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Framework for a more balanced consideration of hydropower development through ecosystem services assessment

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ABSTRACT

Hydropower is a controversial form of clean energy, as it may cause negative impacts on ecosystems. Here we propose a framework associated with ecosystem services (ESs) assessment for a more balanced consideration of hydropower development and to take measures to mitigate trade-offs among different objectives. We applied this framework in a case study evaluation in China's Yalong river basin, using the InVEST platform for the spatial quantification of ESs in three different periods of the hydropower development process (before construction, during construction, and during operation) and considering the interests of three key stakeholder groups (government, developer company, and general public). After controlling for climatic factors, hydropower-induced land use changes were the key factor affecting changes in ESs. Our results show that hydropower development in the Yalong river basin negatively impacted carbon storage and water purification during construction, mainly because of damage on the natural vegetation. Ecological restoration measures reduced negative impacts on ESs while increasing hydropower production. The ESs spatial model provided decision-making support for zoning policy, facilitating hydropower managers' capacity to prioritize their limited resources. For example, vegetation replanting should be implemented in hydropower areas after construction, and natural vegetation protection should be the highest priority in upstream ecologically fragile areas. This study presents a sustainable framework for analyzing ES changes associated to hydropower development. Appropriate measures should be taken to alleviate the hydropower impacts in China and elsewhere.

1. Introduction

1.1. Background

Hydropower allows us to reduce our dependence on fossil energy, but its large-scale engineering construction has impacts on the environment (Wang et al., 2022). Countries worldwide have different attitudes towards hydropower development (Premalatha et al., 2014). The U.S.A. and some European countries (e.g., Sweden, Spain, Portugal, the U.K.) have stopped developing large-scale hydropower projects and started demolishing dams (Connor et al., 2015; Magilligan et al., 2016). As these countries have already exhausted most of their potential for hydropower development, the economic benefits of new dams are generally insufficient to compensate for the damage to river continuity and the environment (Connor et al., 2015). Moreover, many dams have been in place for a long time, and their maintenance costs have risen. However, in countries with suitable conditions (e.g., France and Switzerland), economic and ecological benefits have been achieved through technological innovation on existing dams, and hydropower continues to be an important component of their energy structure (Moran et al., 2018). At the same time, hydropower constitutes a green economy opportunity for countries with rapid economic development (e.g., China, Malaysia, Indonesia, Thailand, and Myanmar). In these countries, there is still potential for hydropower development

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(Tang et al., 2019) because the benefits of hydropower would overcome the environmental burden caused by the current usage of petrochemical energy. This reduction of the dependence on petrochemical energy allows developing countries to avoid economic losses from environmental restrictions in international trade, such as regional carbon tariffs (Fang et al., 2020a).

Given the pros and cons of hydropower, there is an urgent need for a systematic framework to evaluate trade-offs between hydroelectric-caused benefits and ecological losses. The planning of specific hydropower projects requires knowing whether the benefits generated are indeed higher than the costs of their development and operation. The results of such evaluation can be expected to vary substantially among countries and projects due to differences in hydropower potential and ecological environment. This framework would provide a basis for governments to adopt different strategies towards hydropower development (Voegeli et al., 2019). In this study, we try to explore the following issues: (a) how to build an evaluation framework for hydropower development weighing up economic and ecological consequences?; (b) is there any ecological impact of hydropower development that has been omitted from the environmental impact assessment in the existing research?; and (c) how can we realize hydropower development with low environmental impact while still obtaining economic benefits?

1.2. Literature review

The benefits brought by hydropower construction have been addressed in depth in the existing literature (Liu et al., 2022; Yu and Xu, 2016). To consider the negative environmental impact of hydropower, scientists have applied ecosystem services (ESs) theory to study hydropower on different continents (Briones-Hidrovo et al., 2020; Espécie et al., 2019). ESs theory can characterize ecosystems' direct or indirect benefits and costs to humans (MEA, 2000; TEEB, 2010), allowing for holistic evaluations beyond economic benefits. Many negative ESs impacts brought by hydropower have been identified, such as the impacts of hydropower facilities on streamflow in rivers (Nilsson et al., 2005), habitats of animals and plants in river basins (Cooper et al., 2017; Kuriqi et al., 2020), greenhouse gas emissions from flooded areas (Fearnside, 2016; Zhang et al., 2015), soil erosion (Su et al., 2017; Zarfl and Lucía, 2018), and water quality decline (Premalatha et al., 2014). Some scholars have noted these analyses' importance and taken the benefits trade-off as a policy guide in hydropower development (Klauer et al., 2013; Stephenson and Shabman, 2019). However, these trade-offs in different stages of hydropower development have seldom been analyzed in empirical studies (Cooper et al., 2017; Zarfl and Lucía, 2018). Although governments worldwide have afforded great importance to the maintenance of ESs, it is still a rarity to consider ESs theory within the whole lifecycle of hydropower development (Briones-Hidrovo et al., 2020; Espécie et al., 2019).

The hydropower development process requires large-scale engineering construction, which can directly affect the land use and land cover (LULC) of the river basin (Dorber et al., 2018). For example, if natural vegetation is cut down for the transportation of engineering materials, these construction activities are directly altering the biophysical formation process of ESs (Espécie et al., 2019; Boesing et al., 2020). Scholars assessed the severity of these impacts by tracing the state of LULC change at different stages of the hydropower development (Dorber et al., 2018). LULC can affect ESs in two ways: by making direct changes to the ESs supply capacity and by altering the correlation between ESs supply levels (Bai et al., 2021; Willcock et al., 2021). These incidences will directly affect what measures managers should take to manage the basin's ecological protection.

In recent years, many ES models and simulation platforms are becoming more powerful and easier to use (Sharp et al., 2021), which benefits researchers and practitioners (Fang et al., 2021). Among them, InVEST is an integrated model for assessing ESs and their trade-offs, which has been widely used in various countries and regions (Bai et al., 2020; Fisher et al., 2011) and we used in this study. InVEST can illustrate the ESs results spatially on a map, which is helpful to hydropower managers in developing appropriate management measures according to the state of ESs in different regions (Bai et al., 2021; Fang et al., 2022).

