Assessing the Impacts of Land Use and Land Cover Changes on Sediment Yield Using the SWAT Model: A Case Study in the Khlong Bang Yai Watershed, Phuket Island, Thailand

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DOI: https://doi.org/10.52939/ijg.v21i5.4161

Abstract
Land use and land cover (LULC) changes are among the most significant landscape transformations globally, reflecting the dynamic interaction between human activities and Earth's surface processes. Phuket Island, Thailand, exemplifies a region experiencing rapid LULC changes driven by tourism and economic growth, with notable impacts on sediment yield. This study aimed to assess and quantify the LULC changes within the Khlong Bang Yai watershed, Phuket Island, estimate sediment yield, and evaluate the impacts of LULC changes on sediment yield. LULC data from 2002 and 2019 were analyzed using a post-classification comparison approach. A Digital Elevation Model (DEM), stream network, slope, soil, and daily weather data were used to parameterize the SWAT model, which estimated sediment yield under dry (2018–2019) and wet (2016–2017) conditions. Results showed urban and built-up areas expanded from 22.71% in 2002 to 36.71% in 2019, while evergreen forest declined from 25.85% to 21.10%. Sediment yield increased by 16% under dry conditions and by 638% under wet conditions, especially in subwatersheds where evergreen forest was converted to perennial trees and orchards and urban and built-up area. The SWAT model showed strong performance (NSE = 0.75–0.84, RSR = 0.4–0.5, PBIAS < 20%). Correlation analysis indicated negative relationships between evergreen forest and sediment yield (r = –0.409 dry; –0.739 wet), and positive correlations with perennial trees and orchards (r = 0.744 dry; 0.845 wet). Urban and built-up area showed strong negative correlations in low-elevation zones (r = –0.972 dry; –0.868 wet). These findings highlight the role of LULC changes in influencing runoff-driven sediment processes. The results support targeted strategies such as reforestation to address forest loss, riparian buffers and sediment basins for erosion control, slope stabilization in uplands, and improved drainage and zoning to reduce flooding, promoting watershed sustainability in Phuket's rapidly urbanizing and environmentally sensitive landscape.

Keywords: LULC Change, Phuket Island, Sediment Yield, SWAT Model, Watershed

1. Introduction

Phuket Island is a major tourism destination in Thailand, currently facing significant environmental challenges due to land use and land cover (LULC) changes, particularly for the construction of tourism-related infrastructure. Several studies have examined LULC changes in Phuket, revealing substantial deforestation and urban expansion. Previous research documented more than a threefold increase in the rate of forest loss (sq.km/year) between 2000–2011 compared to 1989–2000, indicating an accelerating rate of deforestation [1]. Similarly, other studies examined post-Tsunami land use transformations, highlighting rapid urban expansion at the expense of conservation areas and water bodies [2]. Research utilizing remote sensing techniques has also analyzed vegetation changes, revealing a decline in vegetative cover, particularly in Amphoe Kathu, due to urban encroachment [3].

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Additional studies identified key deforestation hotspots using geospatial modeling [4], while recent findings reported an increase in built-up areas from 125.32 km² in 2014 to 141.64 km² in 2019 [5], reflecting the ongoing conversion of natural landscapes into urban spaces. Globally, LULC changes have been widely studied for their impacts on sediment yield, particularly in rapidly urbanizing regions. In Thailand, the tourism-driven urbanization of Phuket highlights the need for a focused analysis of its watersheds, such as Khlong Bang Yai. Studies from similar tourism-driven regions, such as Bali's Sarbagita areas [6], Turkey's Fethiye-Göcek region [7], and China's Changhai County [8], demonstrate that urban expansion frequently occurs at the expense of natural landscapes and agricultural lands, underscoring the need for sustainable land-use planning.

Within Phuket, the Khlong Bang Yai watershed represents a critical ecological system under increasing pressure from urbanization. The Bang Yai Canal, originating in the Kathu District and flowing through Vichit and Rasada communities before discharging into the Andaman Sea [9], is experiencing significant environmental changes. These include deforestation, hillside construction, and the conversion of natural vegetation into agricultural and impervious surfaces, leading to increased soil erosion and flooding risks. Heavy rainfall further exacerbates these issues by intensifying runoff and sediment deposition in low-lying areas, contributing to water quality degradation [10] and 11].

Previous research has provided valuable insights into specific aspects of these challenges. Prior studies have examined sediment accumulation [12], assessed water quality degradation [13], and investigated heavy metal contamination in sediments [14]. While these studies offer useful information, they do not explicitly address sediment yield dynamics in the context of rapid LULC changes within Phuket's tourism-driven regions. This study addresses this gap by leveraging SWAT modeling to quantify sediment yield and its relationship to LULC transformations. Among available methodological approaches for analyzing watershed dynamics, the Soil and Water Assessment Tool (SWAT) is particularly suitable for simulating runoff and sediment yield under different land-use scenarios. This physically-based distributed hydrological model has been extensively validated worldwide for such applications, offering robust capabilities for scenario studies and mechanistic understanding of land-use impacts [15][16] and [17]. This study aims to assess and quantify LULC changes within the Khlong Bang Yai watershed using GIS and the SWAT model and evaluate the impacts of LULC changes on sediment yield under dry and wet conditions. Specifically, the research objectives are to (1) Assess and quantify LULC changes within the watershed using GIS and remote sensing techniques. (2) Estimate sediment yield using the SWAT model under dry and wet conditions. (3) Evaluate the impacts of LULC changes on sediment yield. The findings are expected to contribute to improved watershed management strategies by providing specific solutions to key environmental challenges in Phuket. To address forest encroachment, the study will propose targeted reforestation and land-use zoning strategies. For flooding, hydrological modeling will inform the development of flood mitigation measures such as retention basins, improved drainage systems, and slope stabilization in upland areas. In response to sediment accumulation, recommendations will focus on soil erosion control practices, including riparian buffer restoration and sediment retention structures. These solutions will support sustainable land and water resource planning, ensuring long-term ecological and economic resilience in Phuket's rapidly urbanizing landscape.

2. Methodology

2.1 Study Area

The Khlong Bang Yai watershed, located on Phuket Island in southern Thailand (Figure 1), covers about 5,502.5 hectares (55.03 km²). The Bang Yai Canal is the main waterway in this area. Originating in Kathu District, it flows through the plains around Mueang Phuket District, passing through important communities such as Vichit Community and Rasada Community. The 20-kilometer-long canal flows into the Andaman Sea on the eastern side of Phuket Island [9]. The Khlong Bang Yai watershed's topography consists of hills and plains, with elevations ranging from 9 meters to 539 meters above mean sea level. Half (50.97%) of the watershed is primarily composed of flat and slightly undulating terrain, while the remaining 46.65% is primarily hilly and steep. The average annual rainfall for the watershed from 2002 to 2011 was approximately 2,350 mm, with an average annual temperature of approximately 28.1 degrees Celsius [18] and [19].

2.2 Data

The data required for the SWAT model, including digital elevation model (DEM), weather, observed sediment yield, land use and land cover (LULC), and soil data. All datasets were collected and prepared prior to model implementation (Table 1).

