the model was continued to calibrate and validate for the sediment simulation using monthly sediment data from 1985 to 2008 at three hydrological stations, including Chiang Sean, Luang Phrabang, and Nakhon Phanom. The SWAT model was warm-up for the 3 years (1980–1982) to appropriately initiate the water and soil processes. The SWAT calibration utilized fifteen hydrological parameters and four sediment parameters (Table 3), which were selected based on a review of existing literature (Khoi & Thang, 2017; Shrestha et al., 2018; Sok et al., 2020). Furthermore, the SWAT calibration was done using the Sequential Uncertainty Fitting version 2 (SUFI-2) integrated in the SWAT Calibration and Uncertainty Program (SWAT-CUP) (Abbaspour, 2015).

The SWAT performance in simulating the river discharge and sediment load for the Mekong RB was evaluated by comparing the observed and simulated data using two efficiency statistics, namely the Nash–Sutcliffe Error (NSE) and percent bias (P_{BIAS}). The NSE statistical index estimates the relative magnitude of the residual variance in comparison to the observed data variance, and it indicates how well the plot of measured versus simulated data fit the 1:1 line (Nash & Sutcliffe, 1970). The P_{BIAS} statistical index compares the average tendency of simulated data in comparison to measured data (Gupta et al., 1999). As reported by Moriasi et al. (2007) and Rodríguez et al. (2021), the SWAT model is considered as satisfactory when NSE above 0.5 and PBIAS within ± 25% for the hydrological simulation and NSE above 0.45 and PBIAS within ± 55% for the sediment simulation are achieved.

LULC scenarios

Three LULC maps in 1997, 2003, and 2010 were used for this investigation (Fig. 2). The LULC data in 1997 were selected for the baseline period. The

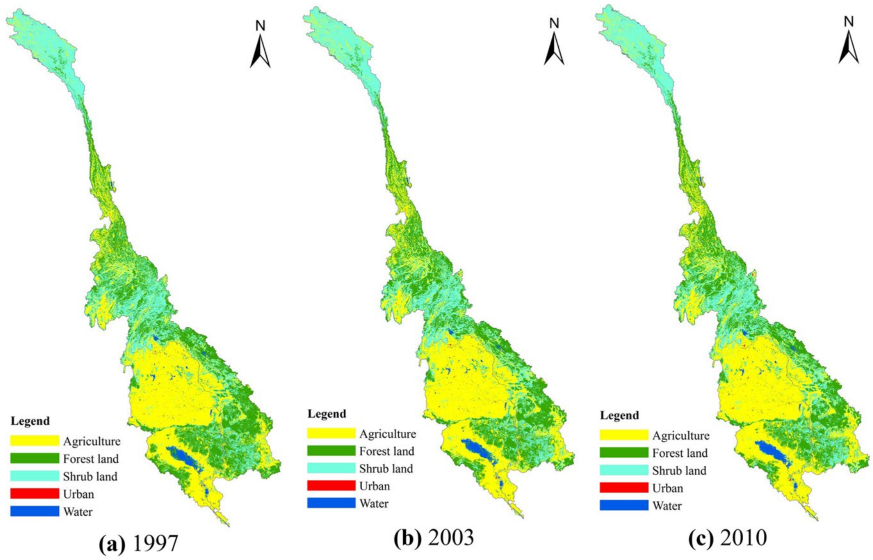

Fig. 2 LULC maps in **a** 1997, **b** 2003, and **c** 2010 for the Mekong RB

alterations of river discharge and sediment load due to LULC changes were calculated in reliance on differences in the simulation results of LULC in 2003 and 2010 to that in 1997.

Results and discussion

Analysis of historical LULC change

The historical LULC maps for the years of 1997, 2003, and 2010 are described in Fig. 2. The LULC maps categorize the Mekong RB into five LULC types, including forest land, agricultural land, shrub land, urban land, and water. Table 2 presents the total area of each LULC type for the study region in the years of 1997, 2003, and 2010. From the year 1997 to 2003, the forest land and shrub land were reduced by 1.36% and 0.21%, while agricultural land, urban land, and water were enlarged by 1.42%, 0.03%, and 0.13%, respectively. From 2003 to 2010, the forest land and shrub land were additionally reduced by 0.99% and 0.07%, while agricultural land, urban land, and water were further enlarged by 0.87%, 0.06%, and 0.13%, respectively. On the whole, the forest land and shrub land were decreased by 2.35% and 0.28%, and agricultural land, urban land, and water were increased by 2.29%, 0.09%, and 0.26%, respectively from 1997 to 2010. The conversion of forest land into agricultural and urban areas was mainly assignable to rapid population growth, urbanization, and economic development in the countries in the Mekong RB (Costa-Cabral et al., 2008). In addition, the rates of agricultural extension and deforestation were nearly identical during the study period. From Fig. 2, it is noted that the loss of forest land mainly happened in the lower downstream of the Mekong River in Cambodia. The finding of FAO (2015) indicates that the deforestation mainly occurred in Cambodia with the annual rate of approximately 1.2%, while

Table 2 LULC change in 1997, 2003, and 2010

LULC type	Area in 1997		Area in 2003		Area in 2010	
	km^2	%	km^2	%	km^2	%
Agricultural land	313,957	40.37	324,983	41.79	331,729	42.66
Forest land	225,898	29.05	215,336	27.69	207,622	26.70
Shrub land	220,918	28.41	219,252	28.19	218,709	28.12
Urban area	763	0.10	985	0.13	1481	0.19
Water	16,147	2.08	17,127	2.20	18,142	2.33

the afforestation happened in neighboring countries, including Laos, Thailand, and Vietnam. Generally speaking, the trend of LULC in the Mekong RB was conversion of forest land and shrub land to agriculture, urban land, and water surface in the period of 1997–2010.