1.3. Research motivation and section arrangement

The motivation of this study was to integrate ESs into a framework to evaluate the impacts of hydropower development. Three objectives need to be achieved for this purpose: (1) to study the states of ESs at different stages of the hydropower development process in a particular area (in our case we used China's Yalong river basin as a case study); (2) to analyze changes in ES provision before and after hydropower development, including mean levels and trade-off relations; and (3) to consider the suitability of hydropower development in specific areas from the perspective of ESs, and to provide management suggestions to enhance ESs within sustainable hydropower development.

Integrating the ES concept into hydropower development and operation would provide important theoretical support for the sustainable development of future hydropower projects. The trade-offs between the socio-economic benefits of hydropower development and potential negative impacts on ESs could be integrated in an extension of the existing evaluation framework. The remaining sections of this paper are arranged as follows. The second section introduces the framework and specific methods of hydropower development impact assessment based on ESs. The third section shows the evaluation results of the Yalong river basin, in China, during each stage of the project development. In the fourth section, based on the evaluation results, we discuss the management implications to improve ecological and economic trade-offs associated to hydropower development. We also explain the limitations of this paper and future research directions. In the last section we present the conclusions of our study.

2. Methods

2.1. Framework for quantifying hydropower construction impacts on ESs

This study develops an integrated and operational framework to quantify ESs in hydropower construction and operation periods (Fig. 1). The framework consists of the following five stages: (1) defining the research period as pre-construction, construction, and operation periods, according to the development schedule of existing hydropower stations in the study area; (2) identifying and fixing climatic factors to be considered throughout the study period, to strip out potential ESs changes due to these factors; (3) determining and estimating the key ESs to be evaluated, which should reflect quantitative impacts of hydropower construction on the environment and the interests of the relevant stakeholder groups; (4) quantifying LULC changes during the construction and operation periods expressed as a land use transition matrix. For this, ESs changes (ANOVA) and trade-offs (Pearson correlation) analyses were conducted by extracting ESs values with an ArcGIS random point sampling tool; and (5) proposing management initiatives to achieve sustainable hydropower development, in our case study, for the development to be consistent with China's ecological civilization strategy.

2.1.1. Key variable identification and control

LULC and climate have been identified as two major factors impacting ESs and their correlations (Fang et al., 2020b; Hoyer and Chang, 2014), and are also the main input parameters to the InVEST model (Sharp et al., 2021). Land composition and configuration changes associated with land use change are the main consequences of hydropower construction and operation in hydropower development (Espécie et al., 2019). We fixed climate factors by using the average

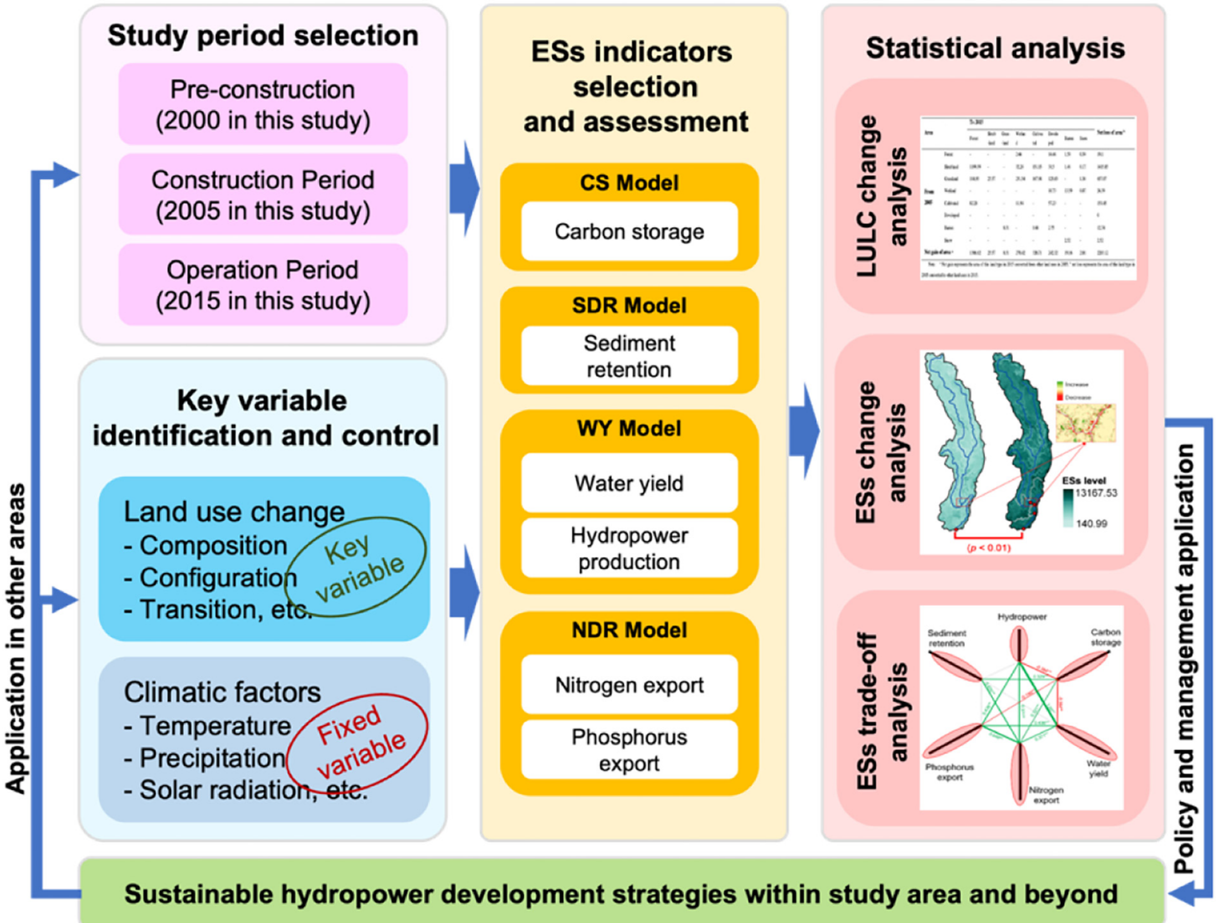

Fig. 1. Integrated framework for sustainable hydropower development strategies. (CS = carbon storage, SDR = sediment delivery ratio, WY = water yield, NDR = nutrient delivery ratio).