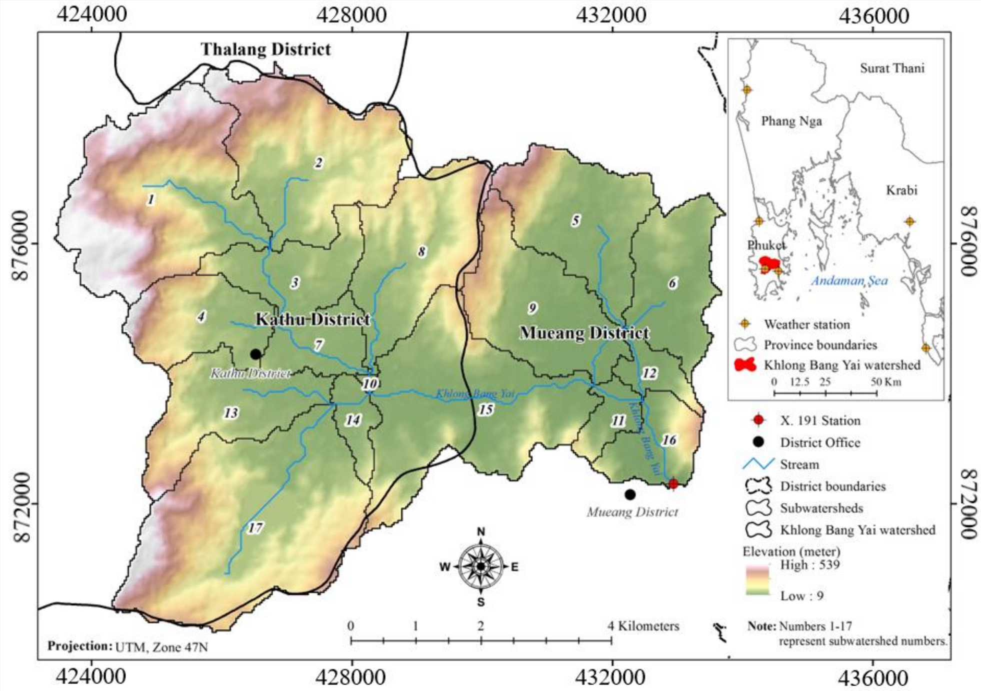

Figure 1: Location map of the Khlong Bang Yai Watershed, Phuket Island, Thailand

Table 1: List of data collection

Data	Source
1. Digital elevation model	The United States Geological Survey
2. LULC data	
2.1 LULC data in 2002 and 2014	[4]
2.2 LULC data in 2019	[5]
3. Soil data	Land Development Department
4. Daily weather data between 1998 and 2019	Thai Meteorological Department and Southern Region Irrigation Hydrology Center, Royal Irrigation Department
5. Daily sediment observed between 2013 and 2019	Region Irrigation Hydrology Center, Royal Irrigation Department
6. Stream networks data	Department of Climate Change and Environment
7. Administrative boundary	Department of Climate Change and Environment

The DEM, with a spatial resolution of 30 meters was obtained from the Shuttle Radar Topography Mission (SRTM) provided by the United States Geological Survey and was used for watershed delineation. Watershed delineation refers to the process of defining the boundary of a watershed, also known as a subwatershed, drainage basin, or river basin. Slope classification was generated using five slope percentage classes (see Appendix A: Table A.1) based on the standard classification from the Land Development Department. LULC data for the years 2002, 2014, and 2019 were obtained from previous studies by [4] and [5]. Soil data were sourced from the Land Development Department (see Appendix A: Table A.2). These spatial datasets were essential for generating the hydrologic response units (HRUs) within each subwatershed. Daily weather data, including precipitation, temperature, solar radiation, wind speed, and relative humidity, were collected from six meteorological stations: Phuket, Phuket Airport, Bang Wad, Krabi, Ko Lanta, and Takua Pa (Figure 1). These data, covering the period from 1998 to 2019, were obtained from the Thai Meteorological Department and the Southern Region Irrigation Hydrology Center, Royal Irrigation Department. Observed daily sediment data from the X.191 station (Figure 1) were acquired from the Southern Region Irrigation Hydrology Center for the period 2013-2019. Additionally, stream network and administrative boundary data were obtained from the Department of Climate Change and Environment.

2.3 Research Methodology

The research methodology workflow (input, process, and output) consists of three components: LULC assessment and change, sediment yield estimation, and the impact of LULC change on sediment yield. These components are displayed in Figure 2.

2.3.1 LULC assessment and LULC change

In this study, the LULC classes consisted of (1) urban and built-up areas (city and commercial, institutional land, industrial land, poultry farms, houses, airport, and seaport), (2) field crops and horticulture, (3) perennial trees and orchards, (4) aquaculture areas, (5) idle land, (6) evergreen forests, (7) scrub forests, (8) water bodies (natural and artificial), and (9) miscellaneous land (beaches, soil pits, laterite pits, and landfill). Firstly, LULC status in 2002 and 2019 was assessed using visual interpretation techniques in ArcGIS software. Secondly, LULC changes during the period were evaluated using a post-classification comparison change detection algorithm in ERDAS IMAGINE software.

2.3.2 Sediment yield estimation

In this study, sediment yield in the Khlong Bang Yai watershed was estimated using the optimized water yield parameter from a previous study in the same area [20], which served as the initial input, as shown in Table 2. The initial parameter was further validated to ensure its reliability in estimating sediment yield under both dry and wet conditions. This approach aligns with the general principle that well-calibrated and validated water yield parameters enhance the reliability of sediment yield predictions, supporting broader applications in watershed management [21][22][23] and [24].

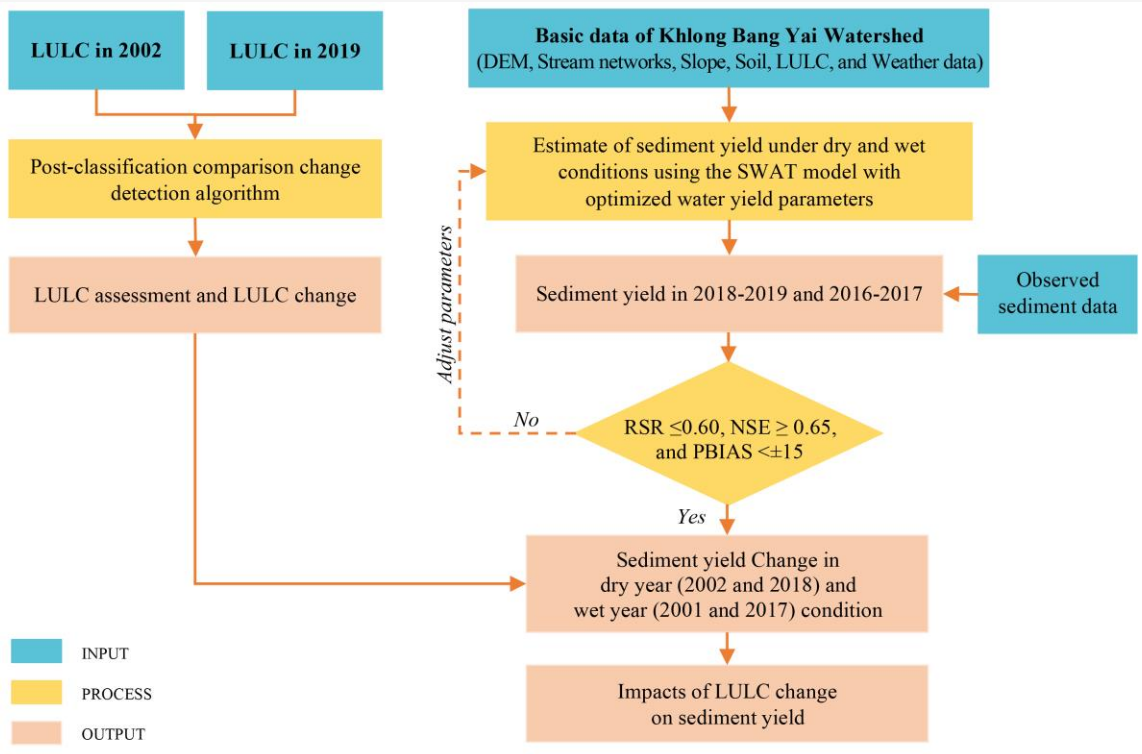

Figure 2: Impacts of LULC changes on sediment yield study workflow

Table 2: Optimum parameter values for water yield estimation under the dry and wet year conditions [20]

Parameter	Definition	Range	Optimum parameter	
			Dry year condition	Wet year condition
SOL_AWC[a]	Available water capacity of the soil layer	0-1	0.19-0.30	0.05-0.16
ESCO	Soil evaporation compensation factor	0-1	0.80	0.96
CN2[b]	Curve number at moisture condition II	30-100	30-68	30-85
GW_REVAP	Groundwater revap coefficient	0-1	0.050	0.157

Note: [a] Varies with soil type, [b] Varies with land use, soil and slope.

The parameters used were derived from previous research [20] on water yield, and a sensitivity analysis was conducted to identify the most influential factors affecting streamflow prediction in the watershed. Model calibration and validation were performed using monthly streamflow data from the X.191 station. Model performance was assessed using RMSE, RSR, NSE, and PBIAS, with threshold values of ≤ 0.60, ≥ 0.65, and ≤ ±15, respectively, following [25]. The optimum local parameter of the SWAT model demonstrated at least good model performance under both dry and wet conditions during the calibration and validation periods.