SWAT calibration and validation for simulations of river discharge and sediment load

Performance of the SWAT model for the Mekong RB was assessed against observed data of river discharge during the period of 1983–2010 and sediment load during the period of 1995–2008. Table 3 shows the selected SWAT parameters for estimations of river discharge and sediment load and their fitted values in the calibration and validation steps.

Time series of daily river discharge plotted between daily observed and simulated data for seven hydrological stations (i.e., Chiang Sean, Luang Phrabang, Nakhon Phanom, Mukdahan, Pakse, Stung Treng, and Kratie) along the mainstream Mekong River are displayed in Fig. 3. In most cases, temporal variability in river discharge was reasonably reproduced by the calibrated SWAT model, except for some cases of high- and low-flow events. This can be attributable to the fact that the spatial distribution of rainfall is uneven and the effect of hydropower dams was not accounted for in the present study. Performance statistics of NSE and P_{BIAS} for the hydrological simulation as presented in Table 4 shows that the daily river discharge was satisfactorily simulated, with NSE > 0.67 and $P_{BIAS} < \pm 15\%$ for the calibration time period and NSE > 0.71 and $P_{BIAS} < \pm 20\%$ for the validation time period in all seven hydrological stations.

Time series of monthly sediment load plotted between monthly observed and simulated data for the three hydrological stations (i.e., Chiang Sean, Luang Phrabang, and Nakhon Phanom) are presented in Fig. 4. Temporal variability in sediment load was acceptable replicated by the model, with

Table 3 Calibrated values of SWAT hydrological and sediment parameters for the Mekong RB

No	Parameter		Initial range	Final value
Hydrological processes				
1	CN2	Initial SCS CN II value [a]	−0.5 to 0.5	0.054
2	ALPHA_BF	Baseflow alpha factor [b]	0 to 1	0.217
3	SFTMP	Snowfall temperature [b]	−5 to 5	−3.952
4	SOL_ALB	Moist soil albedo [a]	−0.25 to −0.09	−0.204
5	CH_K2	Channel effective hydraulic conductivity [b]	0 to 500	182.866
6	GWQMN	Threshold water depth in the shallow aquifer for flow [b]	0 to 5000	4234.075
7	ESCO	Soil evaporation compensation factor [b]	0 to 1	0.102
8	BIOMIX	Biological mixing efficiency [b]	0 to 1	0.971
9	SLUBBSN	Average slope length [a]	0.094 to 0.23	0.105
10	SMTMP	Snow melt base temperature [b]	−5 to 5	−4.565
11	SOL_Z	Soil depth [a]	−0.25 to 0.25	0.187
12	SMFMN	Melt factor for snow on December 21 [b]	0 to 10	9.023
13	SOL_AWC	Available water capacity [a]	−0.5 to 0.5	−0.363
14	EPCO	Plant uptake compensation factor [b]	0 to 1	0.370
15	GW_DELAY	Groundwater delay [b]	0 to 500	130.016
Sediment processes				
1	SPEXP	Linear re-entrainment parameter for channel sediment routing [b]	1 to 1.5	1.160
2	SPCON	Exponent of re-entrainment parameter for channel sediment routing [b]	0.001 to 0.01	0.0005
3	CH_EROD	Channel erodibility factor [b]	0 to 1	0.9244
4	CH_COV2	Channel cover factor [b]	0.001 to 1	0.0612
5	LAT_SED	Sediment concentration in lateral and groundwater flow [a]	−0.25 to 0.25	0.0772

[a]Parameter value is multiple by (1 + a given value)