values for the study period (Fig. S3 in SI) to separate the impact of ESs changes from climatic factors, as it is an important driving factor for ESs but not directly related to the hydropower development (Chen and Unsworth, 2019).

LULC and climate data were used as input to the InVEST model, and various ES indicators of the whole basin were simulated. The class definitions of LULC are shown in Table S3 in SI. Through zoning statistics and land use transfer matrix, the composition and mutual transformation of land use types in the upper-middle basin and the lower basin were analyzed, and differences between hydropower construction areas and non-impacted areas were identified. The focus was on the total quantity and spatial change of various vegetation types (such as forest, shrubland, and grassland) and developed land in the hydropower construction area of the lower basin to analyze the changes in ES indicators driven by these.

2.1.2. ESs selection, assessment, and calibration

We selected ESs based on concerns among three key stakeholders in the hydropower development basin. The key stakeholders were (1) the local government, (2) the general public, and (3) the hydropower company. Their respective interest and the ESs concerned are shown in Table 1.

The local government was deeply concerned about the health of the basin ecosystem, with particular regard to water and soil conservation and vegetation coverage, as the area is designated to be a key conservation area for water and soil resources by the central government,

Table 1
ESs selection based on the analysis of various stakeholders.

Stakeholders	Goals	ESs concerned
Local government	High-quality political achievements: ensure ecological health and balanced regional development	**Soil retention:** Key assessment indicator of regional ecological protection. **Water purification**: directly impacts the quality of public water supply, closely related to public health (Liu and Mao, 2020). **Carbon storage:** reflects the contribution of carbon reduction in the region (Wang, 2019). **Hydropower production:** closely related to development status of local economy.
General public	Access to sufficient clean water	**Water yield:** closely related to the available amount of surface water for the public (Bai et al., 2019). **Water purification:** directly impacts the water quality of public water supply, closely related to public health (Liu and Mao, 2020).
Hydroelectric company	Hydroelectric economic benefits	**Water yield:** closely related to hydropower production quantities. **Hydropower production:** The fundamental purpose and source of behaviour motivation.

according to the Ministry of Ecology and Environment's (MEE) plan (MEE, 2015). The local government was also concerned about the economic performance of the local hydropower development. The general public paid considerable attention to water quantity and quality problems, because the Yalong river is an important water supply source for many cities and towns (MEE, 2010), and problems with the quantity and quality of water could affect their health. The hydroelectric company, meanwhile, was more concerned about economic benefits, water yield, and hydroelectric power generation. We selected six indicators to represent the ESs of interest: carbon storage, sediment retention, nitrogen export, phosphorus export, water yield, and hydropower production. The basic calculation models for the selected ESs were as follows:

Carbon storage: InVEST aggregates the amount of carbon stored in pools according to land use maps and classifications (Sharp et al., 2021). Carbon storage on a land parcel largely depends on the sizes of four carbon pools: aboveground biomass, belowground biomass, soil, and dead organic matter.

Sediment retention: InVEST maps overland sediment generation and delivery to the stream (Sharp et al., 2021). The amount of annual soil loss in each pixel is computed using the revised universal soil loss equation (RUSLE).

Water yield: In InVEST, the annual water yield for each pixel is estimated based on average annual precipitation and the Budyko curve (Sharp et al., 2021). Hydropower production is calculated based on runoff brought about by water yield and information (e.g., height, location, quantity) on hydropower stations.

Water purification: InVEST maps nutrient sources from watersheds and nutrient transport to streams (Sharp et al., 2021). Although there are multiple potentially significant impairments of water quality, this study focused on total nitrogen and total phosphorus.

Part 1 in SI provides a detailed description of our calculation processes. A summary of data availability, sources, and related input parameters can be found in Tables S4-S6 in SI.

To verify the accuracy of the results of our InVest model, we used independent data from other research in the study area. For example, the CS model was compared with the mean levels of soil carbon density from several other studies. Indeed, recent studies have estimated the soil carbon density to be about 100 t hm^{-2}. Based on the example data of the InVEST model, we assigned a carbon density of 100 t hm^{-2} to forest soils, and a value of 80 t hm^{-2} to soils in shrubland, grassland, and cultivated land. These calibration results are consistent with the independent data from other studies. Similarly, we used relevant data to calibrate the analyses of SDR, WY, and NDR (details can be found in Part 2 in SI).

2.1.3. Statistical analysis

(1) LULC change

Hydropower is the pillar industry of the Yalong river basin and the main stimulus of human activities and LULC change in this area. Zoning statistics analyzed land use change data in the different hydropower development periods to represent the land composition of the study area. A land use transition matrix expressed the conversion relationship of various land use types.

(2) ESs change analysis

All six ESs indicators were spatially distributed in the calculations in InVEST. Analysis of variance (ANOVA) was used to test for changes in ESs in the different periods. The specific changes were described by statistics on ESs at the whole basin scale. The data on various indicators in the different periods were compared, and the spatial distribution of the difference (aggregated growth or decline) was expressed spatially by labeling the positive and negative results in different colors. Large quantities of samples (10,000 random points) were collected by ArcGIS random point tools. This large sample size gives us confidence on the reliability of the results, particularly in the case of lack of significant effects.