Four parameters, as shown in Table 2, including Available water capacity of the soil layer, soil evaporation compensation factor, Curve number at moisture condition II, and groundwater revap coefficient, play a critical role in hydrological processes, particularly in regulating soil moisture dynamics, surface runoff generation, and groundwater interactions. Available water capacity of the soil layer (SOL_AWC) refers to the soil's capacity to retain water for plant utilization, which depends on soil properties across different depths and locations within the basin [26] and [27]. The SOL_AWC value was set higher in dry years (0.19-0.30) than in wet years (0.05-0.16). The vadose zone is generally thicker in dry years due to lower groundwater levels, leading to higher water retention capacity [28]. The soil evaporation compensation factor (ESCO) regulates how soil moisture is distributed to meet evaporative demand, affecting both baseflow and surface runoff [27]. ESCO values were set at 0.80 for dry conditions and 0.96 for wet conditions. A higher ESCO value in wet years suggests that less water is drawn from deeper soil layers, while in dry years, more water is extracted to compensate for increased evaporative demand [29]. The curve number (CN2), a key factor in surface runoff estimation, depends on soil type, land use, land cover, and antecedent soil moisture [27]. CN2 values were lower in dry years (30-68) than in wet years (30-85), indicating that higher runoff was expected in wet conditions due to increased rainfall. The groundwater "revap" coefficient (GW_REVAP) controls water transfer from the shallow aquifer to the root zone, particularly during dry periods. This coefficient significantly influences capillary water movement [27]. GW_REVAP was set at 0.050 in dry years and 0.157 in wet years, suggesting that groundwater contributes more to baseflow under wet conditions than under dry conditions.

In this study, the validated optimum water yield parameter from a previous study [20] was used to ensure reliability in estimating sediment yield under both dry and wet conditions, utilizing monthly observed sediment data from Station X.191. Dry and wet years were classified based on the long-term average annual runoff. Specifically, the mean annual runoff recorded at Station X.191 from 1999 to 2019 served as the threshold: years with runoff exceeding this average were classified as wet years, while those with lower runoff were classified as dry years [20]. The following approach was taken: For dry conditions (2018-2019), sediment yield estimates were based on LULC data from 2019, soil, and slope characteristics for each subwatershed. Weather data from 2015 to 2019 was used for model operation, including a three-year warm-up period (2015-2017). The warm-up period is commonly used to allow the model to adjust and stabilize before analyzing data, such as soil moisture and groundwater accumulation, reaching equilibrium. Generally, a 3-year period is recommended [21]. Similarly, for wet conditions (2016-2017), LULC data from 2014, soil, and slope characteristics were used along with weather data from 2013 to 2017, including a warm-up period from 2013 to 2015 to estimate sediment yield. After acquiring all necessary input data, the characteristics of the subwatersheds and hydrologic response units (HRUs) were calculated and employed for sediment yield estimation.

In practice, the HRU was first generated based on LULC, soil, and slope data in the subwatersheds, as shown in Figure 3. The multiple HRU definition was created using a combination of 20 percent land use, 10 percent soil, and 20 percent slope threshold [20]. After that, the required weather data between 1998 and 2019 were extracted from six weather stations. Then, the sediment yield for each HRU was then estimated using the Modified Universal Soil Loss Equation (MUSLE), as expressed in Equation 1:

$$S_y = a\left(Qq_p\right)^b KLSCP$$

Equation 1

Where: S_y is sediment yield (t) event for the entire subwatershed; Q is the runoff volume (m^3); q_p is the peak runoff rate (m^3s^{-1}); and K, L, S, C and P represent the soil erodibility factor ($t \cdot ha \cdot h \cdot MJ^{-1} mm^{-1}$), slope length factor, slope steepness factor, cover management factor, and support practice factor, respectively, similar to those used in the Universal Soil Loss Equation (USLE). Parameters a and b are empirical coefficients specific to the location where the MUSLE was developed, with values of 11.8 and 0.56, respectively [30]. The Modified Universal Soil Loss Equation (MUSLE) improves sediment yield estimation by replacing the rainfall factor in the Universal Soil Loss Equation (USLE) with a runoff-based factor.

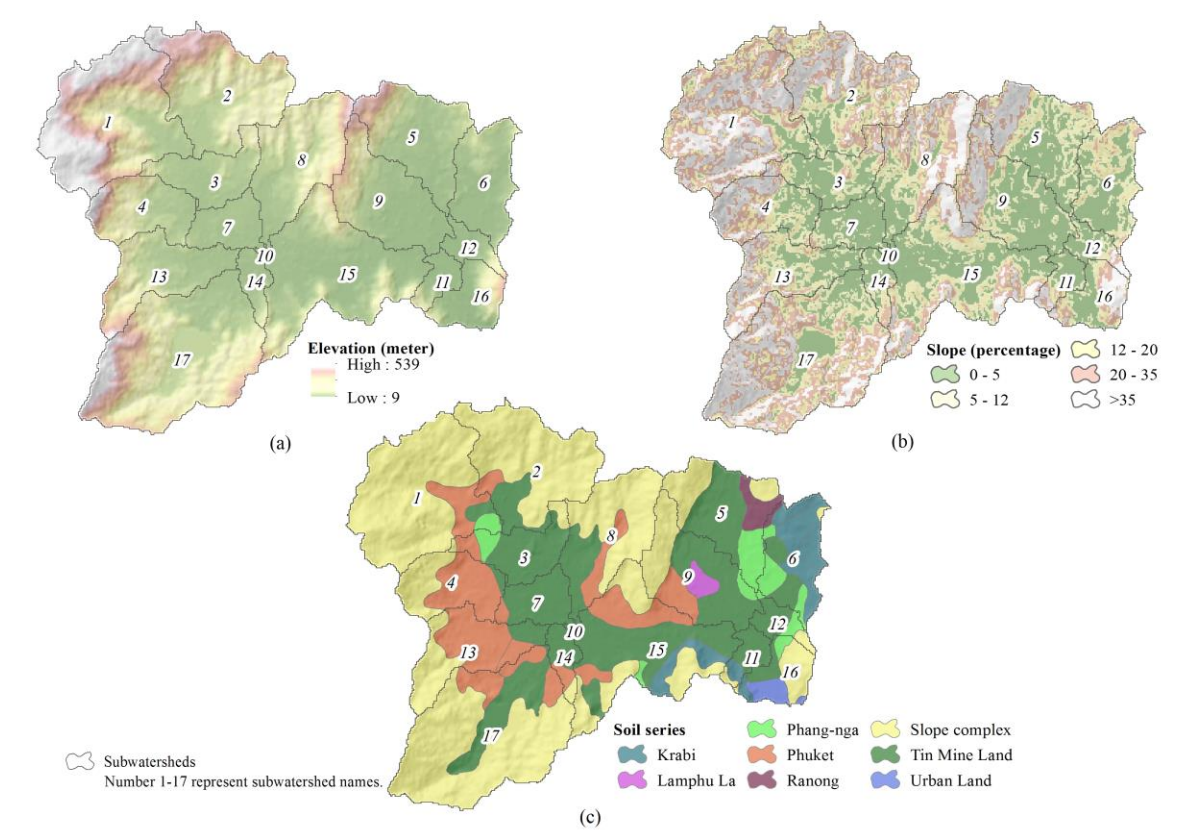

Figure 3: The spatial data for generate the hydrologic response units (HRUs): (a) DEM, (b) Slope, (c) Soil

Table 3: Model performance scale [25]

Performance rating	Model performance measurement indicator		
	RSR	NSE	PBIAS
Very good	0.00 < RSR < 0.50	0.75 < NSE < 1.00	PBIAS < ± 15
Good	0.50 < RSR < 0.60	0.65 < NSE < 0.75	±15 < PBIAS < ± 30
Satisfactory	0.60 < RSR < 0.70	0.50 < NSE < 0.65	±30 < PBIAS < ± 55
Unsatisfactory	RSR >0.70	NSE <0.50	PBIAS > ± 55

This enhances accuracy across dry and wet years, as runoff volume and peak flow better represent erosion processes. In wet years, increased runoff energy amplifies sediment transport, while in dry years, lower runoff limits mobilization. By focusing on runoff energy, MUSLE provides a more reliable, event-based sediment estimation across varying hydrological conditions. The performance of the model in estimating sediment yield was evaluated using several statistical metrics. These included the RMSE-observations standard deviation ratio (RSR) [31], with an acceptable threshold of ≤0.60, the Nash-Sutcliffe efficiency (NSE) [32], where a value of ≥0.65 indicates satisfactory model performance, and percent bias (PBIAS) [33], which assesses the model's tendency to overestimate or underestimate observed values, with an acceptable threshold of ≤±30. The equations used to calculate RSR, NSE, and PBIAS are provided in Appendix B. The model's efficiency was assessed based on these statistical metrics, and their performance was rated according to [25], as summarized in Table 3.

