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Loc, Ho Huu; Thanavanh, Tadam; Nguyet, Dang Anh; Upadhyay, Surabhi; Maung, Thidar Maung et al

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# Understanding the impacts of land use changes on the sustainability of hydrological ecosystem services: the case of Pasak River Basin, Thailand

Ho Huu Loc<sup>1</sup> · Tadam Thanavanh<sup>2</sup> · Dang Anh Nguyet<sup>3,4</sup> · Surabhi Upadhyay<sup>2,5</sup> · Thidar Maung Maung<sup>2</sup> · Sangam Shrestha<sup>2</sup> · Edward Park<sup>6,7</sup> · Perrine Hamel<sup>7</sup>

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## Abstract

The sustainability of hydrological ecosystem services (HESs), that play a vital role in providing benefits to human beings, is intrinsically connected to the land use and land cover management practices. In this study, we investigated the impact of land use change on the HESs of the Pasak River Basin, Thailand. Using the ecosystem service modeling tool, Land Utilization Capability and Indicator (LUCI), we mapped and quantified flood mitigation, water supply, soil loss, erosion risk, and sediment delivery mitigation services under two land use periods (2020 and 2010), and two developed land use scenarios (pro-agriculture and pro-conservation). This represents the first application of LUCI for a case in Thailand. Our results demonstrate dramatic shifts in land use over the previous decade, with significant expansion of urban built-up and agricultural areas and a decrease in forest cover. Accordingly, landscape features contributing to flood mitigation decreased by 410 km<sup>2</sup>. In comparison, non-mitigated areas (no longer benefiting from flood mitigation service) increased by 101.16 km<sup>2</sup>, implying an increased risk of flooding. However, the watershed is not particularly susceptible to severe erosion as moderate-risk and high-risk areas have both significantly decreased. We identified deforestation and agricultural land expansion as the primary causes of HESs deterioration, particularly in flood mitigation services. Additionally, our study also examines the effect of pro-conservation or pro-agriculture scenarios on HESs in the Pasak River Basin in the future. This is a pioneering effort to analyze the sensitivity of land use changes on the delivery of multiple important HESs. The explicit spatial-temporal information on integrated changes in ecosystem services in response to land use changes as reported in this study is much needed to inform decisions to ensure regional ecosystem management and the sustainable provision of HESs in the future.

**Keywords** Hydrological ecosystem services · Land-use land-cover change · Land utilization capability and indicator (LUCI) · Integrated water resources management (IWRM)

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Extended author information available on the last page of the article

## 1 Introduction

Ecosystem services (ESs) represent a full spectrum of benefits that human beings obtain from nature (La Notte et al., 2017). Despite the increasing understanding of the importance of ESs in recent years, human activities continue to deteriorate natural ecosystems providing ESs. The mismatch created between the availability of ESs, and the demands placed on them by society is only projected to intensify in the coming years (Hasan et al., 2020; Fan et al., 2016). As a subset of ecosystem services, hydrological ecosystem services (HESs) focus on the benefits that people obtain from the hydrological cycle (Gao et al., 2017). HESs, dependent on the hydrologic processes within a catchment area, encompasses a wide range of services crucial to human well-being and ecosystem functioning, including water purification, flood control, and erosion prevention (Yohannes et al., 2021).

However, there have been increasing concerns on the global decline, degradation and unsustainable use of HESs in recent years, according to the Millennium Ecosystem Assessment report (Hasan et al., 2020). This is attributed to alteration of land use and the impact of climate change, which have affected hydrological processes such as interception, infiltration, evapotranspiration, streamflow, and runoff (Bai et al., 2019). This affects the provision of HESs, including clean water supply, freshwater availability, and flood control (Shi et al., 2013). Over the past few decades, there has been growing recognition of the externalities associated with land use change, particularly their impact on hydrological responses (Bai et al., 2019; Decsi et al., 2020; Hasan et al., 2020). Specifically, increased land use intensity and resultant shifts in vegetation cover have the potential to increase surface runoff, sedimentation, and extreme hydroclimatic events like floods and droughts (Yohannes et al., 2021).

Investigations and increased focus into this dynamic interrelationship between land use change and HESs have been reiterated in numerous studies to-date (Liu et al., 2019; Lin et al., 2021; Yohannes et al., 2021), emphasizing the need to implement conservation planning of the ESs involving stakeholders to mitigate the negative impacts of land use changes in the ES. For instance, Guo et al. (2021) assessed the impact of land-use change on water yield and water purification in Jianghuai ecological economic zone, China, under climate change and different land-use change scenarios. The results showed that the water yield in each land-use change scenario decreased by 10.41% (rapid urbanization scenario), 12.43% (farmland protection scenario), 13.69% (ecological protection scenario), and 13.83% (farmland to lake scenario). Another study by Bai et al. (2019) assessed the impact of land-use change on water, soil, and nutrient retention service in Kentucky, USA. Although water retention increased 53.80% and 46.19% in central and eastern Kentucky due to the increased precipitation, widespread forest loss, and land expansion, resulted in a decrease in water retention in the east-central and southern part of eastern Kentucky. Li et al. (2020) and Hasan et al. (2020) further demonstrated the effects of land use changes on water retention for flood mitigation. These studies showed that the expansion of built-up areas and conversion from forest to grassland and cropland, are associated with decreased soil conservation and flood regulation. These findings highlight the importance of vegetation in controlling soil erosion, regulating water flow, and maintaining HESs.

To model such interactions, researchers often employ a range of methods and tools, such as hydrological models, ecosystem services models, or land use change models (Nedkov et al., 2022; Vigerstol & Aukema, 2011; Irvine et al., 2021). Numerous ecological models that

incorporate spatial information have been developed to assess ecosystem services (ESs). These models include TESSA (Toolkit for Ecosystem Service Site-based Assessment), Land Utilization and Capability Indicator (LUCI) (Jackson et al., 2013; Trodahl et al., 2017), Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) (Bai et al., 2019; He et al., 2016; Posner et al., 2016), and Artificial Intelligence for Ecosystem Services (ARIES). These models allow for the simulation of different land use change scenarios and their impacts on HESs and enable the identification of potential trade-offs and synergies between different ecosystem services. Recently, Dang et al. (2021) reviewed 108 publications and found that the number of ES assessment publications, mapping and modelling in Southeast Asia have been growing, following the Millennium Ecosystem Assessment carried out from 2001 to 2005. In Thailand, InVEST has received increased attention in its ES study (Arunyawat & Shrestha, 2018; Trisurat et al., 2017). However, LUCI, with its publicly available version, is particularly useful as it provides fine-scale outputs for local or national-scale applications. It can also provide trade-off maps for multiple ecosystem services, allowing decision-makers to evaluate the potential trade-offs between different land-use scenarios (Dang et al., 2021; Sharps et al., 2017; Trodahl et al., 2017).

In Thailand, land use has undergone significant changes in recent decades due to commercial logging, agricultural area expansion, and urban development driven by population growth (Royal Forest Department, 2009). This has led to a decrease in forest cover from 53% in 1961 to 30% in 2006 between 2015 and 2016, urbanization and agricultural area expansion increased by 8% and 2%, respectively, while the forest area decreased by 3% from 2010 to 2013 (Land Development Department, 2017). This is despite government efforts to maintain the forest cover at 50% of the country's area. In the Pasak River Basin (PRB), predominantly located in Northern Thailand, land use continues to change drastically. Although the forest cover increased from 28% to 31% of the basin area from 2002 to 2006 due to the Royal Forest Department's strict policy on preventing deforestation and planting forests (HII, 2012), agricultural areas continued to expand at the expense of paddy fields and cropland. The ESs provided by the basin are currently under stress due to the conversion of forest areas to agriculture and the geography of the basin itself. In the basin, during the rainy season, water flows rapidly, while in the dry season, water becomes scarce. This has resulted in severe soil erosion, and consequently, sediment accumulation in the river (HII, 2012). Given the ongoing land use changes, the future trajectory of these ecosystem services remains uncertain. Therefore, this study aims to support decision-making related to soil and water conservation by mapping and quantifying ecosystem services using LUCI and assessing their vulnerability to land-use changes within the area. Specifically, the three research objectives are (1) to analyze the past and recent changes of the PRB, (2) to quantify and map the important HESs of PRB on the two time frames, and (3) to develop and evaluate different scenarios for enhancing these HESs in the future. This study therefore presents for a novel effort to use LUCI modelling tool to effectively map and evaluate important HES in PRB, Thailand. The innovation of the study also relates to sensitivity analysis to explore how land use land cover changes affect the ability of the PRB to sustainably deliver these HES.