(3) ESs trade-off analysis

We used Pearson correlation analyses, a standard method (Roy et al., 2018) to evaluate ESs trade-offs and trend changes in the different stages of hydropower development. Correlations among ESs can be either synergistic or trade-off correlations (Bai et al., 2021), and these may change with hydropower development and other human activities (Chen et al., 2018). Therefore, it is essential to identify how LULC might influence this correlation and which LULC situation might help improve the overall state of ESs, leading to management decisions for a win-win output of hydropower development. In this study, we combined the change rate and correlation analysis to identify changes in correlations between various ESs driven by hydropower development. We also explored the optimal LULC plan to enhance synergies and reduce trade-offs based on the spatial distribution of ESs change results. The year 2000 was set as the base year in correlation analysis, and all indicators in 2005 and 2015 were standardized to the level in 2000. ArcGIS random point tools collected ten thousand sampling points for Pearson correlation analysis, which was conducted to investigate the pixel-scale correlations between ESs in different periods.

2.2. Empirical case introduction

China has the richest hydropower resources and the highest annual energy production in the world. It has the theoretical capacity to generate 6.06 trillion kWh of hydropower per year and the potential capacity for technically exploitable hydropower of 500,000 MW (Chang et al., 2010; Li et al., 2018). Hydropower will become an important energy supply for China in the future; China has promised to achieve carbon neutrality by 2060 (Mallapaty, 2020).

Yalong river (25°12′N–34°9′N, 96°47′E–102°42′E) is located in the western part of China's Sichuan Province and covers an area of about 137,000 km^2, being one of the largest tributaries of the Yangtze river (Wang et al., 2019). The Yalong river basin has very complex climate conditions, with an annual average rainfall of 500–1200 mm and an annual temperature of 7.5 °C. It is mainly affected by the western atmospheric circulation and southwest monsoon at high altitudes, and is characterized by changes in topographic elevation and latitude between north and south, leading to differences not only in climate conditions between different parts of the basin (e.g., higher rainfall and lower temperature in the north than in the south (He et al., 2015); drier weather and higher temperature in valleys than in mountains) but also in socioeconomic conditions of the upper-middle and lower regions of the basin (Litang river estuary is the dividing point of the lower basin of Yalong river; see Fig. 2). Compared with the upper-middle basin, the lower basin has more developed industry and agriculture, a more concentrated population, and better social infrastructure.

The planned installed capacity of the Yalong River Hydropower Base ranks third in China's hydropower bases, which is of great significance in supporting China's energy strategy. All current hydropower facilities were built and used in the lower basin (Fig. 2). Detailed hydropower stations introduction and development process are shown in Part 3 in SI.

Five hydropower stations (Guandi, Jinping I, and Jinping II, Ertan, Tongzilin) are now operating along the Yalong river (Fig. 2). Tongzilin station was put into operation on Anning river in 2018. Thus, the available LULC data cannot represent its impact, and this station was not considered in the analysis. Therefore, we only considered four stations (Guandi, Jinping I, Jinping II, and Ertan) to evaluate hydropower impacts on ESs across three periods: pre-construction (before 2000), construction (2000–2005), and operation (2005–2015). These time periods were defined according to the development cycle of three stations: Guandi, Jinping I, Jinping II. The remaining station, Ertan, has been operating since 1999, so its hydropower production service will be measured throughout all periods. In other words, all hydropower production before 2015 was provided by Ertan station alone, while the hydropower production in 2015 was provided by all the four stations. All operating hydropower stations were built on the Yalong river