2.3.3 Evaluation of LULC change impacts on sediment yield

The evaluation focused on assessing the impacts of LULC change on sediment yield under two contrasting hydrological conditions: dry and wet years. The dry year condition was evaluated from the years 2002 and 2018. In the practice, the sediment yield in 2002 was estimated based on LULC data in 2002, soil, and slope characteristics of each subwatershed.

The weather data from 1999 to 2002 were extracted and used for model operation, with a three-year warm-up period from 1999 to 2001. Meanwhile, the sediment yield in 2018 was estimated based on LULC data in 2019, soil, and slope characteristics of each subwatershed. The weather data from 2015 to 2018 were extracted and used for model operation, with a three-year warm-up period from 2015 to 2017. In contrast, the wet year condition was evaluated from the years 2001 and 2017. In the practice, the sediment yield in 2001 was estimated based on LULC data in 2002, soil, and slope characteristics of each subwatershed. The weather data from 1998 to 2001 were extracted and used for model operation, with a three-year warm-up period from 1998 to 2000.

Meanwhile, the sediment yield in 2017 was estimated based on LULC data in 2019, soil, and slope characteristics of each subwatershed. The weather data from 2014 to 2017 were extracted and used for model operation, with a three-year warm-up period from 2014 to 2016. After acquiring all necessary input data, the characteristics of the subwatersheds and HRUs were calculated. These characteristics were then employed in the sediment yield estimations. To isolate the effects of hydrological variability from land use change, hydrologically representative years were matched with consistent LULC datasets: 2001–2002 (LULC data in 2002) and 2017–2018 (LULC data in 2019). This approach minimized confounding factors and enabled a more accurate attribution of sediment yield variations to differences in runoff dynamics. Finally, the impact of LULC change was assessed by comparing sediment yield estimates between baseline (LULC data in 2002) and changed (LULC data in 2019) conditions under both dry and wet years.

3. Results and Discussion

3.1 LULC Assessment and Change between 2002 and 2019

The area and percentage of LULC data in 2002 and 2019 are summarized in Table 4, while the spatial distribution of LULC maps in the study period are displayed in Figure 4. As results, the top three most dominant LULC types in 2002 are evergreen forest, urban and built-up area, and perennial trees and orchards, which covers the area of 1,422.50 ha or 25.85%, 1,249.75 ha or 22.71% and 1,240.00 ha or 22.54%, respectively. At the same time, the top three most dominant LULC types in 2019 are still urban and built-up area, perennial trees and orchards, and evergreen forest, which cover the area of 2,019.75 ha or 36.71%, 1,279.25 ha or 23.25% and 1,161.00 ha or 21.10%, respectively.

In the meantime, the transitional change matrix of LULC change between 2002 and 2019 is presented in Table 5. As a result, the most dominant LULC types that increased were urban and built-up areas and perennial trees and orchards. In contrast, the most dominant LULC types that decreased were idle land, evergreen forest, and scrub forest.

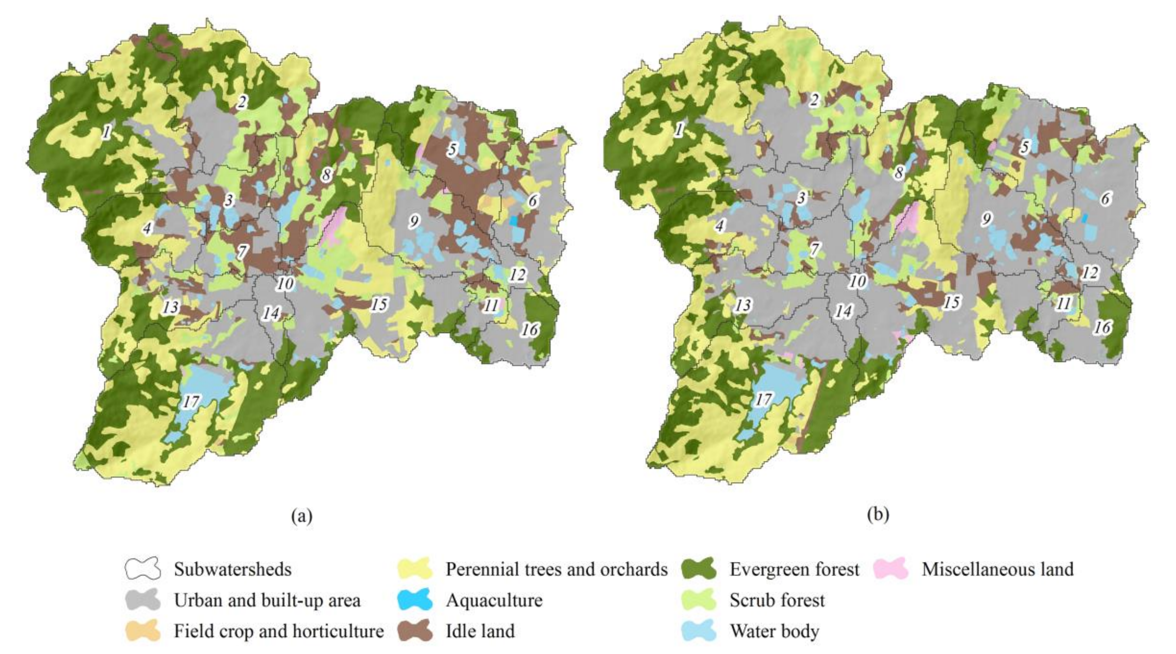

Figure 4: Spatial distribution of LULC classification in 2002(a) and 2019(b)

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Table 4: Area and percentage of LULC data in 2002 and 2019

No	LULC type	LULC data in 2002		LULC data in 2019		Change	
		Area in ha	Percent	Area in ha	Percent	Area in ha	Percent
1	Urban and built-up area	1,249.75	22.71	2,019.75	36.71	770.00	61.61
2	Field crop and horticulture	9.75	0.18	1.50	0.03	-8.25	-84.62
3	Perennial trees and orchards	1,240.00	22.54	1,279.25	23.25	39.25	3.17
4	Aquaculture	2.50	0.05	1.25	0.02	-1.25	-50.00
5	Idle land	716.75	13.03	390.00	7.09	-326.75	-45.59
6	Evergreen forest	1,422.50	25.85	1,161.00	21.10	-261.50	-18.38
7	Scrub forest	586.25	10.65	399.50	7.26	-186.75	-31.86
8	Waterbody	244.00	4.43	218.25	3.97	-25.75	-10.55
9	Miscellaneous land	31.00	0.56	32.00	0.58	1.00	3.23
	Total	**5,502.5**	**100**	**5,502.5**	**100**		

Table 5: LULC change between 2002 and 2019 as a transitional matrix

	LULC types	LULC in 2019 (ha)									
		Ur	Fch	Po	Aq	Id	Ef	Sf	Wa	Mi	Total
LULC in 2002 (ha)	Urban and built-up area (Ur)	**1,206.25**	-	5.25	0.25	7.50	9.50	7.75	12.50	0.75	**1,249.75**
	Field crop and horticulture (Fch)	9.00	**0.75**	-	-	-	-	-	-	-	**9.75**
	Perennial trees and orchards (Po)	172.25	-	**973.00**	-	32.25	49.25	11.00	0.75	1.50	**1,240.00**
	Aquaculture (Aq)	1.50	-	-	**1.00**	-	-	-	-	-	**2.50**
	Idle land (Id)	323.75	0.25	58.50	-	**228.25**	9.25	83.50	13.25	-	**716.75**
	Evergreen forest (Ef)	44.00	0.50	212.25	-	31.75	**1,069.25**	51.75	5.50	7.50	**1,422.50**
	Scrub forest (Sf)	218.50	-	29.00	-	72.25	16.50	**237.00**	7.25	5.75	**586.25**
	Water body (Wa)	33.50	-	0.75	-	18.00	6.50	6.00	**179.00**	0.25	**244.00**
	Miscellaneous land (Mi)	11.00	-	0.50	-	-	0.75	2.50	-	**16.25**	**31.00**
	Total	**2,019.75**	**1.50**	**1,279.25**	**1.25**	**390.00**	**1,161.00**	**399.50**	**218.25**	**32.00**	**5,502.50**

The increasing of urban and built-up areas in 2019 are mostly converted from idle land (323.75 ha) scrub forest (218.50 ha) and perennial trees and orchards (172.25 ha) in 2002. In the meantime, the increasing of perennial trees and orchards areas in 2019 are converted from the evergreen forest (212.25 ha) idle land (58.50 ha) and scrub forest (29.00 ha) in 2002.