## 2 Study area

The PRB is in the north-eastern and upper central regions of Thailand. It lies between latitude 14° 15' North to latitude 16° 20' North and between longitude 100° 30' East and 101° 30' East longitude. The basin covers most of the Phetchabun Province with 8,493 km<sup>2</sup> (54.35% of the basin's area, 68.78% of the province's area) (Hydro-Informatic Institute, 2012). The Pasak River is the main river of the basin, which originates from the Phetchabun Mountain Range in the Dan Sai District in the south of Loei Province. It flows through Phetchabun, Lop Buri, and Saraburi provinces, and runs into the Chao Phraya River. The river provides several important HESs that support the natural ecosystems and facilitate local agriculture and fishery. The most important anthropogenic infrastructure of the PRB is the Pasak Jolasid Dam, which plays a crucial role in mitigating floods and storing water resources for agricultural and domestic purposes (Electricity Generating Authority of Thailand, 2018). The PRB and its important landscape features are illustrated in Fig. 1.

## 3 Methods and materials

### 3.1 Hydrological ecosystem services

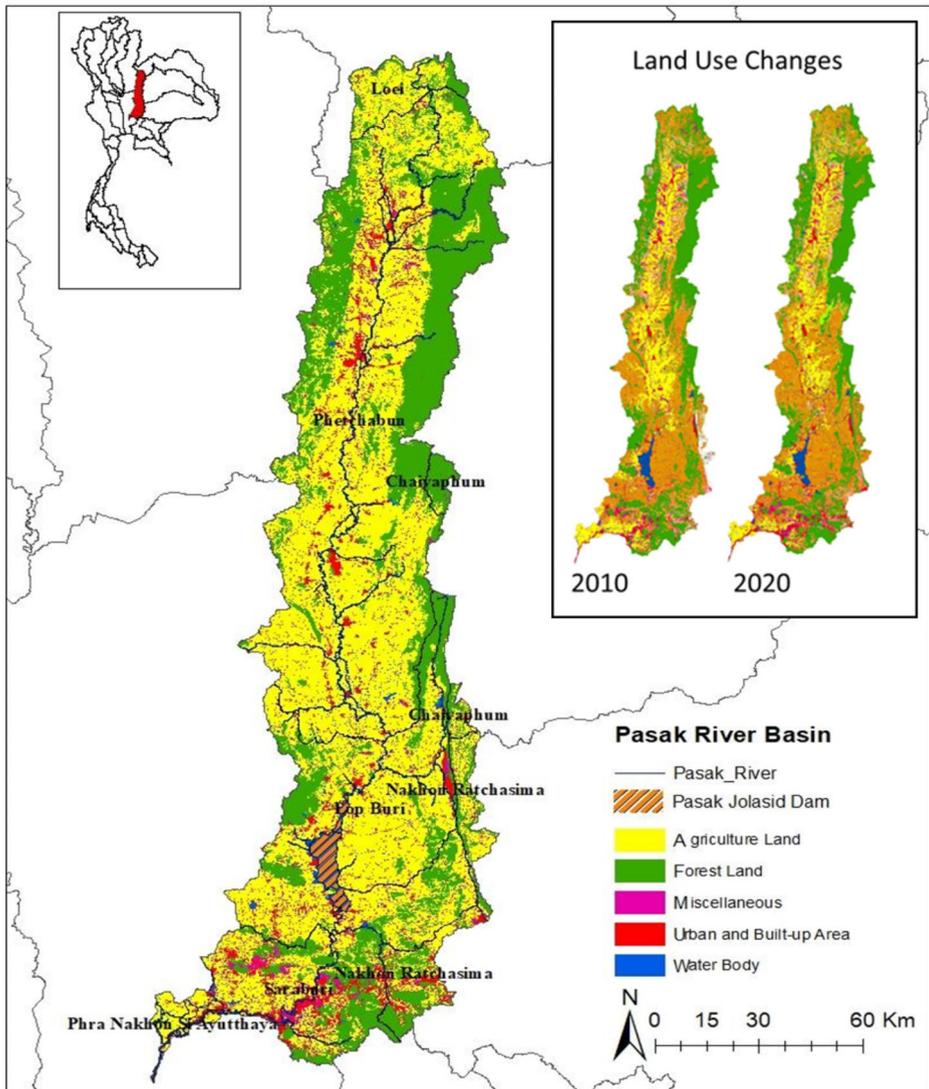
HESs are a subset of terrestrial ESs that encompass the benefits provided by terrestrial ecosystems to freshwater. HESs are mostly recognized as provisioning and regulating services. Provisioning services include the supply of water for household use, hydropower generation, industrial purposes, and irrigation. Regulating services involve water damage mitigation, water purification, sediment retention, and flood mitigation. Furthermore, cultural services such as water-associated recreational activities and education are also recognized as HESs (Brauman et al., 2007). The relationship of these eco-hydrological processes to HESs is illustrated in Fig. 1A in the supplementary materials.

### 3.2 Methodological framework

In this study, the Land Utilization Capability Indicator (LUCI) was used to assess the HES associated with the PRB. The quantification and mapping of PRB's HES were carried out at 30-meter spatial resolution under two timeframes: 2020 represents the recent condition and 2010 represents past conditions. Wherever applicable, simulated results were also validated with relevant ground-truth data. For instance, the gauged annual flows were used to validate flood mitigation HES, whilst the erosion risk mitigation simulated results were compared with the erosion risk map published by Thailand's land development department. Finally, based on the spatial correlations of the HES and different land use land covers (LULC), we propose and evaluate different land use management strategies. Figure 2 illustrates the comprehensive methodological framework adopted to achieve the study's research objectives.

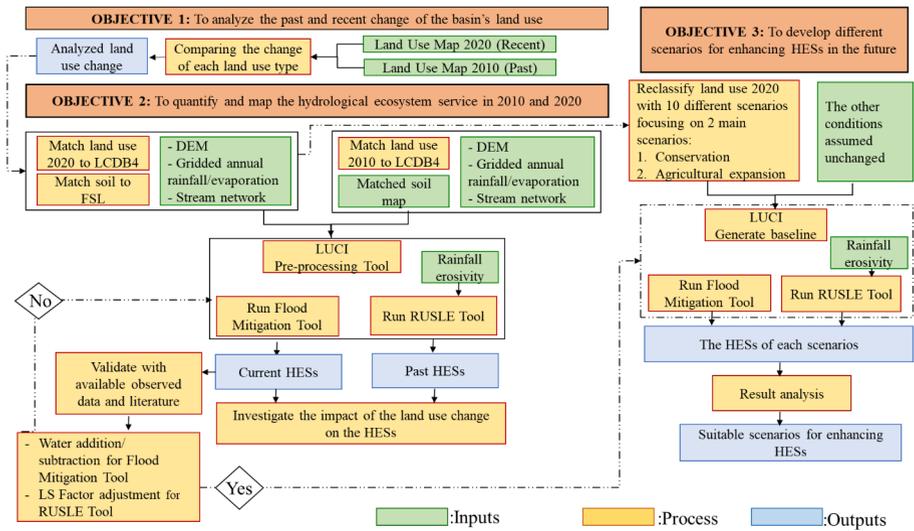
### 3.3 Land utilization and capability indicator model (LUCI)