[b]Parameter value is replaced by a given value

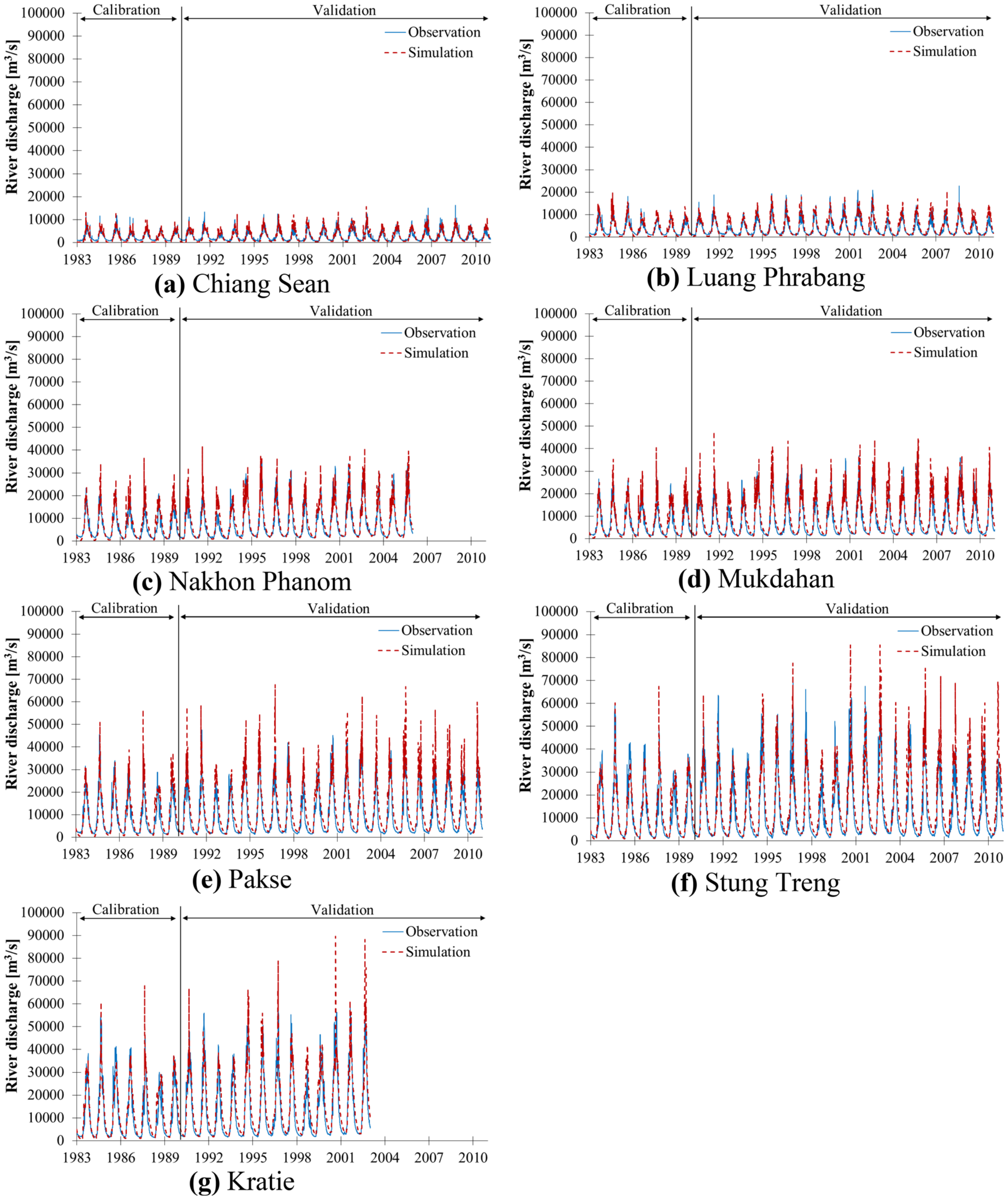

Fig. 3 Observed and simulated daily discharge for the calibration and validation time periods at seven gauging stations along the mainstream Mekong River

Table 4 Performance statistics of the SWAT model in simulating daily discharge during the calibration and validation time periods

Gauging station	Calibration			Validation		
	Period	*NSE*	P_{BIAS}	*Period*	*NSE*	P_{BIAS}
Chiang Sean	1983–1989	0.67	11.6%	1990–2010	0.71	−2.3%
Luang Phrabang	1983–1989	0.73	−1.7%	1990–2010	0.71	−19.7%
Nakhon Phanom	1983–1989	0.75	−14.3%	1990–2005	0.87	−3.2%
Mukdahan	1983–1989	0.82	−5.6%	1990–2010	0.81	−11.5%
Pakse	1983–1989	0.81	−11.3%	1990–2010	0.75	−24.4%
Strung Treng	1983–1989	0.86	−6.9%	1990–2010	0.80	−19.3%
Kratie	1983–1989	0.83	−14.4%	1990–2002	0.89	−14.8%

the exception of the peaks of sediment load during the flood season. This could be due to shortage and poor quality of sediment data (Kummu & Varis, 2007) and uncounted presence of hydropower dams. Before using the sediment data for the model calibration and validation, the results of data quality analysis show that there were no anomalous values and the percentage of missing data were less than 5% for the three hydrological stations. The poor quality of sediment data can be attributed to the fact that the samples are collected near the surface of river (approximately 0.3-m depth) using a bottle rather than a true sampler (Walling, 2008). The performance statistics as shown in Table 5 also suggests agreeable simulations of sediment load for the three hydrological stations in accordance with the "goodness of fit" criteria of Moriasi et al. (2007). Particularly, the NSE and P_{BIAS} values were within the ranges of 0.57 to 0.70 and 14.0 to 38.3% for the calibration time period, and 0.50 to 0.53 and 37.7 to 49.9% for the validation time period, respectively.