In contrast, areas of idle land in 2002 are mostly converted into urban and built-up areas (323.75 ha), scrub forest (83.50 ha), and perennial trees and orchards (58.50 ha) in 2019. Likewise, evergreen forest in 2002 are converted into the perennial trees and orchards (212.25 ha), scrub forest (51.75 ha), and urban and built-up area (44.00 ha) in 2019. Similarly, areas of scrub forest in 2002 are converted into urban and built-up area (218.50 ha), idle land (72.25 ha), and perennial trees and orchards (29.00 ha) in 2019. The expansion of urban and built-up areas in the Khlong Bang Yai watershed has encroached upon idle land, scrub forest, and perennial tree and orchard areas. This growth is likely driven by government policies promoting tourism in Phuket province, which have spurred the development of infrastructure and accommodations to support the increasing number of visitors. As a result, natural and agricultural lands have been converted into urbanized areas. Notable developments reflecting this urban growth include educational institutions, commercial centers, and numerous housing estates.

In addition, urban growth contributes to channel encroachment, causing water way to become narrower and shallower [11]. This phenomenon is similar to what has been documented in several tourist destinations around the world. The development of tourism has often led to substantial changes in LULC, with natural habitats such as forests, vegetation, and water bodies being converted into built-up areas and urban infrastructure. While tourism can contribute to economic growth, it is essential to have comprehensive planning and the integration of local, national, and regional policies to mitigate the adverse environmental impacts and promote sustainable tourism development [6] [7] and [8].

3.2 Sediment Yield Estimation for Dry and Wet Year Conditions

In this study, sediment yield was estimated using the Modified Universal Soil Loss Equation (MUSLE), integrated within the SWAT model framework and parameterized with an optimal water yield parameter set validated in a previous study [20].

The model revealed distinct sediment yield patterns under dry and wet year conditions, with estimated values of 8,658.00 tons for dry years (2018–2019) and 23,818.69 tons for wet years (2016–2017). Model performance was evaluated by comparing simulated sediment yields with observed data from the X.191 gauging station using standard performance metrics, including the RMSE-observations standard deviation ratio (RSR), Nash–Sutcliffe Efficiency (NSE), and Percent Bias (PBIAS), as shown in Table 3. The results, presented in Table 6 and illustrated in Figure 5, demonstrate the model's reliability and its capability to simulate sediment transport under dry and wet year conditions. For the dry year condition, RSR, NSE, and PBIAS values were 0.50, 0.75, and 17.18, respectively, indicating very good model performance for RSR and NSE, and good performance for PBIAS based on the model performance scale [25]. Similarly, the wet year condition yielded RSR, NSE, and PBIAS values of 0.40, 0.84, and 18.80, respectively, also classified as very good for RSR and NSE and good for PBIAS. These findings confirm that the SWAT model, when applied with calibrated local water yield parameters, performs reliably in estimating sediment yield under dry and wet year conditions. This aligns with the conclusion by [21], which emphasizes that streamflow is a primary driver of hydrologic response. Furthermore, the results are supported by previous research highlighting the importance of accurately calibrating and validating streamflow parameters in improving sediment yield simulations. This integrated modeling approach enhances the robustness and reliability of watershed-scale sediment assessments, which is critical for effective watershed management and erosion control planning [22] [23] and [24].

However, the PBIAS values for both dry (17.18%) and wet (18.80%) years fall within the good performance range, indicating a slight tendency of the model to overestimate sediment yield. To further improve model reliability, future studies should focus on refining parameter calibration, improving the accuracy of input data, and conducting sensitivity analyses [25] and [21]. In addition, it is important to recognize potential sources of model uncertainty related to rainfall dynamics, input data quality, and parameter sensitivity.

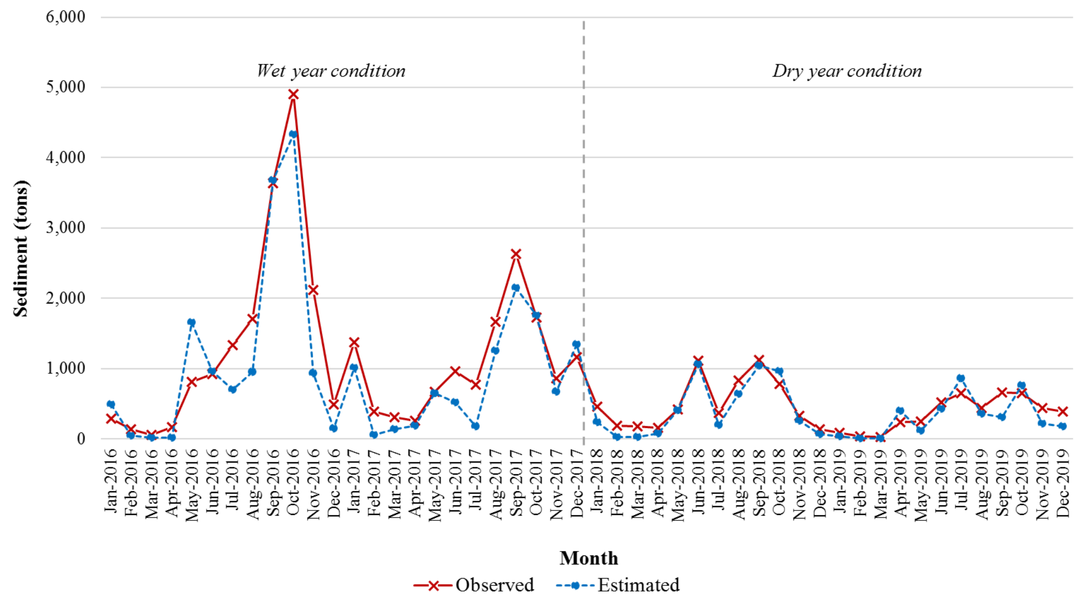

Figure 5: Monthly observed and estimated sediment yield at Khlong Bang Yai watershed under dry and wet year condition

Table 6: Performance of the SWAT model for sediment estimation under dry and wet year condition [25]

Indicator	Dry year condition (2018-2019)		Wet year condition (2016-2017)	
		Performance rating		Performance rating
RSR	0.50	Very good	0.40	Very good
NSE	0.75	Very good	0.84	Very good
PBIAS	17.18	Good	18.80	Good

Although the MUSLE approach enhances simulation accuracy by using runoff volume and peak flow to estimate sediment yield, it may still oversimplify the effects of rainfall intensity and frequency, particularly under extreme weather conditions [34]. Such rainfall variability can significantly influence sediment transport, especially during short-term storm events that are unevenly distributed across space and time [35]. Combining high-resolution gauge-based rainfall data with satellite or radar-derived products can improve both spatial and temporal resolution. When integrated with event-specific calibration and comprehensive uncertainty analysis, this approach can greatly strengthen model robustness and predictive performance.

3.3 Impacts of LULC change on Sediment Yield

The comparative analysis between LULC in 2002 (baseline) and 2019 (changed) under dry and wet year conditions revealed significant changes in sediment yield within the Khlong Bang Yai watershed, as presented in Table7. The spatial distribution of sediment yield is displayed in Figure 6. The findings can be described as follows.

Under dry year conditions, total sediment yield increased from 50,909.70 tons (9.26 t/ha) in 2002 to 59,055.90 tons (10.74 t/ha) in 2018, representing a 16% increase. Similarly, at the watershed outlet (subwatershed 16), sediment yield exhibited a more pronounced increase of approximately 125%, rising from 2,269 tons to 5,117 tons during the same period. In 2002, the top three subwatersheds with the highest sediment yield values were found in subwatersheds 10, 8, and 13 (70.40, 28.89, and 21.90 t/ha, respectively), while the lowest values were recorded in subwatersheds 3, 15, and 7 (0.74, 1.70, and 2.54 t/ha, respectively). The dominant LULC types across these areas primarily consisted of idle land and perennial trees and orchards, both characteristically susceptible to erosion processes. Idle land refers to land that is cultivated but is now in a state of disuse, abandoned land, and fallow land. This typically lacks sufficient vegetation cover, increasing vulnerability to water-induced erosion. Similarly, perennial tree crops like orchards often leave the soil exposed between the tree rows, particularly in the absence of cover crops, further exacerbating the potential for erosion.