The LUCI model applied in this study is the second-generation extension and software implementation of the Polyscape framework. A full description of the modeling package



**Fig. 1** Land use/ land cover in the PRB. The inset map on the top-right corner depicts the location of the Pasak River Basin within Thailand and the one on the top-left corner summarizes the land use changes between 2010 and 2020, being the period of analyses

can be found in Sharps et al. (2017), and Tomscha et al. (2021). LUCI is a valuable tool for assessing ecosystem functions and services, considering the biophysical and geophysical characteristics of the landscape. It enables a spatially explicit evaluation of ecosystem functions and services, including the HESSs associated with recent utilization of the landscape. It also estimates the potential capability of the landscape, highlighting areas where changes may bring benefits or where maintaining the current status may be desirable. The development of a LUCI model involves two key steps. First, the generation of baseline conditions



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**Fig. 2** Overall methodological framework of the study. In each objective (I, II, and III), spatial data is analyzed using QGIS, both to generate inputs for the LUCI model and to visualize its outputs. The quantification of each HES is conducted with corresponding LUCI module, as detailed in Sect. 3.3

using the *pre-processing tool*. Second, the simulation of individual ES models using the *Flood Mitigation* and *Revised Universal Soil Loss (RUSLE)* tools.

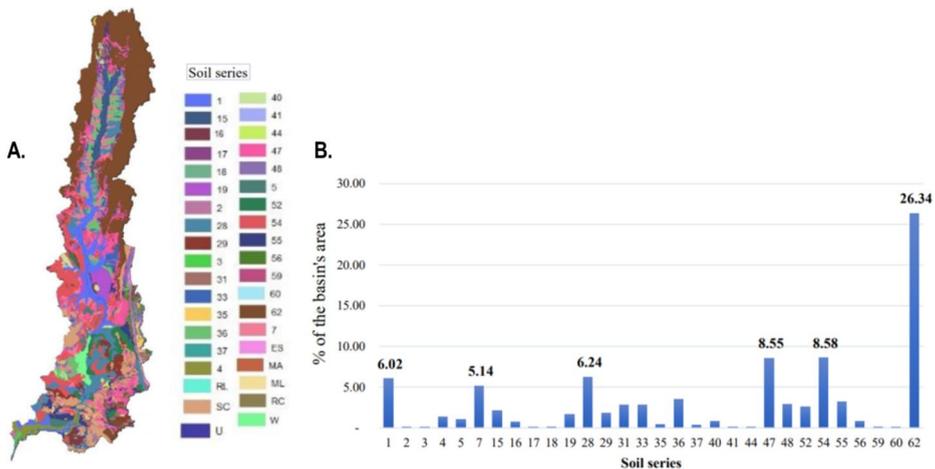
### 3.3.1 Preprocessing tool

The first step of LUCI model development involves the execution of the LUCI Preprocessing Tool to generate the baseline topographical and hydrological configurations for the study area. The soil series represent various soil types, each with distinct physical characteristics, e.g., erodibility, hydraulic conductivity, etc., which in turn will lead to different values of hydrological ecosystem services, including flood mitigation and sediment delivery. It's important to note that the default classification of soil series of the LUCI model only relates to New Zealand, where the model was originally developed (Dang et al., 2021). Hence, it is necessary to reclassify the soil series to align with the conditions of the study area in Thailand with the LUCI's configurations. First, we re-classified the land uses of the study area to match the local typologies, as developed by Thailand's Land Development Department (LDD), and those recognized by the LUCI calculation engine. Table 1 summarizes the matching of all land use categories considered in this study.

In line with land uses, it is necessary to match the local soil series with those of LUCI. There are more than 300 soil series in Thailand, classified into 62 groups based on their physical characteristics, properties, farming potential, and soil management practices. For this study, we considered 30 different types of soil series, many of which are clay and loamy soils mixed with rock and gravel with low to moderate drainage capacity and fertility. Figure 3 depicts the spatial distribution of different soil series in the PRB along with their areal

**Table 1** Alignment of LDD land use classification with LUCI preprocessing tool

LDD classifications	LUCI codes and descriptions
Deciduous forest	68 - Deciduous hardwoods
Evergreen forest	69 - Indigenous forest
Forest plantation	71 - Exotic forests
Rangeland	56 - Mixed exotic shrubland
Paddy field	30 - Short rotation cropland
Perennial crop	33 - Orchard/vineyard/perennial crops
Pasture and farm	40 - High producing exotic grassland
Aquatic plant	45 - Herbaceous freshwater vegetation
Beach	10 - Sand/Gravel
City, village, institution, industry	1 - Built-up area
Built ups	2 - Urban parkland/open space
Communication & utility	5 - Transport infrastructure
Mine/pit, other miscellaneous	6 - Surface mine and dumps
Artificial water body	20 - Lake and pond
Natural water body	21 - River



**Fig. 3** Soil series of Pasak River Basin, where, (A) spatial distribution of soil series in the study area wherein number denotes LUCI codes, ES is escarpment, MA is marsh, ML is made land, RC is rock crop, RL is rubble land, SC is soil complex and U is Urban area, and (B) areal percentage of each soil series

percentages. The figure also presents a summary of the soil series matchmaking results and their description considered in this study.

### 3.3.2 Flood mitigation tool

The flood mitigation tool calculates the average flow delivered to all points in the river and lake networks. It estimates the volume of water supplied in cubic meters per second (m<sup>3</sup>/s) based on topographical routing, considering storage and infiltration as functions of soil and

land use. The model subsequently classifies the study area into three different categories: “mitigating features”, “mitigated features”, and “non-mitigated features”. The first category refers to the areas, such as forests, that have the capacity to mitigate flows. The second category, “mitigated features” constitute areas that receives mitigation benefits. Finally, the third category, “non-mitigated areas” are those with low permeability and water storage capacity, allowing unmitigated flow to pass directly to the closest water bodies. See Fig. 2A in the supplementary materials for a conceptual representation of these categories.

The areal classification, as noted above, is based on mitigation opportunities calculated via the volume of water accumulated that can be considered as a significant pathway for transporting water to the stream network of the study area, specified as a multiplier of the area. For example, the value of 5 refers to all land cells with limited mitigation capabilities, e.g., permeability or storage thus accumulating the flow more than 5 times their area from uphill contribution. These land cells are considered significant pathways that need interventions for mitigation.

### 3.3.3 Water supply tool

The water supply HES refers to the accumulation of flow over the landscape supplied to all point of streams/rivers/lakes across the PRB.

### 3.3.4 Revised universal soil loss (RUSLE) tool

The RUSLE tool provides the estimation of the average annual soil loss  $A$  (in tons.  $\text{ha}^{-1}$ .  $\text{year}^{-1}$ ) using the Revised Universal Soil Loss Equation:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P$$

where,

R: rainfall-runoff erosivity factor,

L: slope length factor,

S: slope steepness factor,

C: cover management factor, and.

P: supporting practices factor.

In this study, the R factor is adjusted following the recommendation by Thailand’s LDD as  $R = 0.4669X - 12.1415$  where  $X$  is the annual rainfall depth in mm. Like the flood mitigation tool, the RUSLE tool also classifies the area into different categories of erosion risks according to the volume of annual soil loss. For this study, we adopted the classification recommended by Thailand’s LDD summarized in Table 2.

**Table 2** Classification of erosion risks by Thailand’s LDD

SN	Annual soil loss tons. $\text{ha}^{-1}$ . $\text{year}^{-1}$	Erosion risk level
1	0–2	Low
2	2–5	Medium
3	5–15	High
4	15–20	Very High
5	>20	Extremely High

### 3.3.5 Validation of LUCI models

The calibration and validation of ES models are more challenging than hydrological or hydrodynamics models due to the lack of observed data (e.g., of flood mitigation). In this study, we chose different *proxies* to validate the developed LUCI models to enhance the reliability of the model results. More specifically, the water supply service was validated using the observed discharge at the downstream station of the Pasak River. Similarly, we used the soil erosion risk map published by Thailand's LDD to validate the results generated by LUCI's RUSLE tool.