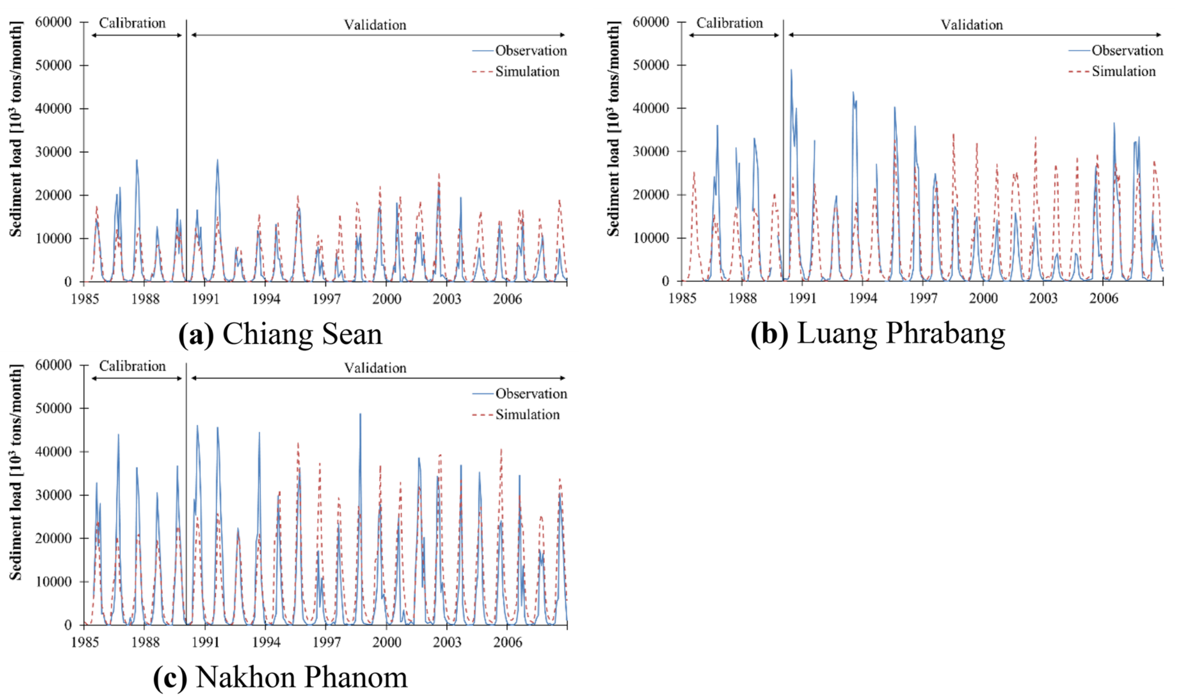

Fig. 4 Observed and simulated monthly sediment load for the calibration and validation time periods at seven gauging stations along the mainstream Mekong River

Table 5 Performance statistics of the SWAT model in simulating monthly sediment load during the calibration and validation time periods

Gauging station	Calibration			Validation		
	Period	*NSE*	P_{BIAS}	*Period*	*NSE*	P_{BIAS}
Chiang Sean	1985–1989	0.67	21.5%	1990–2008	0.52	−49.9%
Luang Phrabang	1985–1989	0.57	38.3%	1990–2008	0.50	−27.7%
Nakhon Phanom	1985–1989	0.70	14.0%	1990–2008	0.53	−34.0%

Generally speaking, the result of model calibration and validation evidences that the SWAT model could satisfactorily replicate the observed discharge and sediment load. The finding is in conformity with that of Sok et al. (2020). Consequently, it is appropriate to conclude that the calibrated SWAT model is trustworthy to simulate the soil and water processes in the Mekong RB, and this mode could be applied to investigate the LULC impacts on river discharge and sediment load.

Spatial contributions of river discharge and sediment load in the Mekong RB

Proportional contributions of each sub-basin to the Mekong River's river discharge and sediment load based on the calibrated SWAT model during 1983–2015 are illustrated in Fig. 5. In comparison to the outlet of the Mekong RB, the Chiang Sean sub-basin (upper Mekong RB to Chiang Sean) contributed 14.08% of annual river discharge and 24.02% of annual sediment load. Regarding the Mekong 1 (Chiang Sean to Vientiane), Mekong 2 (Vientiane to Pakse), and Mekong 3 (Pakse to Kratie) sub-basins, the contributions of river discharge to the Mekong flow were 18.04%, 19.07, and 7.56%, and the contributions of sediment load to the Mekong sediment flux are 23.24%, 7.76%, and 6.34%, respectively. Additionally, the Chi-Mun, 3S (Sesan, Sekong, and Srepok), and Tonle Sap sub-basins, which are main tributaries of the Mekong River, contributed 10.39%, 14.46%, and 10.15% of river discharge, and 11.15%, 18.46%, and 4.40% of sediment load, respectively. On the whole, the highest contributions of river discharge can be