Notably, terrain characteristics significantly influenced sediment yield distribution, with rolling and hilly landforms (Subwatersheds 8 and 13) demonstrating substantially higher sediment yields compared to flat or almost flat and slightly undulating terrains (Subwatersheds 3, 15, and 7). An exception was observed in Subwatershed 10, where the highest sediment yield reflected cumulative contributions from upstream subwatersheds rather than intrinsic terrain features. In 2018, the top three subwatersheds with the highest sediment yield values were observed in subwatersheds 10, 11, and 16 (236.96, 52.78, and 32.42 t/ha, respectively). These areas were predominantly characterized by urban and built-up areas, with elevated yields largely attributable to accumulated sediment transport from upstream subwatersheds.

Table 7: Sediment yield under dry and wet year conditions in each subwatershed

Subwatersheds	**Area (ha)**	**Sediment yield under dry year condition**					**Sediment yield under wet year condition**				
		2002 (t)	2018 (t)	2002 (t/ha)	2018 (t/ha)	Δ (t/ha)	2001 (t)	2017 (t)	2001 (t/ha)	2017 (t/ha)	Δ (t/ha)
1	685.57	3,934.00	8,527.00	5.74	12.45	6.70	17,120.00	166,700.00	24.99	243.31	218.32
2	531.29	3,651.00	6,716.00	6.88	12.65	5.77	15,610.00	110,300.00	29.40	207.73	178.33
3	214.36	159.00	706.90	0.74	3.30	2.56	561.30	1,450.00	2.62	6.77	4.15
4	254.29	4,791.00	1,943.00	18.85	7.65	-11.21	3,300.00	23,700.00	12.98	93.25	80.27
5	375.98	3,731.00	1,303.00	9.93	3.47	-6.46	1,878.00	13,250.00	5.00	35.26	30.26
6	278.03	2,506.00	1,529.00	9.02	5.50	-3.52	704.30	6,957.00	2.53	25.04	22.50
7	145.61	370.10	1,287.00	2.54	8.84	6.30	1,061.00	2,496.00	7.29	17.15	9.86
8	407.72	11,770.00	6,323.00	28.89	15.52	-13.37	6,874.00	82,980.00	16.87	203.64	186.78
9	391.15	1,489.00	902.40	3.81	2.31	-1.50	5,661.00	19,690.00	14.48	50.37	35.89
10	7.44	523.50	1,762.00	70.40	236.96	166.55	1,476.00	3,349.00	198.49	450.38	251.88
11	76.67	1,633.00	4,044.00	21.31	52.78	31.47	3,470.00	7,824.00	45.29	102.12	56.83
12	75.54	319.80	501.60	4.24	6.64	2.41	614.40	995.30	8.14	13.18	5.05
13	312.31	6,834.00	3,249.00	21.90	10.41	-11.49	4,497.00	34,080.00	14.41	109.19	94.78
14	74.79	236.30	648.00	3.16	8.67	5.51	654.20	1,322.00	8.75	17.69	8.94
15	659.29	1,121.00	3,007.00	1.70	4.56	2.86	2,604.00	5,811.00	3.95	8.82	4.87
16	157.95	2,269.00	5,117.00	14.37	32.42	18.04	4,628.00	9,939.00	29.32	62.96	33.65
17	854.53	5,572.00	11,490.00	6.52	13.45	6.93	23,920.00	207,500.00	28.01	242.97	214.96
	5,502.50	**50,909.70**	**59,055.90**	**9.26**	**10.74**	**1.48**	**94,633.20**	**698,343.30**	**17.21**	**126.99**	**109.78**

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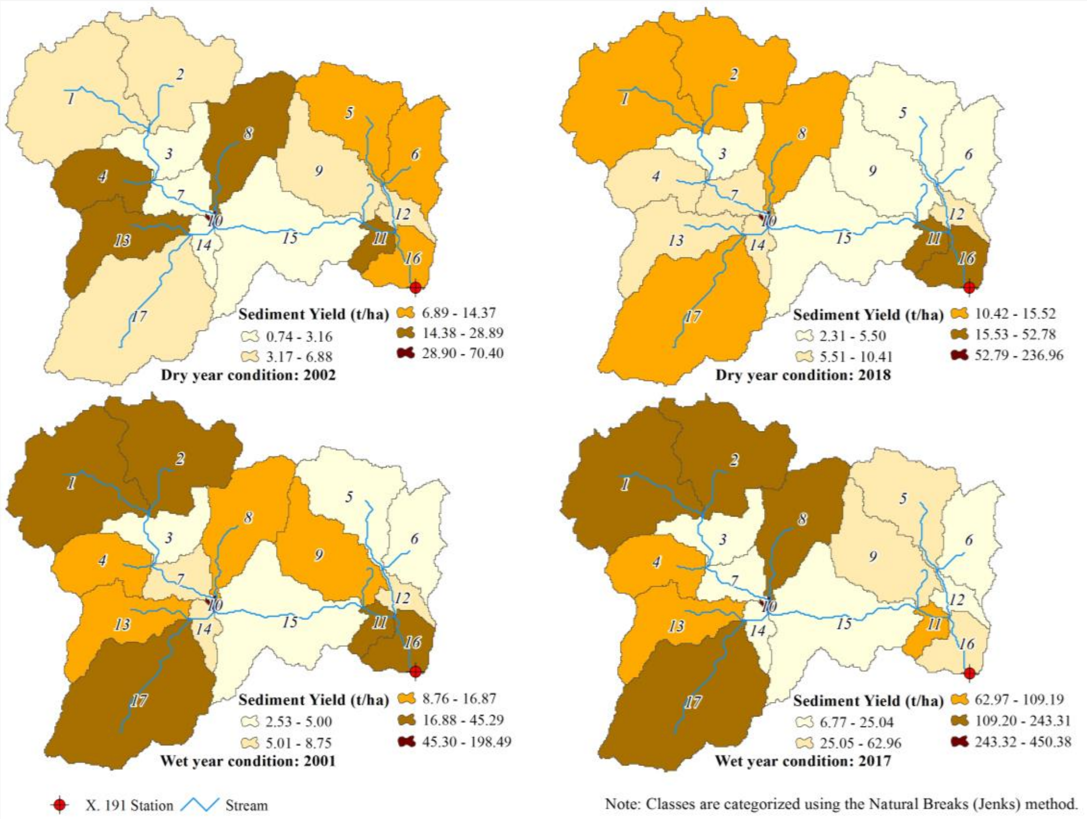

Figure 6: Spatial distribution of sediment yield under dry and wet year conditions in each subwatershed

Conversely, the lowest sediment yields were recorded in subwatersheds 9, 3, and 5 (2.31, 3.30, and 3.47 t/ha, respectively). Despite the presence of typically erosion-prone LULC types (idle land and perennial trees and orchards), the relatively flat topography within these subwatersheds appeared to mitigate sediment mobilization, resulting in comparatively low sediment yield observed.

Under wet year conditions, the impact of LULC change on sediment yield was considerably more pronounced. Total sediment yield across the Khlong Bang Yai watershed increased dramatically from 94,633 tons (17.21 t/ha) in 2001 to 698,343 tons (126.99 t/ha) in 2017, representing an approximately 638% increase. This pattern was similarly reflected at the watershed outlet (subwatershed 16), where sediment yield increased from 4,628 tons to 9,939 tons during the same period. In 2001, the top three subwatersheds with the highest sediment yield values were found in subwatersheds 10, 11, and 2 (198.49, 45.29, and 29.40 t/ha, respectively). The dominant LULC types in subwatersheds 10 and 11 were predominantly characterized by urban and built-up areas, with elevated yields attributable to accumulated sediment transport from upstream subwatersheds.

Meanwhile, subwatershed 2, dominated by idle land and perennial trees and orchards situated on rolling and hilly terrain, demonstrated high susceptibility to erosion processes, resulting in substantial sediment generation. In contrast, the lowest sediment yields were recorded in subwatersheds 6, 3, and 15 (2.53, 2.62, and 3.95 t/ha, respectively). Despite the presence of erosion-prone LULC types (idle land and perennial trees and orchards), the flat or nearly flat and slightly undulating topography within these subwatersheds appeared to minimize sediment mobilization. In 2017, the top three subwatersheds with the highest sediment yield values were found in subwatersheds 10, 1, and 17 (450.38, 243.31, and 242.97 t/ha, respectively). While subwatershed 10 maintained its status as a high-yield area due to accumulated upstream contributions and LULC predominantly comprising urban and built-up areas, subwatersheds 1 and 17 emerged as significant sediment sources. The dominant LULC types in these areas, characterized by perennial trees and orchards on rolling and hilly terrain, demonstrated heightened susceptibility to erosion processes.