### 3.4 Data collection

Secondary data were mostly retrieved from related departments in Thailand, namely LDD, Thailand Meteorological Department (TMD), Department of Water Resources (DWR), and Royal Irrigation Department (RID). We also made use of publicly available global datasets such as the 30-m Digital Elevation Model (DEM), land use, soil properties, annual rainfall, annual evaporation, and stream network. The annual rainfall and evaporation datasets were converted to a 3-m resolution grid size. Soil erosion risk map and annual river flow for 7 gauging stations were used to validate the model results. Table 3 summarizes the collected data and their sources.

### 3.5 Land use change analysis and scenarios

We conducted a comparative analysis of land use patterns across the PRB across the 10-year analyzed period, from 2010 to 2020. For each type of HESs simulated, 3 types of features

**Table 3** Data sources used in the study

Data	Year	Format/Resolution	Source
Digital Elevation Model	2022	Raster – 30 m	<a href="https://search.earthdata.nasa.gov/">https://search.earthdata.nasa.gov/</a>
Land use map	2010 & 2020	Polygon – 1:25,000	Land Development Department (LDD)
Soil map	2018	Polygon – 1:25,000	Land Development Department (LDD)
Stream network	2018	Polyline – 1:50,000	Department of Water resources (DWR)
Annual Rainfall	2020	Raster – 30 m	Thailand Meteorological Department (TMD)
Annual Evaporation	2020	Raster – 30 m	Thailand Meteorological Department (TMD)
Rainfall Erosivity	2000 & 2010	Raster – 1 km	<a href="https://esdac.jrc.ec.europa.eu/">https://esdac.jrc.ec.europa.eu/</a>
Soil erosion risk map	2020	Polygon-1:25,000	Land Development Department (LDD)
River Discharges	2020	Spreadsheet	Royal Irrigation Department (RID)

are generated, i.e., mitigating, mitigated, and non-mitigated. Mitigating features are areas that “provide” HES, e.g., mitigating floods, mitigated feature are areas that “receive” HES, e.g., benefiting from the flood mitigation upstream, and non-mitigated neither provide nor receive. For each type of HES, these relate to several different factors, including permeability, soil types, slopes, etc. Thereupon, 10 different land use scenarios were developed assuming the different levels of conservation and agricultural expansion. In essence, we conducted a sensitivity analysis to determine the implications of different land use management decisions on sustainable flow of HES across the PRB, considering both positive and negative aspects.

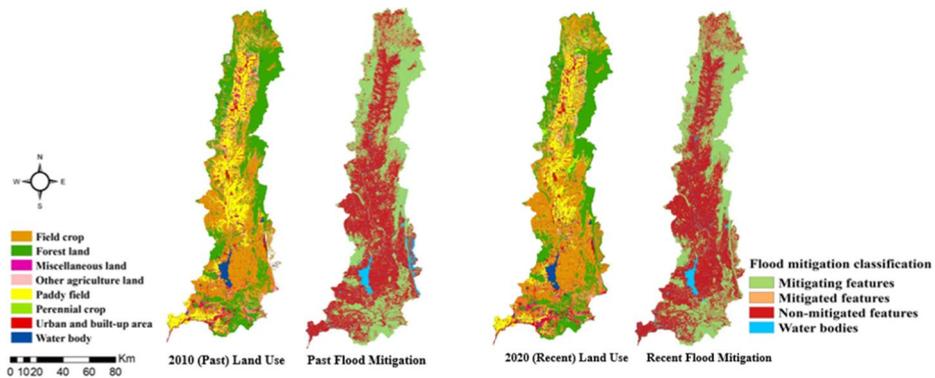
## 4 Results

### 4.1 Land use change analyses

Covering an area of 15,616 km<sup>2</sup>, the PRB’s land use is predominantly agriculture and forests (Fig. 6). Within the agricultural sector, field crops and paddy fields have the highest coverage. A comparison of the two periods, 2010 and 2020, reveals significant changes. Specifically, in 2010, the field crop that covered 32.94% of the basin area, which increased 3.70% by 2020. In contrast, paddy fields decreased from 17.48% in 2010 to 13.45% in 2020. This shift in agricultural practices is most prominent in the middle part of the basin. Another notable change occurred in forest areas, which used to cover 31.52% of the entire basin area in 2010 but declined to 29.61% in 2020. This can be attributed to deforestation and agricultural expansion activities. Deforestation is most evident in the upper part of the basin. Finally, urbanization is most notable in the downstream portion of the basin, as the combined coverage of urban and built-up areas has increased from 5.29% in 2010 to 8.85% in 2020. Table 4 and the inset map in Fig. 1 provide a comprehensive comparison of the shifts in land use between the two periods of analysis.

**Table 4** Changes in land use patterns between 2010 and 2020

Categories	Area (km <sup>2</sup> and %)		Change (km <sup>2</sup> and %)
	2010	2020	
Urban and built-up area	818.10 5.29%	1,072.69 6.85%	↑ <b>254.58</b> ↑ <b>1.55%</b>
Agricultural area	8,896.69 57.57%	9,053.10 57.78%	↑ <b>156.40</b> ↑ <b>0.22%</b>
Forest area	4,870.84 31.52%	4,639.71 29.61%	↓ <b>231.13</b> ↓ <b>1.90%</b>
Water bodies	326.24 2.11%	436.07 2.78%	↑ <b>109.83</b> ↑ <b>0.67%</b>
Miscellaneous	542.47 3.51%	465.95 2.97%	↓ <b>76.52</b> ↓ <b>0.54%</b>



**Fig. 4** Comparison of flood mitigation HES and their association with land use under the past (2010) and recent (2020) conditions

**Table 5** Flood mitigation features under the past and recent land use conditions

SN	Categories	2010 % of the basin area	2020 % of the basin area
1	Mitigating Features	38.2	35.57
2	Mitigated Features	5.48	5.81
3	Non-mitigated Features	46.73	47.38
4	Water bodies	9.6	9.24

## 4.2 HES under the past (2010) and recent (2020) land use conditions

### 4.2.1 Flood mitigation

Under the recent land use conditions, forest and perennial crop areas are most associated with the “mitigating features”. They provide flow sinks and good permeable surfaces along the runoff pathway. Basin-wide, these mitigating features cover 37.57% of the total area and provide flood mitigation HES to the mitigated features, which account for 5.81% of the total area. These mitigated lands, therefore, generally experience the lowest flood risk as they receive the smallest flow rate. Conversely, non-mitigated features cover approximately 47.38% of the PRB; they are mostly agriculture (paddy fields, field crops), and built-up areas. These areas, in general, have a low sink and permeability capacity. Compared to past land use conditions, mitigating, mitigated, and non-mitigated features accounted for 38.2%, 5.48%, and 46.73% of the basin area, respectively. Spatial patterns remained consistent across the study period, where mitigating features are mostly forests, while non-mitigated features are associated with paddy fields and perennial crops. Figure 4 illustrates the spatial distribution of flood mitigation HES of the PRB, paddy field, and perennial crops, while Table 5 summarizes their numerical comparison.

### 4.2.2 Water supply service

The provisioning HES related to the water supply was evaluated via the accumulated flow delivery along the river and stream network. Under the 2020 land use conditions, the average flow was estimated to be  $5.63 \text{ m}^3/\text{s}$ , comparable to the observed value of  $5.93 \text{ m}^3/\text{s}$ . In the 2010 land use conditions, the average flow was found to be slightly higher at  $5.66 \text{ m}^3/\text{s}$ . Figure 8 compares the water supply HES between the two analyzed periods. However, spatial changes are not clearly discernible due to the relatively slight changes in the calculated results. The difference of this type of HES is depicted in Fig. 3A in the supplementary materials.