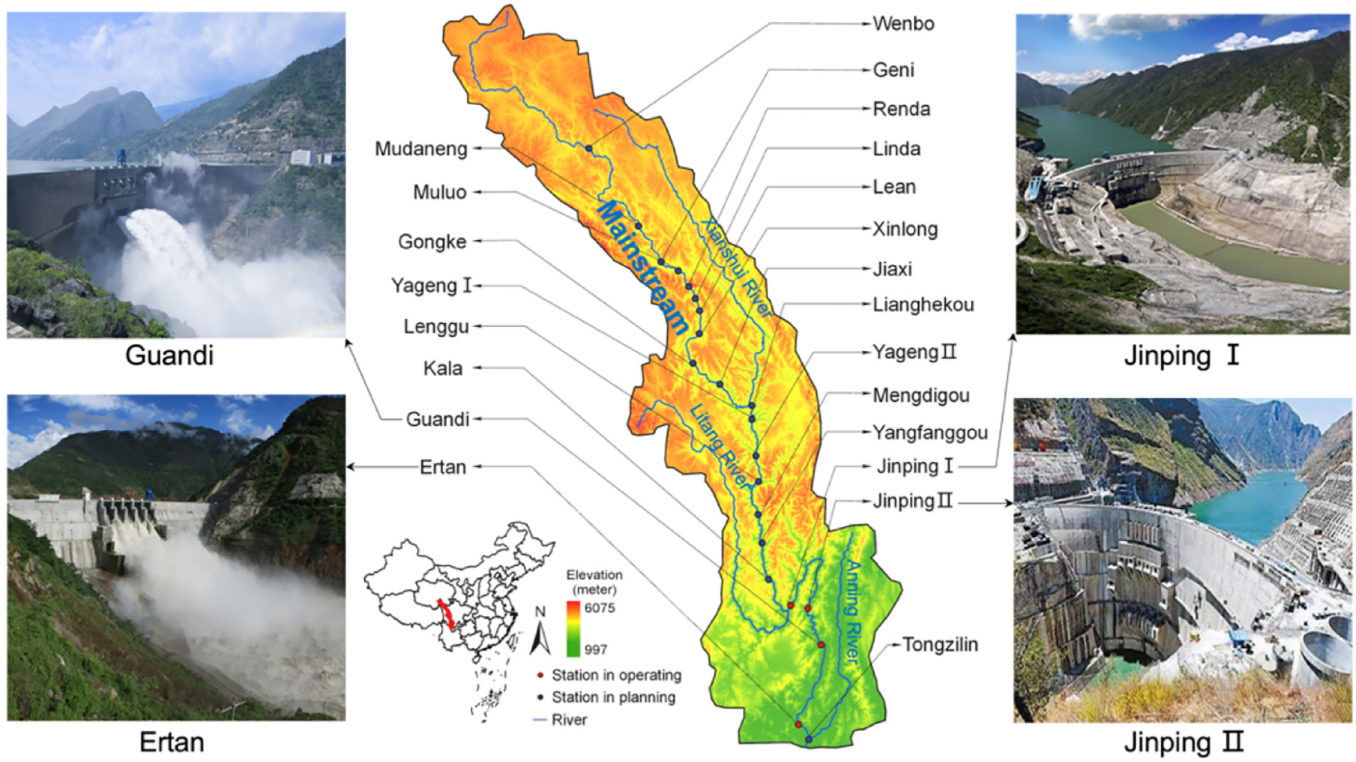

Fig. 2. Location of the Yalong river basin in Southwest China and distribution of all hydropower stations (in planning or operation in 2015) along downstream river reaches (pictures from the website of Yalong River Hydropower Development Co., Ltd. http://www.ehdc.com.cn/webCenter/home.do).

mainstream, and Anning river, a downstream confluence tributary (as shown in Fig. 2.), cannot contribute to hydropower services supply.

3. Results

3.1. Hydropower-induced land use changes

Under the influence of hydropower development, land use changed slightly in the construction period (2000–2005) while showing relatively larger changes in the operation period (2005–2015) (Table 2). Natural vegetation (forest, shrubland, and grassland) occupied most of the area (over 85 %) in the whole basin all the time (Table 2). Overall, there was no drastic change in LULC composition in the entire basin.

We present details of LULC changes during the operation period (2005–2015) in Table 3. Forest area showed the most area gain by 1387 km^2 from 2005 to 2015, mainly converted from shrubland, grassland, and cultivated land. Shrubland showed the greatest area loss, with 1416 km^2, mainly through conversion into forest and cultivated land. Grassland area also decreased by 657 km^2, mainly changing into wetlands, developed land, cultivated land, and forests. Developed land increased by 242 km^2, mostly converted from grassland and cultivated land. Cultivated land showed noticeable two-way changes, with 321 km^2 gained and 151 km^2 lost, simultaneously. The primary loss of cultivated land was through conversion to forest and developed land, while the main gain in cultivated land was through conversion from shrubland and grassland.

3.2. Changes in ESs supply capacity

Overall, the only statistically significant change was hydropower production, which occurred between 2015 and the previous periods ($p < 0.01$). The difference in hydropower production between 2000 and 2005 was not significant ($p > 0.05$). Hydropower production showed a tremendous increase from 11.98 billion kWh to 51.77 billion kWh, with a growth rate of 332 % from 2005 to 2015 (Table S8 in SI). No other significant statistical differences were found in other ESs during the study period (Fig. 3).

Table 2
Land use composition of Yalong river basin in 2000, 2005 and 2015.

Area (km^2)	2000 (pre-construction)		2005 (construction period)		2015 (operation period)	
	Area	Percentage	Area	Percentage	Area	Percentage
Forest	36,089.69	24.39 %	36,102.46	24.40 %	37,456.02	25.31 %
Shrubland	32,843.85	22.20 %	32,765.40	22.14 %	31,453.43	21.26 %
Grassland	59,838.33	40.44 %	59,861.59	40.45 %	59,188.01	40.00 %
Wetland	4671.50	3.16 %	4677.92	3.16 %	4925.62	3.33 %
Cultivated	7944.76	5.37 %	7955.26	5.38 %	8116.68	5.49 %
Developed	174.85	0.12 %	196.48	0.13 %	417.25	0.28 %
Barren	5810.28	3.93 %	5814.15	3.93 %	5816.50	3.93 %
Snow	597.89	0.40 %	597.89	0.40 %	597.64	0.40 %
Total	147,971.15	100.00 %	147,971.15	100.00 %	147,971.15	100.00 %

Table 3
Conversion balance between different land uses in the Yalong river basin, China, 2005–2015.

Area (km^2)		To 2015								Area loss
		Forest	Shrubland	Grassland	Wetland	Cultivated	Developed	Barren	Snow	
From 2005	Forest	–	–	–	2.66	–	14.46	1.59	0.39	19.1
	Shrubland	1199.39	–	–	32.28	151.05	31.5	1.46	0.17	1415.85
	Grassland	104.95	25.57	–	231.54	167.98	125.65	–	1.38	657.07
	Wetland	–	–	–	–	–	10.73	13.59	0.07	24.39
	Cultivated	82.28	–	–	11.94	–	57.23	–	–	151.45
	Developed	–	–	–	–	–	–	–	–	0
	Barren	–	–	8.31	–	1.68	2.75	–	–	12.74
	Snow	–	–	–	–	–	–	2.52	–	2.52
Area gain		1386.62	25.57	8.31	278.42	320.71	242.32	19.16	2.01	2283.12

Despite the lack of statistically significant changes in ES provisioning (except for hydropower production), slight differences in trend can still be noted (Table S8 in SI). For example, during 2000–2005, water yield, nitrogen export, and phosphorus export showed a slightly increasing trend, while carbon storage and sediment retention services decreased. During 2005–2015, carbon storage, nitrogen export, phosphorus export, and sediment retention showed non-significant increases, while water yield showed a non-significant decrease.