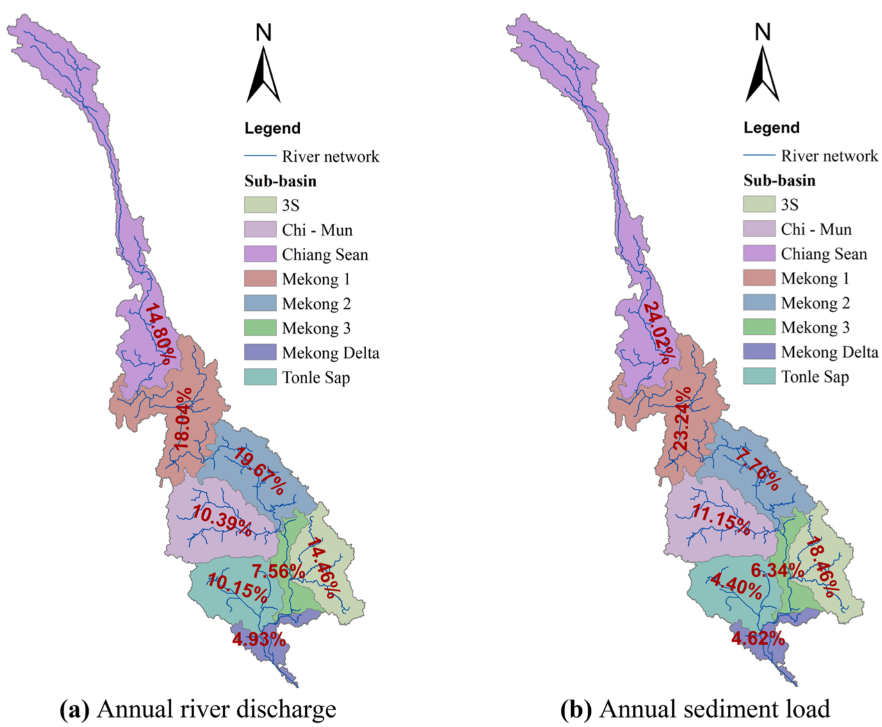

Fig. 5 Percent contributions of each sub-basin to the Mekong River's total river discharge and sediment load in the period of 1983–2015

found in Mekong 2 and 3S sub-basins. This is in line with the spatial distribution of annual rainfall in the Mekong RB. The high rainfall focuses on the regions in the left bank of Mekong River, including Laos and central highlands of Vietnam (Liu et al., 2020). In addition to meteorological factors, other factors influencing the sediment yield consist of LULC, topography, and soil. It is noted that in the Mekong 2 sub-basin in Laos, notwithstanding the highest contribution of river discharge, the contribution of sediment load was low because most of the highland region was covered by forest land. The largest contribution of sediment load was found in the Chiang Sean sub-basin because this region has high topography and steep slope.

Impact of historical land-cover changes on river discharge and sediment load

The river discharge and sediment load were simulated using the calibrated SWAT model, climate data during the period 1980–2015, and LULC conditions in 1997, 2003, and 2010. Compared to the baseline condition (climate data during 1983–2015 and LULC in 1997), the percent changes in river discharge and sediment load under the LULC conditions in 2003 and 2010 are displayed in Fig. 6. In the context of LULC changes, annual river discharge and sediment load had upward trends at all seven hydrological stations along the mainstream Mekong River during the period of 1983–2015. At the Kratie station (considered as the outlet of the Mekong RB), the annual river discharge and sediment load increased from 0.24 to 0.32% and 1.78 to 2.86%, respectively. The upward trends of river discharge and sediment load could be assigned to the extension of agricultural land and deforestation in the study region. Generally speaking, the sediment load has greater response to LULC change compared to the river discharge. This can be due to the fact that a power function is generally used to describe the relation between sediment load and river discharge (Azari et al., 2016). Additionally, the impacts of LULC changes on river discharge and sediment load of the Mekong RB are small.