### 4.2.3 Soil loss

Applying the LS-factor value of 0.48, the RUSLE tool estimates the average annual soil loss of  $6.73 \text{ tons. ha}^{-1}$  for the recent land use condition, corresponding to a study by Rangsiwanichpong et al. (2018). As for the previous land use conditions, the annual average soil loss was estimated at  $6.35 \text{ tons. ha}^{-1}$ . The distribution of soil loss between 2010 and 2020 conditions is summarized in Fig. 4A in the supplementary materials.

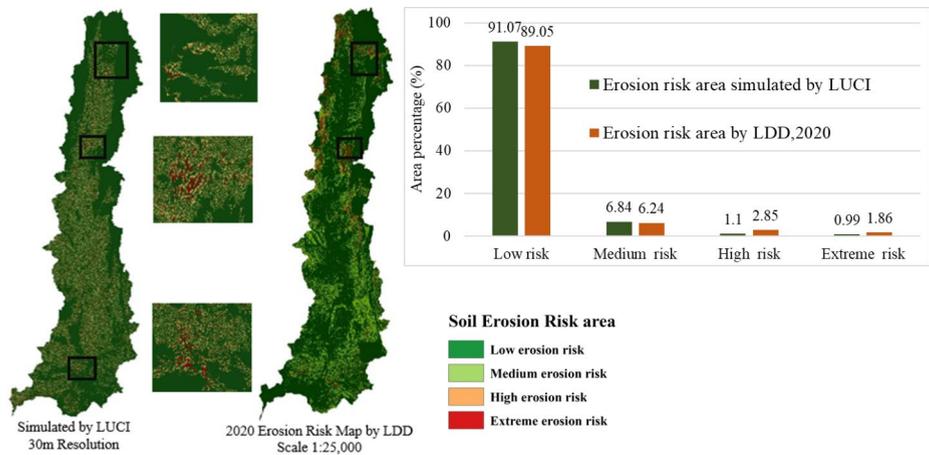
### 4.2.4 Erosion risk

The erosion risk was classified into 4 levels, ranging from low, medium, high, and extreme. Applying the LS-factor of 0.48 in the RUSLE tool, the model speculates that across the basin, 81.52%, 6.84%, 1.1%, and 0.99% of the geographical area are classified as low, medium, high, and extreme erosion risk areas, respectively. Quantitatively, these are comparable to the investigation results of Thailand's LDD, as shown in Fig. 10. Overall, the PRB exhibits a low risk for soil erosion. It should be noted that even though the low, high, and extreme risk areas may appear unmatched, this comparison is generally accepted because the simulation carried out in this study excluded water bodies, which accounted for 9.55% of the basin area. In this case, since water bodies do not contribute to soil erosion, it can be positioned in the range of "Low Erosion Risk" Fig. 5.

The LUCI model generated high and extreme erosion risk across the entire basin area. By comparing the spatial distribution of the map, of 30 m grid size, with the erosion risk map of 2020 by LDD, slight differences were observed. However, both maps generally agree on the presence of the extreme erosion risk in the upper part of the basin (Phetchabun and Leoi) and the lower part in Nakhon Rasasima. This is likely due to the loss of forest area and steep terrain in these areas. Table 6 summarizes the percentages of the basin exposed to different risk levels between 2010 and 2020.

### 4.2.5 Sediment delivery mitigation HES

The sediment delivery relates to the probability of eroded soil reaching rivers or streams. This HES is closely linked to the soil loss HES and heavily depends on the topographical characteristics of the basin. Unlike other HES, which can be categorized as either positive or negative, the sediment delivery HES has mixed effects. On the one hand, the sediment delivered can act as a source of natural fertilizers to support agricultural production. On the



**Fig. 5** Comparison of erosion risk between the simulated results and the risk map developed by Thailand’s Land Development Department

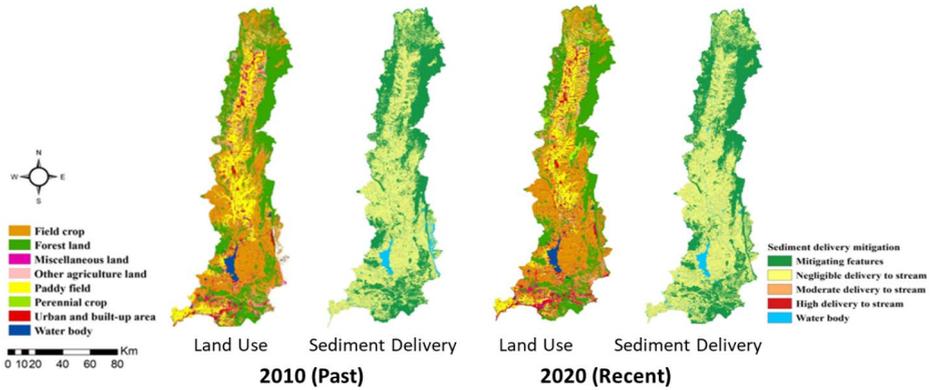
**Table 6** Erosion risk distribution under the past and recent land use conditions

SN	Categories	2010 % of the basin area	2020 % of the basin area
1	Low	91.17	1.07
2	Medium	6.94	6.84
3	High	1.05	1.1
4	Extreme	0.8	0.99

**Table 7** Erosion risk distribution under the past and recent land use conditions

SN	Categories	2010 % of the basin area	2020 % of the basin area
1	Sediment Erosion Mitigating	38.2	37.57
2	Negligible Risk of Sediment Delivery to stream	50.51	52.72
3	Moderate Risk of Sediment Delivery to stream	0.92	0.42
4	High Risk of Sediment Delivery to stream	0.77	0.05
5	Water Bodies	9.6	9.24

other hand, high sediment loads can deteriorate the water quality and increase flood risks. In this study, sediment delivery is considered to have negative impacts, and the results are analyzed accordingly. In line with the results of the flood mitigation tool, upon simulation, the PRB area is categorized into (i) mitigating features, (ii) negligible risk of sediment delivery to streams, (iii) moderate risk of sediment delivery to streams, and (iv) high risk of sediment delivery to streams. Table 7; Fig. 6 illustrate these categories for both past and current land use conditions.



**Fig. 6** Comparison of sediment delivery HES and their association with land uses under the past (2010) and recent (2020) conditions

**Table 8** Developed land use change scenarios

Land use types	Pro-conservation scenarios					Pro-agriculture scenarios				
	C1	C2	C3	C4	C5	A1	A2	A3	A4	A5
<b>Forest &amp; Perennial</b>	↑5%	↑10%	↑15%	↑20%	↑25%	↓5%	↓10%	↓15%	↓20%	↓25%
<b>Field Crop &amp; Paddy</b>	↓5%	↓10%	↓15%	↓20%	↓25%	↑5%	↑10%	↑15%	↑20%	↑25%

### 4.3 Impacts of land use decisions on HES

#### 4.3.1 Land use change scenarios

From the evaluation of the provisioning HES in the PRB under different land use conditions, we observed that forests and perennial crops are most associated with the mitigating features, while field crops and paddy are most associated with the non-mitigated features across the simulated HES. From this preliminary observation, we developed 10 hypothetical land use scenarios, divided into two development pathways: pro-conservation and pro-agriculture (Table 8; Fig. 12). Pro-conservation scenarios examined the effect of an increase in forested land from 5 to 25%, while pro-agriculture scenarios examined the effect of an increase in agricultural land from 5 to 25%. Each scenario was simulated while keeping other conditions unchanged, constituting a sensitivity analysis of the amounts of forested and agricultural land to quantify the potential implications of land use management decisions on the provisioning of multiple HES across the basin (Table 8). It should be noted that the water supply HES was not considered in this analysis, as the meteorological conditions of the study were assumed to remain unchanged, resulting in no significant changes in water supply. Similarly, the erosion risk was also excluded as it has been found that the PRB is not significantly vulnerable to the risks of soil erosion. Therefore, the comparison related to sediment delivery focused on changes in the areal percentage of the sediment erosion mitigating features and negligible soil erosion risk (Table 7) (Fig. 7).