3.3. Spatial mapping of ESs changes

Hydropower production services of the whole basin increased in 2015 with the newly built hydropower stations. We did not map this change because the entire basin was rising (except for the Anning river sub-basin with no hydropower stations). Other ESs' slight changes in 2000–2005 were mainly concentrated in the downstream area, where hydropower facilities were built (Fig. 4). For example, the spatial

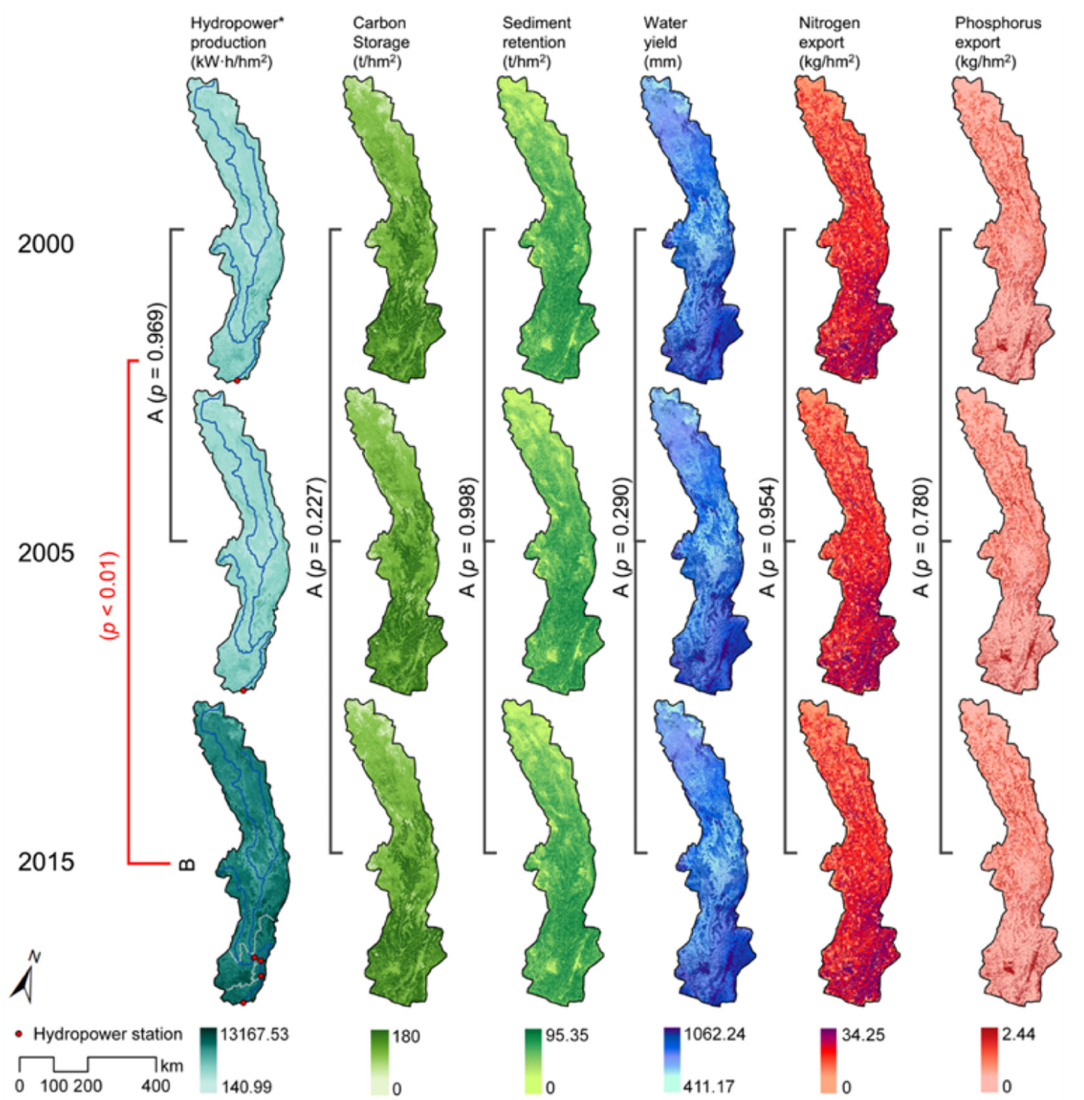

Fig. 3. Spatial distribution of ecosystem services in 2000, 2005, and 2015. (Note: p indicates significant difference tested by ANOVA between means in different years.)