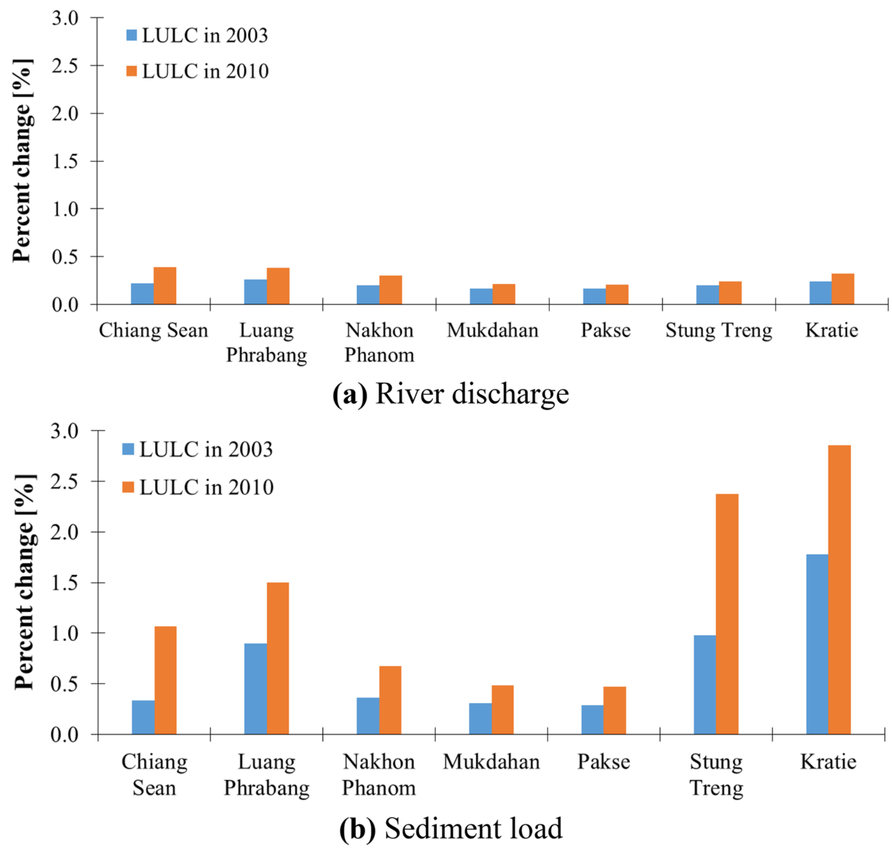

Fig. 6 Percent changes in **a** river discharge and **b** sediment load under the impacts of LULC changes

The Pearson correlation was also examined between changes in LULC classes and river discharge/sediment load. Results indicated that the agricultural land positively correlated with the river discharge and sediment load, with the Pearson's correlation coefficients of 0.453 and 0.327 at the significance level of 0.01, respectively. In addition, negative correlations of forest land with river discharge and sediment load were found (Pearson's correlation coefficients of 0.352 and 0.363 at the significance level of 0.01).

Discussion

Understanding the LULC impacts on hydrological processes is a prerequisite for development and implementation of land and water resource management plans. In this study, the impact of historical LULC changes on river discharge and sediment in the Mekong RB was investigated. LULC due to intensive agriculture and deforestation caused increases in river discharge and sediment load in the period 1980–2015. The upward trends of river discharge and sediment load as a consequence of agricultural expansion and deforestation were also acquired in other investigations in some parts of the study region (Khoi & Thom, 2015; Sayasane et al., 2016). Several published studies have also indicated upward trends of river discharge and sediment yield under the effect of LULC changes due to the agricultural expansion and deforestation (e.g., Chotpantarat & Boonkaewwan, 2018; Munoth & Goyal, 2020; Afonso et al., 2021). In addition, our finding is compatible with that of Wagner et al. (2016). They indicated that the LULC impacts on river discharge and sediment load are insignificant. Other results of our study are in accordance with the findings presenting that expansion of cultivated land can increase (Woldesenbet et al., 2017) and deforestation can increase streamflow and sediment yield (Mango et al., 2011), while afforestation can decrease streamflow and sediment yield (Öztürk et al., 2013).

In general, the results of this study on the impacts of agricultural expansion and deforestation on soil and water resources provide vital knowledge to further strengthen and manage the water and food security in the Mekong RB. Also, they seek to develop a basis for country-specific enhancement of water and land management and contribute useful implementations of strategic plans or action plans for sustainable management of the transboundary Mekong RB.

Conclusions

This study examined the responses of river discharge and sediment to historical LULC changes during the period 1980–2015 in the transboundary Mekong RB using the SWAT model. Generally, the SWAT model could replicate the observed river discharge and sediment load for the study region with satisfactory accuracy (NSE = 0.67 ÷ 0.89 for the daily streamflow simulation and NSE = 0.50 ÷ 0.70 for the monthly sediment simulation). In terms of LULC features in the Mekong RB in 1997, the forest land covered 29.05% of the basin, and the agricultural land covered 40.37%. Analysis of historical LULC changes, the forest land had the downward trend of 2.35% and agricultural land had the upward trend of 2.29% during the period 1997–2010. These changes were assigned to population growth, urbanization, and economic development in the countries in the study region. Under the impact of historical LULC changes, the river discharge and sediment load of the Mekong RB had upward trends of 0.24 to 0.32% and 1.78 to 2.86%, respectively during the period of 1980–2015. Furthermore, the river discharge and sediment load have positive correlation with agriculture and negative correlation with forest land at the significance level of 0.01. Results obtained from this study consequently are expected to have significant implications for efficient management of soil and water resources and aquatic biodiversity conservation in the Mekong RB. Future work will consider the effect of future LULC changes and uncertainties associated with the LULC projections on river discharge and sediment yield in the study region.

Author contribution TTS: investigation; formal analysis; visualization; writing—original draft; writing—review and editing. DNK: conceptualization; methodology; investigation; formal analysis; writing—review and editing; and paper administration.

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Declarations

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References

Abbaspour, K. C. (2015). *SWAT-CUP: SWAT calibration and uncertainty programs—A user manual*. Eawag: Swiss Federal Institute of Aquatic Science and Technology.