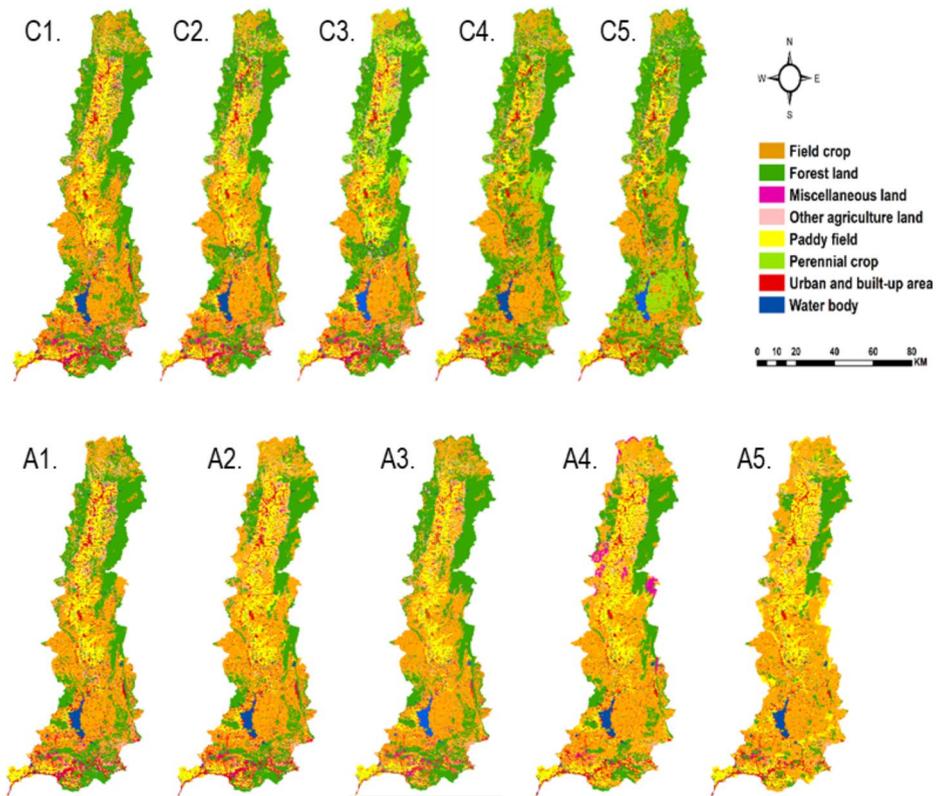
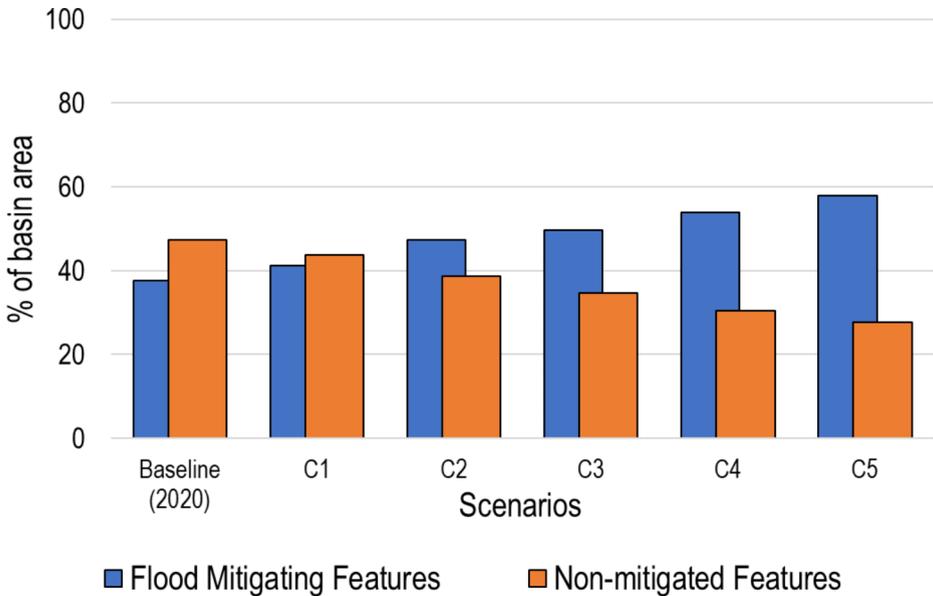


Fig. 7 Simulated land use change scenarios

### 4.3.2 HES under pro-conservation scenarios

Several strong correlations can be observed between land use changes and the generated HES. Specifically, there is a notable expansion of mitigating features within the PRB. The mitigating features expand from 37.57% of the basin area under the baseline conditions (2020) to 57.97% under the most reforestation-intensive scenario (C5). In contrast, 47.38% of the basin area consisted of non-mitigated features under the baseline conditions, which was effectively reduced to 27.63% under C5 scenario. This indicates that for every percent of forest and perennial cover converted from field crop and paddy, we can expect an increase of 0.729% of basin area, equivalent to 113.46 km<sup>2</sup>, of flood mitigating features. Concurrently, there would be a decrease of 0.791% of basin area, equivalent to 122.61 km<sup>2</sup>, of non-mitigated features (Fig. 8).

Regarding sediment delivery and soil loss HES, similar trends were observed. As the intensity of conversion increases, the area of mitigating features expanded while the area of negligible risk features shrunk, resulting in a decline in average annual soil loss. By means of comparison, for every % of pro-conservation land use conversion, an increase of 0.816% of basin area, equivalent to 126.27 km<sup>2</sup>, of mitigating features is expected. Concurrently, a



**Fig. 8** Flood mitigation HES changes under different pro-conservation scenarios

decrease of 0.76% of basin area or 117.12 km<sup>2</sup> of the negligible risks can be expected. In addition, the annual soil loss will also decrease by 0.058 tons/ha or 5.8 tons in total (Fig. 9).

#### 4.3.3 HES under pro-agriculture scenarios

The pro-agriculture scenarios represent an approach opposite to the pro-conservation scenarios. Similarly strong correlations between these scenarios and the generated HES, though in a reversed direction. Specifically, in terms of flood mitigation (Fig. 10), for every percent of forest and perennial cover converted to field crop and paddy, we can expect an increase of 144.57 km<sup>2</sup> of non-mitigated features and a decrease of 131.76 km<sup>2</sup> of mitigating features. More importantly, in the most extreme scenario (i.e. A5) where 25% of the forest and perennial is compromised, the mitigating features would shrink to only 16.21% while the non-mitigated features would expand to 70.59% of the entire basin. This will drastically increase the frequency and severity flood risks in the PRB.

As the intensity of agricultural expansion increases, the area of mitigating features shrinks while the area of negligible risk features expands. More specifically, for every percent of conversion, a decrease of 162.87 km<sup>2</sup> of mitigating features while an increase of 159.21 km<sup>2</sup> of the negligible risks can be observed. In addition, soil loss will also increase by 3.97 tons on a yearly basis. These changes are illustrated in Fig. 11.