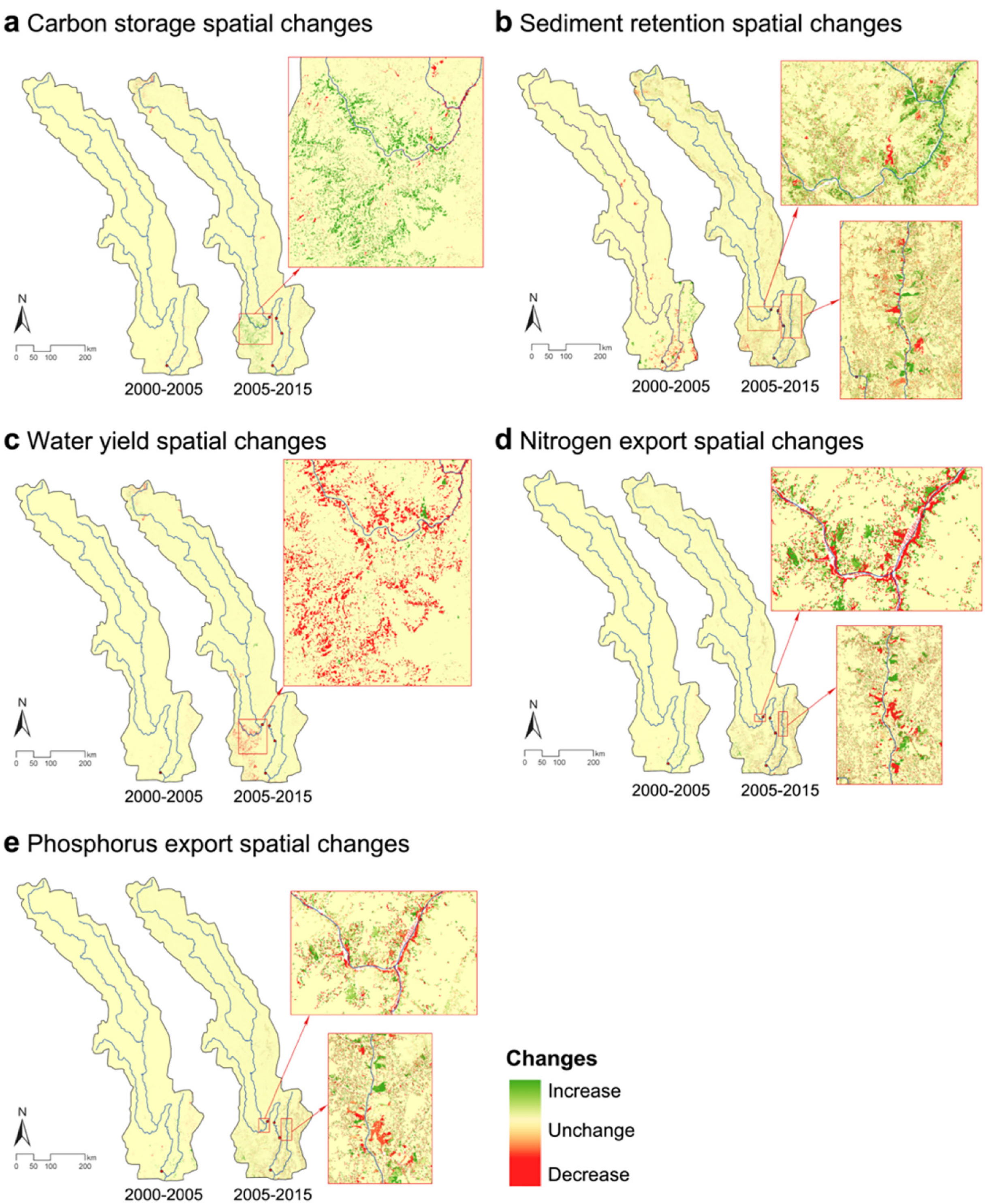

Fig. 4. Spatial distribution of ecosystem services change in Yalong river basin in 2000–2005 and 2005–2015.

changes of sediment retention downstream during 2000–2005 are identified (Fig. 4b).

Changes in other ESs were mainly concentrated around two areas from 2005 to 2015: Jinping I reservoir (the highest-level reservoir) and Anning river (the Yalong river downstream tributary). The most apparent ESs changes in these areas were the increase in carbon storage and sediment retention (Fig. 4a-b) and the decrease in water yield (Fig. 4c). Nitrogen and phosphorus export changes showed complex interlacing characteristics, as both increases and decreases co-occurred around the confluence of Litang river's mainstream and in the Anning river sub-basin (Fig. 4d-e). During the study period, the ESs upstream without hydropower development did not show spatial changes (Fig. 4a-e).

3.4. Trade-offs between hydropower and other ESs

The correlations between hydropower production and other ESs showed no essential change (no correlation conversion from positive to negative, or opposite) from 2000 to 2015 (Fig. 5). Significant positive correlations were detected between hydropower production and three

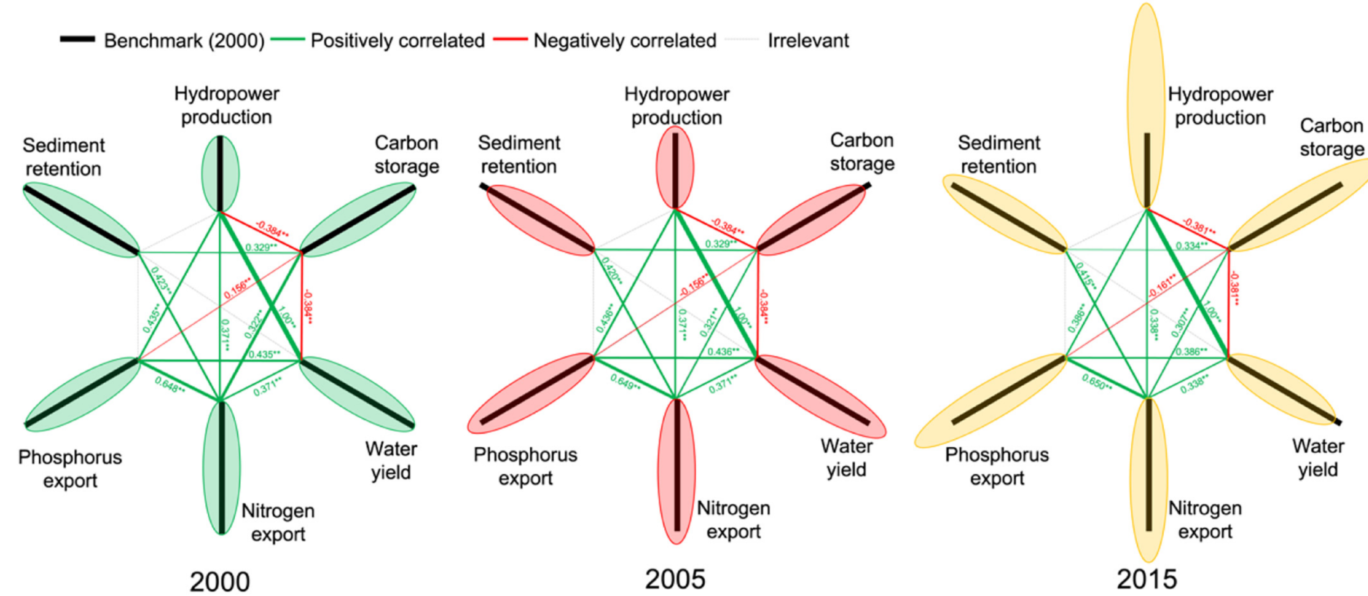

Fig. 5. Trade-offs between different ecosystem services indicators over time (n = 10,000; **p < 0.01.)

other ESs (water yield, phosphorus export, and nitrogen export). In contrast, there was a negative correlation between hydropower production and carbon storage (Fig. 5) and no significant correlation between hydropower production and sediment retention (Fig. 5).