Afonso, E., de Oliveira, S., Madson Tavares, S., Thomás Rocha, F., et al. (2021). Impacts of land use and land cover changes on hydrological processes and sediment yield determined using the SWAT model. *International Journal of Sediment Research*. https://doi.org/10.1016/j.ijsrc.2021.04.002

Aghsaei, H., Mobarghaee Dinan, N., Moridi, A., et al. (2020). Effects of dynamic land use/land cover change on water resources and sediment yield in the Anzali wetland catchment, Gilan, Iran. *Science of the Total Environment, 712*, 136449. https://doi.org/10.1016/j.scitotenv.2019.136449

Azari, M., Moradi, H. R., Saghafian, B., & Faramarzi, M. (2016). Climate change impacts on streamflow and sediment yield in the North of Iran. *Hydrological Sciences Journal, 61*, 123–133. https://doi.org/10.1080/02626667.2014.967695

Bieger, K., Hörmann, G., & Fohrer, N. (2015). The impact of land use change in the Xiangxi Catchment (China) on water balance and sediment transport. *Regional Environmental Change, 15*, 485–498. https://doi.org/10.1007/s10113-013-0429-3

Borrelli, P., Robinson, D. A., Panagos, P., et al. (2020). Land use and climate change impacts on global soil erosion by water (2015–2070). *Proceedings of the National Academy of Sciences, 117*, 21994–22001. https://doi.org/10.1073/pnas.2001403117

Bosmans, J. H. C., van Beek, L. P. H., Sutanudjaja, E. H., & Bierkens, M. F. P. (2017). Hydrological impacts of global land cover change and human water use. *Hydrology and Earth System Sciences, 21*, 5603–5626. https://doi.org/10.5194/hess-21-5603-2017

Chotpantarat, S., & Boonkaewwan, S. (2018). Impacts of land-use changes on watershed discharge and water quality in a large intensive agricultural area in Thailand. *Hydrological Sciences Journal, 63*, 1386–1407. https://doi.org/10.1080/02626667.2018.1506128

Costa-Cabral, M. C., Richey, J. E., Goteti, G., et al. (2008). Landscape structure and use, climate, and water movement in the Mekong River basin. *Hydrological Processes, 22*, 1731–1746. https://doi.org/10.1002/hyp.6740

Eastham, J., Mpelasoka, F., Mainuddin, M., et al. (2008). *Mekong River Basin water resources assessment: Impacts of climate change*. Australia: Canberra.

FAO. (2011). *AQUASTAT transboundary river basins—Mekong River Basin*. Italy.

FAO. (2015). Global forest resources assessment 2015: Desk reference. New York, USA.

Gupta, H. V., Sorooshian, S., & Yapo, P. O. (1999). Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *Journal of Hydrologic Engineering, 4*, 135–143. https://doi.org/10.1061/(ASCE)1084-0699(1999)4:2(135)

Hwang, S.-A., Hwang, S.-J., Park, S.-R., & Lee, S.-W. (2016). Examining the relationships between watershed urban land use and stream water quality using linear and generalized additive models. *Water, 8*, 155. https://doi.org/10.3390/w8040155

IPCC. (2019). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. In press.

Jin, G., Wang, P., Zhao, T., et al. (2015). Reviews on land use change induced effects on regional hydrological ecosystem services for integrated water resources management. *Physics and Chemistry of the Earth, Parts A/B/C, 89–90*, 33–39. https://doi.org/10.1016/j.pce.2015.10.011

Khoi, D. N., & Thang, L. V. (2017). Climate change impacts on streamflow and non-point source pollutant loads in the 3S rivers of the Mekong Basin. *Water Environment Journal, 31*, 401–409. https://doi.org/10.1111/wej.12256

Khoi, D. N., & Thom, V. T. (2015). Impacts of climate variability and land-use change on hydrology in the period 1981–2009 in the central highlands of vietnam. *Global Nest Journal, 17*, 870–881.

Kim, I., Arnhold, S., Ahn, S., et al. (2019). Land use change and ecosystem services in mountainous watersheds: Predicting the consequences of environmental policies with cellular automata and hydrological modeling. *Environmental Modelling and Software, 122*, 103982. https://doi.org/10.1016/j.envsoft.2017.06.018

Kummu, M., & Varis, O. (2007). Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. *Geomorphology, 85*, 275–293. https://doi.org/10.1016/j.geomorph.2006.03.024

Lauri, H., Räsänen, T. A., & Kummu, M. (2014). Using reanalysis and remotely sensed temperature and precipitation data for hydrological modeling in monsoon climate: Mekong River case study. *Journal of Hydrometeorology, 15*, 1532–1545. https://doi.org/10.1175/JHM-D-13-084.1

Liu, L., Bai, P., Liu, C., et al. (2020). Changes in extreme precipitation in the Mekong Basin. *Advances in Meteorology, 2020*, 1–10. https://doi.org/10.1155/2020/8874869

Mango, L. M., Melesse, A. M., McClain, M. E., et al. (2011). Land use and climate change impacts on the hydrology of the upper Mara River Basin, Kenya: Results of a modeling study to support better resource management. *Hydrology and Earth System Sciences, 15*, 2245–2258. https://doi.org/10.5194/hess-15-2245-2011

Marhaento, H., Booij, M. J., & Hoekstra, A. Y. (2018). Hydrological response to future land-use change and climate change in a tropical catchment. *Hydrological Sciences Journal, 63*, 1368–1385. https://doi.org/10.1080/02626667.2018.1511054