Conversely, the lowest sediment yields were recorded in subwatersheds 3, 15, and 12 (6.77, 8.82, and 13.18 t/ha, respectively), areas predominantly comprising urban and built-up areas situated on flat or nearly flat and slightly undulating terrain. This observation aligns with established understanding that impervious surfaces typically associated with urbanized areas can limit sediment mobilization when not influenced by upstream contributions.

These findings highlight that sediment yield within the watershed is significantly governed by the interaction between LULC types and topographic setting [36] and [37]. Moreover, wet year conditions were found to intensify the erosional impacts of specific LULC types more markedly than under dry year conditions [38]. To evaluate the impacts of LULC changes on sediment yields within the Khlong Bang Yai watershed, transformations between 2002 and 2019 in six subwatersheds (1, 2, 3, 7, 15, and 17) were analyzed. These subwatersheds were selected due to significant increases in the change (Δ) of sediment yield under both dry and wet conditions, as well as total LULC change exceeding 50 hectares per subwatershed (Table 8).

In the upstream subwatersheds (17, 1, and 2), considerable reductions in evergreen forests and scrub forests were associated with expansions in perennial trees and orchards and urban and built-up areas. Specifically, in subwatershed 17, a reduction of evergreen forest (-35.02 ha) and scrub forest (-28.90 ha) coincided with increases in perennial trees and orchards (+32.38 ha) and urban and built-up areas (+12.61 ha), resulting in sediment yield increases of 6.93 t/ha under dry conditions and 214.96 t/ha under wet conditions (Table 7). Similarly, subwatershed 1 experienced decreases in evergreen forest (-48.00 ha) alongside increased perennial trees and orchards (+45.75 ha) and urban and built-up areas (+12.52 ha), leading to sediment yield increases of 6.70 t/ha (dry) and 218.32 t/ha (wet). In subwatershed 2, substantial evergreen forest (-92.62 ha) and idle land losses (-20.43 ha), replaced by perennial trees and orchards (+45.65 ha) and urban and built-up areas (+40.19 ha) and scrub forest (+25.32 ha), also contributed to elevated sediment yields of 5.77 t/ha (dry) and 178.33 t/ha (wet). These results underline the vulnerability of soils to erosion when transitioning from forested to urban and agricultural uses.

Lower-elevation downstream subwatersheds (3, 7, and 15), receiving runoff and sediment from upstream areas, experienced compounded sediment yield impacts due to their topographic positions. In subwatershed 3, significant declines in idle land (-59.02 ha) and scrub forest (-32.29 ha), coupled with substantial urban and built-up areas expansion (+96.10 ha), contributed to increased sediment yields of 2.56 t/ha (dry) and 4.15 t/ha (wet). Subwatershed 7, directly downstream from subwatershed 3, showed reductions in idle land (-49.42 ha) and increased urban and built-up areas (+45.56 ha), resulting in sediment yield increases of 6.30 t/ha (dry) and 9.86 t/ha (wet). Similarly, subwatershed 15, downstream of subwatershed 10, experienced notable forest reductions (-18.17 ha evergreen forest; -59.21 ha scrub forest), a decrease in perennial trees and orchards (-53.18 ha), and a substantial expansion in urban and built-up areas (+94.22 ha), correlating with sediment yield increases of 2.86 t/ha (dry) and 4.87 t/ha (wet). However, Subwatershed 10 illustrated the cumulative downstream effect of sediment transport from upstream subwatersheds. Despite minimal internal LULC changes, subwatershed 10 exhibited notably high sediment yields (166.55 t/ha dry; 251.88 t/ha wet), driven primarily by upstream urban runoff.

Collectively, these analyses demonstrate that sediment yield within the Khlong Bang Yai watershed increased substantially as a result of LULC conversions. In particular, the loss of evergreen forests, along with the expansion of perennial trees and orchards and urban and built-up areas, contributed to significant sediment yield increases under both dry and wet conditions across all six subwatersheds. To further support these findings, a correlation analysis was conducted to assess the relationships between specific LULC types and sediment yield under both dry and wet conditions (Table 9). Urban and built-up areas exhibited strong negative correlations with sediment yield ($r = -0.972$ for dry years; $r = -0.868$ for wet years), suggesting that these areas often function as sediment deposition zones or experience lower internal erosion due to impervious surfaces and downstream positioning. In contrast, perennial trees and orchards showed strong positive correlations ($r = 0.744$ for dry years; $r = 0.845$ for wet years), indicating their contribution to sediment generation, particularly in recently converted or poorly managed areas. Field crop and horticulture ($r = 0.530$ for dry years; $r = 0.549$ for wet years) and scrub forest ($r = 0.640$ for dry years; $r = 0.427$ for wet years) also showed positive associations with sediment yield, reflecting the erosion potential of cultivated and transitional land uses. Meanwhile, idle land ($r = 0.415$) and water bodies ($r = 0.698$) exhibited moderate positive correlations under wet conditions, likely due to enhanced surface runoff and sediment transport during heavy rainfall events. Conversely, evergreen forests demonstrated clear negative correlations ($r = -0.409$ for dry years; $r = -0.739$ for wet years), reaffirming their essential role in reducing soil erosion and stabilizing watershed hydrology.

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Table 8: Subwatersheds with significant LULC and sediment yield changes (2002–2019)

Subwatersheds	LULC type	LULC area (ha)						Change
		In 2002	Percent	In 2019	Percent	Δ (area)	Δ (Percent)	
17	Urban and built-up area	110.98	13.00	123.59	14.47	12.61	1.48	Gain
	Field crop and horticulture	0.66	0.08	2.16	0.25	1.51	0.18	Gain
	Perennial trees and orchards	298.10	34.91	330.48	38.70	32.38	3.79	Gain
	Idle land	5.37	0.63	19.11	2.24	13.74	1.61	Gain
	Evergreen forest	325.11	38.07	290.10	33.97	-35.02	-4.10	Loss
	Scrub forest	43.39	5.08	14.50	1.70	-28.90	-3.38	Loss
	Water body	69.18	8.10	69.18	8.10	0.00	0.00	-
	Miscellaneous land	1.22	0.14	4.89	0.57	3.67	0.43	Gain
	Total	**854.01**	**100.00**	**854.01**	**100.00**			
1	Urban and built-up area	53.84	7.86	66.36	9.69	12.52	1.83	Gain
	Perennial trees and orchards	231.08	33.73	276.83	40.40	45.75	6.68	Gain
	Idle land	17.60	2.57	8.09	1.18	-9.51	-1.39	Loss
	Evergreen forest	380.65	55.56	332.64	48.55	-48.00	-7.01	Loss
	Scrub forest	1.13	0.16	0.38	0.06	-0.75	-0.11	Loss
	Water body	0.85	0.12	0.85	0.12	0.00	0.00	-
	Total	**685.15**	**100.00**	**685.15**	**100.00**			
2	Urban and built-up area	93.00	17.52	133.19	25.08	40.19	7.57	Gain
	Perennial trees and orchards	131.59	24.78	177.24	33.38	45.65	8.60	Gain
	Idle land	65.42	12.32	44.99	8.47	-20.43	-3.85	Loss
	Evergreen forest	151.73	28.58	59.11	11.13	-92.62	-17.44	Loss
	Scrub forest	87.54	16.49	112.86	21.26	25.32	4.77	Gain
	Water body	1.69	0.32	3.58	0.67	1.88	0.35	Gain
	Total	**530.97**	**100.00**	**530.97**	**100.00**			
3	Urban and built-up area	41.60	19.42	137.71	64.28	96.10	44.86	Gain
	Field crop and horticulture	0.28	0.13	0.00	0.00	-0.28	-0.13	Loss
	Perennial trees and orchards	3.20	1.49	2.16	1.01	-1.04	-0.48	Loss
	Idle land	87.73	40.95	28.71	13.40	-59.02	-27.55	Loss
	Evergreen forest	8.57	4.00	6.21	2.90	-2.35	-1.10	Loss
	Scrub forest	50.45	23.55	18.17	8.48	-32.29	-15.07	Loss
	Water body	22.40	10.46	21.27	9.93	-1.13	-0.53	Loss
	Total	**214.23**	**100.00**	**214.23**	**100.00**			
7	Urban and built-up area	49.89	34.28	95.44	65.59	45.56	31.31	Gain
	Perennial trees and orchards	1.69	1.16	0.94	0.65	-0.75	-0.52	Loss
	Idle land	60.81	41.79	11.39	7.83	-49.42	-33.96	Loss
	Scrub forest	25.32	17.40	31.81	21.86	6.49	4.46	Gain
	Water body	7.81	5.37	5.93	4.08	-1.88	-1.29	Loss
	Total	**145.52**	**100.00**	**145.52**	**100.00**			
15	Urban and built-up area	236.07	35.83	330.29	50.13	94.22	14.30	Gain
	Perennial trees and orchards	161.24	24.47	108.06	16.40	-53.18	-8.07	Loss
	Idle land	25.13	3.81	58.64	8.90	33.51	5.09	Gain
	Evergreen forest	102.32	15.53	84.15	12.77	-18.17	-2.76	Loss
	Scrub forest	93.47	14.19	34.26	5.20	-59.21	-8.99	Loss
	Water body	23.53	3.57	22.97	3.49	-0.56	-0.09	Loss
	Miscellaneous land	17.13	2.60	20.52	3.11	3.39	0.51	Gain
	Total	**658.89**	**100.00**	**658.89**	**100.00**			