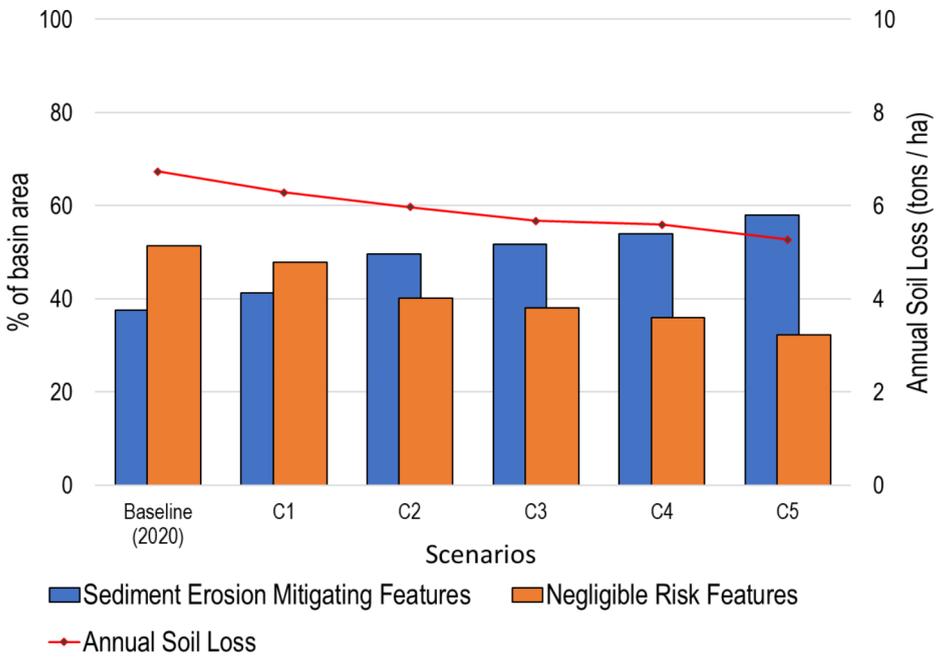


Fig. 9 Sediment delivery and annual soil loss HES changes under different pro-conservation scenarios

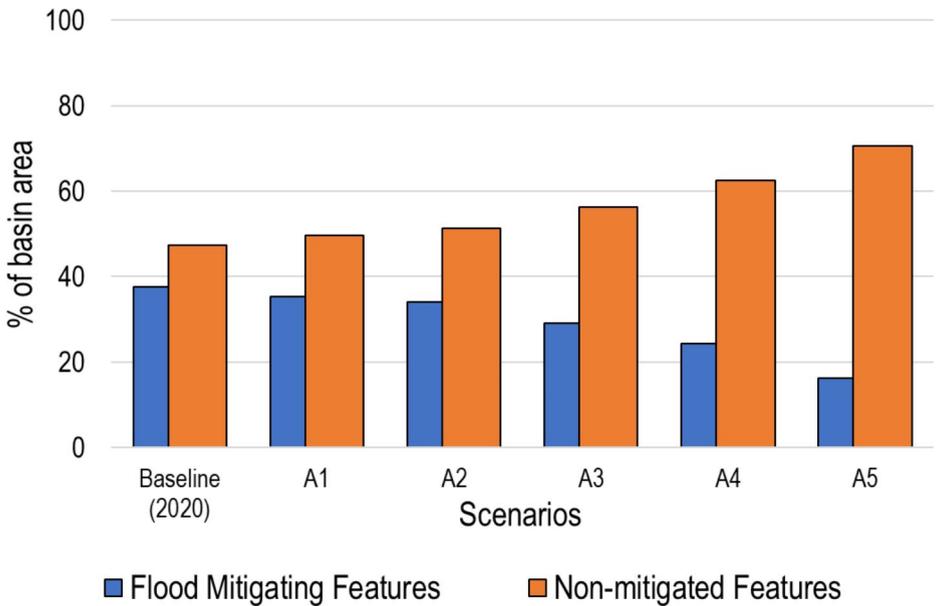


Fig. 10 Flood mitigation HES changes under different pro-agriculture scenarios

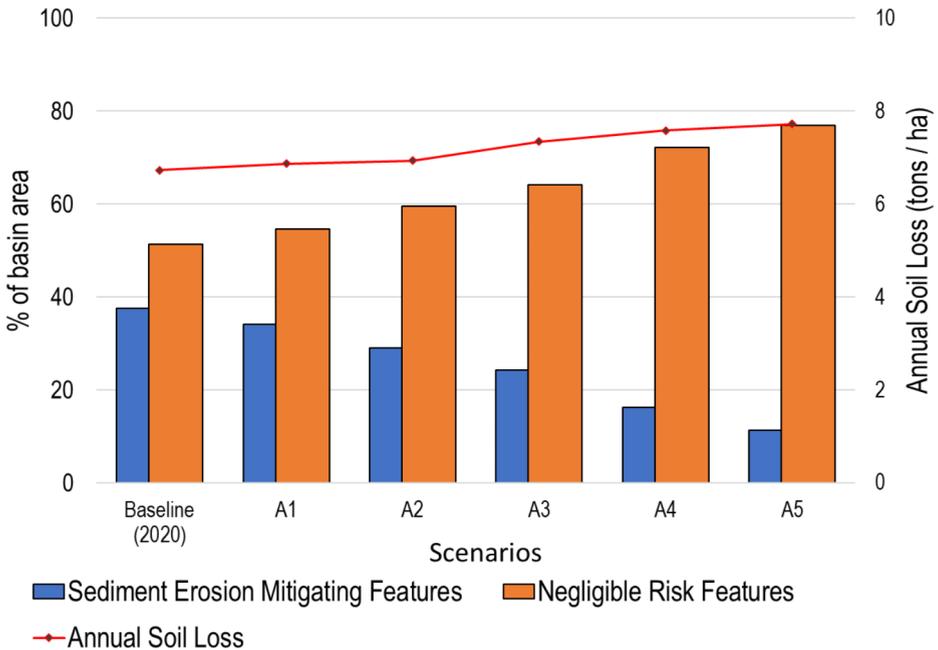


Fig. 11 Sediment delivery and annual soil loss HES changes under different pro-agriculture scenarios

## 5 Discussions

### 5.1 Methodological implications

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2016) emphasizes the use of modeling approaches in decision-making to integrate ESs effectively. To achieve this, it is necessary to have scientific information indicating where ecosystem services are provided, how they have been used, and how different plans and policies may influence them (Silvestri et al., 2013). However, most research studies on ESs explicitly analyze the provision of specific ESs by particular ecosystems or groups (Turkelboom et al. 2016). This approach overlooks the interconnected nature of ESs and their often highly nonlinear relationships (Power et al., 2010). It is, therefore, crucial to identify multiple relevant ESs and consider the underlying mechanisms of ecosystem interactions while making decisions and developing sustainable adaptive management strategies (e.g., Kandziora et al., 2013). The interaction among multiple ESs can be classified as negative (potential trade-offs) or positive (potential synergies) (Turkelboom et al. 2016). The trade-off occurs when the provision of one service rises at the expense of another, while synergy happens when multiple services strengthen or weaken concurrently (Raudsepp-Hearne et al., 2010). Conducting evidence-based trade-off analysis between ecosystem services is thus crucial for implementing a credible policy framework that reflects the spatial-temporal scale of trade-offs, highlights strategies to reduce undesirable trade-offs and related conflicts, and promotes desirable synergies (Turkelboom et al., 2016; Loc et al., 2018).

In addition, previous studies on ES interactions have predominantly been qualitative or semi-quantitative. However, there is a lack of knowledge of quantitative research on multiple ESs (Hong et al., 2020) and integrated evaluation of quantitative ES index that can reflect the capacity of ecosystems to support services on a broader scale (Zhang et al., 2021). This limited understanding of various ESs across the landscape hinders the development of effective ecosystem conservation policy (Zhang et al., 2021). To address these research gaps, studies should prioritize the total value of ESs (Huang et al., 2020) and the spatiotemporal dynamics of ecosystem service index across the area of research.

The quantitative evaluation of ESs, as demonstrated in this study, is an important tool for effectively communicating the significance of ecosystems to decision-makers and policy planners (Vačkář et al., 2018). This reduces the ignorance surrounding the use and non-use wetlands assets, primarily social, cultural, and archaeological values (Loc et al., 2016; Aedasong et al., 2019) during planning for conservation, socio-economic development, and other public policy objectives (Barbier et al., 2007; Chaikumbung et al., 2016). In addition, conducting economic valuation offers a means to evaluate and compare the diverse benefits of ecosystem services with the costs associated with conservation strategies. Quantitative valuations also help to understand user preferences and the relative values placed on ESs (de Groot et al., 2012; Loc et al., 2017). When there are several competing uses for a watershed resource, valuing these services is essential for policymakers and stakeholders to make informed decisions regarding resource optimization (Chaikumbung et al., 2016). However, it should be noted that, unlike hydrological models, modelling HESs or ESs in general is more challenging to calibrate and validate, and the results rely on the accuracy of the input data. In this case, the input models were collected from the official department in Thailand (thus assumed to be reliable). In this study, we were only able to validate the results for erosion risk, as presented in Sect. 4.2.4. More specifically, we compared the results from the LUCI model with the soil erosion risk map from the Land Development Department of Thailand (see Fig. 5). For the other models, we could not validate the results due to the lack of data. Future studies are hence recommended to seek non-traditional ways to validate, e.g., extreme events or through proxies.