Meynell, P.-J. (2017). Wetlands of the Mekong River basin, an overview. *The wetland book* (pp. 1–22). Springer.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., et al. (2007). Model evaluation guidelines for systematic quantification

of accuracy in watershed simulations. *Transactions of the ASABE, 50*, 885–900.
MRC. (2010). *State of the basin report 2010*. Lao PDR: Vientiane.
MRC. (2005). *Overview of the hydrology of the Mekong Basin*. Lao PDR: Vientiane.
Munoth, P., & Goyal, R. (2020). Impacts of land use land cover change on runoff and sediment yield of Upper Tapi River Sub-Basin, India. *International Journal of River Basin Management, 18*, 177–189. https://doi.org/10.1080/15715124.2019.1613413
Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models: Part I—A discussion of principles. *Journal of Hydrology, 10*, 282–290. https://doi.org/10.1016/0022-1694(70)90255-6
Neitsch, A. L., Arnold, J. G., Kiniry, J. R., et al. (2011). *Soil and water assessment tool theoretical documentation version 2009*. Texas A&M University.
Öztürk, M., Copty, N. K., & Saysel, A. K. (2013). Modeling the impact of land use change on the hydrology of a rural watershed. *Journal of Hydrology, 497*, 97–109. https://doi.org/10.1016/j.jhydrol.2013.05.022
Pandey, B. K., Khare, D., Kawasaki, A., & Meshesha, T. W. (2021). Integrated approach to simulate hydrological responses to land use dynamics and climate change scenarios employing scoring method in upper Narmada basin, India. *Journal of Hydrology, 598*, 126429. https://doi.org/10.1016/j.jhydrol.2021.126429
Piao, S., Friedlingstein, P., Ciais, P., et al. (2007). Changes in climate and land use have a larger direct impact than rising CO2 on global river runoff trends. *Proceedings of the National Academy of Sciences, 104*, 15242–15247. https://doi.org/10.1073/pnas.0707213104
Pokhrel, Y., Burbano, M., Roush, J., et al. (2018). A review of the integrated effects of changing climate, land use, and dams on Mekong River hydrology. *Water, 10*, 266. https://doi.org/10.3390/w10030266
Power, A. G. (2010). Ecosystem services and agriculture: Tradeoffs and synergies. *Philosophical transactions of the royal society B: biological sciences, 365*, 2959–2971. https://doi.org/10.1098/rstb.2010.0143
Rodríguez, R., Pastorini, M., Etcheverry, L., et al. (2021). Water-quality data imputation with a high percentage of missing values: A machine learning approach. *Sustainability, 13*, 6318. https://doi.org/10.3390/su13116318
Sayasane, R., Kawasaki, A., Shrestha, S., & Takamatsu, M. (2016). Assessment of potential impacts of climate and land use changes on stream flow: A case study of the Nam Xong watershed in Lao PDR. *Journal of Water and Climate Change, 7*, 184–197. https://doi.org/10.2166/wcc.2015.050
Shrestha, B., Cochrane, T. A., Caruso, B. S., & Arias, M. E. (2018). Land use change uncertainty impacts on streamflow and sediment projections in areas undergoing rapid development: A case study in the Mekong Basin. *Land degradation & development, 29*, 835–848. https://doi.org/10.1002/ldr.2831
Sok, T., Oeurng, C., Ich, I., et al. (2020). Assessment of hydrology and sediment yield in the Mekong River Basin using SWAT model. *Water, 12*, 3503. https://doi.org/10.3390/w12123503
Tan, M. L., Gassman, P. W., Yang, X., & Haywood, J. (2020). A review of SWAT applications, performance and future needs for simulation of hydro-climatic extremes. *Advances in Water Resources, 143*, 103662. https://doi.org/10.1016/j.advwatres.2020.103662
Wagner, P. D., Bhallamudi, S. M., Narasimhan, B., et al. (2016). Dynamic integration of land use changes in a hydrologic assessment of a rapidly developing Indian catchment. *Science of the Total Environment, 539*, 153–164. https://doi.org/10.1016/j.scitotenv.2015.08.148
Walling, D. E. (2008). The changing sediment load of the Mekong River. *Ambio, 37*, 150–157.
Woldesenbet, T. A., Elagib, N. A., Ribbe, L., & Heinrich, J. (2017). Hydrological responses to land use/cover changes in the source region of the Upper Blue Nile Basin, Ethiopia. *Science of the Total Environment, 575*, 724–741. https://doi.org/10.1016/j.scitotenv.2016.09.124
Woldesenbet, T. A., Elagib, N. A., Ribbe, L., & Heinrich, J. (2018). Catchment response to climate and land use changes in the Upper Blue Nile sub-basins, Ethiopia. *Science of the Total Environment, 644*, 193–206. https://doi.org/10.1016/j.scitotenv.2018.06.198
Worku, T., Khare, D., & Tripathi, S. K. (2017). Modeling runoff–sediment response to land use/land cover changes using integrated GIS and SWAT model in the Beressa watershed. *Environment and Earth Science, 76*, 550. https://doi.org/10.1007/s12665-017-6883-3
Zhao, G., Kondolf, G. M., Mu, X., et al. (2017). Sediment yield reduction associated with land use changes and check dams in a catchment of the Loess Plateau, China. *CATENA, 148*, 126–137. https://doi.org/10.1016/j.catena.2016.05.010