Note: Water body is water body and aquaculture area.

Table 9: Correlation between LULC area changes and sediment yield changes under dry and wet year conditions

LULC	Correlation coefficient (r)	
	Dry year condition	Wet year condition
Urban and built-up area	-0.972	-0.868
Field crop and horticulture	0.530	0.549
Perennial trees and orchards	0.744	0.845
Idle land	0.133	0.415
Evergreen forest	-0.409	-0.739
Scrub forest	0.640	0.427
Water body	0.261	0.698
Miscellaneous land	-0.083	0.064

Moreover, the differences in correlation levels for idle land, evergreen forests, scrub forests, water bodies, and miscellaneous land between dry and wet years highlight the influence of climatic variability on sediment dynamics. During wet years, the correlation for idle land became stronger because increased rainfall intensity amplified surface runoff and erosion from poorly vegetated areas. Similarly, water bodies showed a higher positive correlation under wet conditions, as enhanced runoff carried greater sediment loads into aquatic systems. In contrast, evergreen forests exhibited a more negative correlation during wet years, emphasizing their critical role in mitigating erosion under intense rainfall by maintaining canopy cover and soil stability. Scrub forests showed a reduced correlation from dry to wet years, likely due to denser and healthier vegetation during wet periods, which enhances soil protection and reduces erosion rates. Miscellaneous lands, which include beaches, soil pits, laterite pits, and landfill areas, exhibited a slightly positive correlation during wet years. These disturbed or exposed areas become more vulnerable under heavy rainfall conditions, contributing moderately to sediment generation. These variations reinforce the importance of both land use type and hydrological conditions in shaping sediment yield responses across the watershed.

These patterns are consistent with spatial observations in the study area and reinforce the hydrological importance of maintaining vegetative cover, particularly in erosion-prone and low-lying downstream regions. The conversion of forested and scrubland areas to agricultural and urban uses disrupts soil structure, reduces infiltration, and accelerates surface runoff, thereby intensifying sediment transport. This aligns with previous research showing that deforestation, urban expansion, and agricultural development increase runoff volumes, peak flows, and erosion potential at the watershed scale [39][40] and [41].

Furthermore, the variation in sediment yield between dry and wet years highlights the amplifying effect of climatic variability on land use impacts. During wet conditions, disturbed and unprotected soils are particularly vulnerable to accelerated erosion. These findings underscore the need for integrated watershed-scale planning and targeted conservation practices that consider both topographic context and climatic variability to enhance long-term sediment control and watershed resilience.

4. Conclusions

This study evaluated the impacts of LULC changes on sediment yield within the Khlong Bang Yai watershed, Phuket Island, Thailand, from 2002 to 2019, using the SWAT model. The findings highlight a substantial increase in urban and built-up areas, primarily replacing idle land and forested areas, particularly evergreen and scrub forests. These LULC transitions, largely driven by tourism-related development, have altered the hydrological balance of the watershed, increasing surface runoff and sediment transport. The reduction of forested areas, known for their high infiltration and soil retention capacities, significantly contributed to sediment yield escalation. Model simulations conducted under dry (2018–2019) and wet (2016–2017) conditions, validated with observed data using NSE, RSR, and PBIAS, confirmed high model reliability. Results indicated that sediment yield increased by 16% under dry conditions and dramatically by 638% under wet conditions, emphasizing the dominant role of runoff in driving sediment dynamics. Subwatersheds undergoing forest-to-urban and forest-to-orchard conversions, especially in areas with steep terrain, exhibited notably elevated sediment yields. Conversely, urban subwatersheds with flat terrain showed sediment accumulation primarily from upstream sources rather than local erosion. Correlation analysis further supported these findings.

Evergreen forests exhibited negative correlations with sediment yield (r = -0.409 dry; r = -0.739 wet), reaffirming their role in reducing erosion and stabilizing soils. In contrast, perennial trees and orchards showed strong positive correlations (r = 0.744 dry; r = 0.845 wet), indicating their potential contribution to sediment generation, particularly in areas lacking ground cover or undergoing recent land conversion. Scrub forest and agricultural lands also showed positive correlations, while urban and built-up areas had strong negative correlations (r = -0.972 dry; r = -0.868 wet), especially in flat downstream zones acting as sediment sinks. The findings of this study underscore the importance of adopting integrated watershed management strategies to address the impacts of rapid land use and land cover (LULC) change. Key measures should include reforestation, restoration of riparian buffer zones, implementation of erosion control structures, slope stabilization techniques, and sustainable urban planning. These interventions are essential for mitigating issues such as forest encroachment, increased flooding, and water quality degradation, particularly in rapidly urbanizing coastal regions. Furthermore, to improve the predictive capability and robustness of sediment yield modeling, future research should consider the integration of high-resolution gauge-based rainfall with satellite- or radar-derived precipitation data to enhance both spatial and temporal resolution. Calibration of localized parameters, such as saturated hydraulic conductivity (SOL_K) and soil depth (SOL_Z), along with the assessment of seasonal variations in sediment dynamics, is also recommended. The methodology employed in this study can be effectively applied to other similar watersheds, contributing to science-based decision-making to inform land use policies and support sustainable watershed management.

Acknowledgements

The authors gratefully acknowledge the following individuals and organizations for their invaluable contributions to this study: Assoc. Prof. Dr. Suwit Ongsomwang and Dr. Krittawat Boonchoo for providing access to the land use and land cover datasets. The Thai Meteorological Department and National Centers for Environmental Prediction for providing the weather data. The Southern Region Irrigation Hydrology Center, Royal Irrigation Department, for providing the observed daily sediment data.

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Appendix A

Slope classification

The slope classification is categorized based on percentage values, which indicate the steepness of the terrain. The classification follows the criteria set by [42], as shown in Table A.1.

Soil series

The soil series classification describes various soil types and their corresponding textures, as defined by [43], as shown in Table A.2.

Table A.1: Slope classification

No	Slope (%)	Landform
1	0-5	Flat or almost flat
2	5-12	Undulating
3	12-20	Rolling
4	20-35	Hilly
5	>35	Steep

Table A.2: Soil series classification

No	Series Name	Texture
1	Krabi	Clay loam
2	Lamphu La	Loam
3	Phang-nga	Sandy loam
4	Phuket	Sandy clay loam
5	Ranong	Sandy loam
6	Slope complex	-
7	Tin Mine Land	-
8	Urban Land	-

Appendix B

Model Evaluation Equations

The model performance metrics RSR, NSE, and PBIAS were computed using the following equations B.1 - B.3:

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n}\left(O_i - E_i\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2}}$$

Equation B.1

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - E_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$

Equation B.2

$$PBIAS = \frac{\sum_{i=1}^{n}\left(O_i - E_i\right)}{\sum_{i=1}^{n} O_i} \times 100$$

Equation B.3

Where: E_i is the estimated sediment yield and O_i is the observed sediment yield at the time i. $\bar{O}$ represents the mean observed sediment yield, and n is the total number of observations.