Consequently, numerical models play a crucial role in quantifying the value of ecosystem services. They help to identify and assess tradeoffs between different land uses and the benefits they provide. This in turn aid in informed decision-making that maximizes benefits and minimize the negative impacts. It also plays a crucial role in identifying potential synergies between different land uses, such as combining agriculture and conservation for mutual benefits (Faksomboon, 2023; Wang et al., 2023).

## 5.2 Policy implications

The issue of water scarcity has become a growing concern due to human activities, which threaten the natural balance of the environment. This situation presents challenges for policymakers and managers tasked with developing evidence-based plans to conserve water resources and optimize water usage. It is now apparent that managing water resources requires a comprehensive approach that considers the interrelated nature of various factors. Integrated water resource management (IWRM) has emerged as the prevailing approach for addressing water-related issues, as it is grounded in the practical knowledge and experience

of experts in the field. This approach seeks to maximize the economic and social well-being of society in an equitable manner while ensuring the sustainability of critical ecosystems.

According to Chopra et al. (2022), it is paramount to clearly articulate the assessment of the benefits of ecosystems to the policymakers, administrators, and communities, to ensure the implementation of sustainable practices and integration of conservation into decision-making processes. While many countries have adopted sustainable adaptive management strategies for ESs as high-level policies, there is still a need for greater application of these broad policies in the field, tailoring them to meet the specific needs of the overall ecosystem (Loc et al., 2020). Since land use change has been identified as a critical driver of flooding, implementing systematic land use change policy and management will help reduce flood-prone areas (Loc et al., 2021). This study revealed that shifts in land cover in the PRB have influenced the characteristics of runoff, which can lead to a rise in inundation of downstream areas. The pro-agricultural scenario has demonstrated that forest-to-agriculture conversions in this watershed will negatively impact runoff, as evidenced by the expansion of non-mitigated flood areas under this scenario. To reduce flood susceptibility in downstream areas, it is necessary to develop land use policies that restore watershed forests and restrict rapid land use changes. This will increase the additional water retention area for flood mitigation. Another critical policy implication is that restriction of land use changes in ecological preservation districts, which tend to provide high levels of ecosystem services.

Payment for ecosystem services (PES) has gained substantial interest in recent years, as an innovative socio-economic policy for conserving ecosystem services, especially in protecting river basins' resources (R Jarungrattanapong, 2016; Saluja et al., 2024). PES offers a new financial source, providing incentives to promote effective ecosystem service management (Smith et al., 2006; Wunder, Enger, and Pagiola, 2008). It recognizes the limitations of the typical approach (e.g., command-and-control tactics) from government sources, which often cannot provide adequate funds for the sustainable protection of these services (R Jarungrattanapong, 2016). Implementing PES projects yields numerous benefits. It can enhance economic growth related to environmental change, assist in ecological conservation, and increase landowner income in a win-win approach (UN ESCAP, 2009). However, in comparison with the other Southeast Asian nations, Thailand still lacks effective implementation of PES policies. Although some of the activities involving payments for specific ecosystem provisions exist, they may lack certain elements necessary to qualify as practical PES projects. As such, there is a need to enforce legalized rules and regulations to adopt the PES as a mechanism for the sustainable future of ecosystem services in Thailand.

## 6 Conclusions

During the ten-year baseline assessment, significant land use changes were observed across the PRB, primarily due to various socio-economic development activities. Urban built-up and agricultural areas expanded considerably, by 254.58 km<sup>2</sup> and 156.43 km<sup>2</sup>, respectively. In contrast, forest areas shrank by 231.13 km<sup>2</sup> during the same period. Consequently, the flood-mitigating features decreased by 410 km<sup>2</sup> while the non-mitigated areas increased by 101.16 km<sup>2</sup>. Notably, despite an overall increase in flood risks, the HES water supply remained stable, with no significant shifts in average flow between 2010 and 2020. The spatial distribution of the erosion risk in the PRB, like flood risks, exhibited notable

changes. Yet, there was still an increase of 2.21%, equivalent to 345.114 km<sup>2</sup>, in areas with negligible risks, alongside a slight decrease of 0.63%, or 98 km<sup>2</sup> in risk-mitigating features. Meanwhile, both moderate-risk and high-risk areas shrank notably. While the PRB is not particularly prone to serious erosion, as reported by the LDD, the expansion of the risk areas and the shrinkage of mitigating features should not be overlooked, especially in relation to land use decisions.

Based on the findings, several recommendations are proposed for future improvements in methodology and policy formulation. To enhance the effectiveness of sustainable ecosystem management policies, it is essential to study the important multiple ecosystem services to attain a comprehensive understanding of their interconnections, including trade-offs and synergies of ecosystem services. It is also necessary to conduct research on the regional quantitative evaluation of ecosystem services for developing conservation strategies and decision-making. Numerical modeling is also an essential tool for the assessment of ecosystem values. In terms of policy implementation, IWRM is recommended to address water scarcity, as it strives to maximize the social and economic prosperity of society while preserving the sustainability of critical ecosystems. It is also recommended to restrict land use changes in ecologically conserved areas to restore forests and enhance floodwater retention. Additionally, payment for ecosystem services (PES), the innovative socioeconomic policy that provides long-term sustainability of ecosystem services, must be adopted. In the future, it is recommended to conduct thorough sensitivity analyses to better quantify the correlations between the changes of land use and land cover on the provision of HES. In addition, researchers should also explore the implications of climate impacts, which is another important factor driving not only HES but also other ES. Finally, for a better understanding of the spatial and temporal trend of ecosystem services, additional implications in methodologies such as analysis of ecosystem index and coupling of land use change model and ecosystem model are recommended for future studies.

**Data availability** All the data used in this study are either publicly available or primarily collected by the authors. They can be made available upon request.

## Declarations

**Conflict of interest** All authors declare that they do not have any conflicts of interest.

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## Authors and Affiliations

Ho Huu Loc<sup>1</sup>  · Tadam Thanavanh<sup>2</sup> · Dang Anh Nguyet<sup>3,4</sup> · Surabhi Upadhyay<sup>2,5</sup> · Thidar Maung Maung<sup>2</sup> · Sangam Shrestha<sup>2</sup> · Edward Park<sup>6,7</sup> · Perrine Hamel<sup>7</sup>

✉ Ho Huu Loc  
josh.ho@wur.nl

<sup>1</sup> Earth Systems and Global Change, Environmental Sciences Group, Wageningen University and Research, Wageningen, Netherlands

<sup>2</sup> Water Engineering and Management, School of Engineering and Technology, Asian Institute of Technology, Pathum Thani, Thailand

<sup>3</sup> School of Geography, Environment and Earth Sciences, Victoria University of Wellington, P.O. Box 600, Wellington 6140, New Zealand

<sup>4</sup> BEEA Ltd, P.O. Box 28105, Wellington 6150, New Zealand

<sup>5</sup> Hydrologic Science and Engineering, Colorado School of Mines, Golden, CO, USA

<sup>6</sup> National Institute of Education (NIE) and Earth Observatory of Singapore (EOS), Nanyang Technological University (NTU), Singapore, Singapore

<sup>7</sup> Asian School of the Environment (AS) and Earth Observatory of Singapore (EOS), Nanyang Technological University (NTU), Singapore, Singapore