Hydropower production was strictly bound with water yield due to the physical generation mechanism of hydropower, which shows a complete positive correlation (Pearson $r = 1$, $p < 0.05$) (Fig. 5). The new hydropower stations in 2015 made a significant leap in hydropower generation capacity provided by per unit runoff. These stations brought a massive increase in total hydropower production, even though the water yield decreased (Fig. 5). This change in the unit production capacity of hydropower might also weaken all the correlations between hydropower production and other ESs; both positive and negative correlation values were closer to 0 from 2005 to 2015 (Fig. 5).

4. Discussion

4.1. Achieving a win-win situation between hydropower production and ESs

Dam construction, reservoir impounding, and other hydropower development activities will influence the biophysical processes that lead to ESs generation by shaping different ecological landscape patterns. This makes it difficult for us to achieve both hydropower and ecological benefits at the same time. In this study of the Yalong river, trade-offs did exist between hydropower production and some other ESs, which were mainly manifested in downstream changes in vegetation during the construction period. These vegetation changes had a positive outcome in increasing water production and negative ones by reducing soil conservation and increasing nitrogen and phosphorus exports in downstream areas (Qi et al., 2019). During the operation period, the rising economic benefits of hydropower are likely to increase the level of urbanization downstream and the expansion of construction land, further increasing nitrogen and phosphorus exports from the basin (van Puijenbroek et al., 2019).

As we detected, hydropower development in the Yalong river basin impacted the correlations of ESs by slightly weakening their degree but without radically altering their properties (Fig. 5). For example, there was a significant trade-off between hydropower production and carbon storage caused by the exclusive use of water resources. If water is absorbed by natural vegetation and used for plant growth, it will not directly form surface confluence as the source of hydropower generation. Moreover, the engineering construction in the process of hydropower development will inevitably damage the natural vegetation on the surface, which will further lead to a decline in carbon storage. Additionally, even the synergistic relationship may also be a constraint for hydropower. For example, the benefits of hydropower and water production can be unified (entirely positive correlation), but the capacity of water yield also limits the benefits of hydropower. As shown in Fig. 5, both hydropower production and water yield declined in 2005.

This trade-off relationship is an objective law. However, we can still use these rules to lead the whole ecological benefits in a beneficial direction for humanity. In the case of the Yalong river, additional hydropower stations and afforestation are both effective ways to deal with this trade-off. First, hydropower generation should have declined along with the water yield in 2015, owing to their entirely positive correlation (Fig. 5). However, both parameters changed in the opposite direction (i.e., they both increased), mainly due to a massive increase in electricity generation efficiency brought by newly built hydropower stations (Chang et al., 2010). Second, the significant negative correlation between hydropower production and carbon storage should have led both to change in opposite directions, yet they both rose in 2015. According to our investigation, Yalong River Basin Hydropower Development Co. Ltd. implemented a 2.4 km^2 afforestation program around the reservoir in 2003, with an average tree survival rate of 90 % (Wang, 2018). These trees matured during the operation period and were observed by remote sensing, which impacted the assessment of carbon storage. Afforestation can increase carbon storage capacity, water conservation capacity, and sediment retention capacity (Vogl et al., 2016).

Many other ecological protective measures, such as fish breeding and release, fishing facilities, and other ecological protection measures that require enormous investments, have been taken to reduce the impact of hydropower construction and operation in the Yalong river basin on aquatic ecology. For example, the Yalong River Basin Hydropower Development Co. Ltd. has invested 150 million RMB and set up China's largest fish breeding and release station. When ecological restoration and other measures, such as building sewage treatment facilities to control nitrogen and phosphorus export from downstream urban areas (van Puijenbroek et al., 2019), afforestation (Bernard et al., 2009), and fish breeding and release (Song et al., 2019) in the mainstream hydropower development zones are implemented appropriately, a win-win outcome in improving economic benefits while also improving ecological benefits could be achieved (Liu et al., 2022; Qi et al., 2019).

4.2. Managerial implications and policy implementation

Due to the different contexts and perceptions of its ecological impacts, countries adopt different strategies towards hydropower. It is arbitrary to affirm or deny the absolute value of hydropower in the absence of a contextualized evaluation; instead, a trade-off analysis should be conducted considering economic and ecological consequences associated to hydropower development, as proposed by this research. This study presents a framework for analyzing the ecological impact of hydropower development, based on the evaluation of ESs of concern to several key stakeholders. It provides an approach for a better-balanced consideration of hydropower development. Such a framework is also consistent with China's strategy of 'ecological civilization', which aims to transform the country's primary national policy goal from merely focusing on gross domestic product (GDP) growth into a harmonic integration of social inclusion, environmental sustainability, and economic development, according to China's State Council (SC, 2015).

By controlling the meteorological factors to remain unchanged as the base year, we could attribute the observed ESs changes to changes in LULC induced by hydropower development. The main impact observed was the loss of natural vegetation (forest, shrubs, and grassland) in local areas during construction, which are the main providers of ESs. Economic benefits brought by hydropower also promoted urbanization and increased built-up and cultivated land, which may further lead to increased nitrogen and phosphorus exports. Such kind of trade-offs between economic development (in this case hydropower) and other ESs may be the unshakable objective laws of human will. However, we found that in cases like the Yalong river basin, we can still achieve win-win situations through technological upgrading and ecological restoration.

Based on spatial modeling of biophysical process platforms (such as InVEST, used in this study), changes in ESs can be mapped into the refined spatial grid, which allows hydropower managers to focus on areas with key ESs changes driven by hydropower-induced LULC changes (Fu et al., 2014). This makes it possible to implement different policies in different areas, according to management needs. In the case study of the Yalong river basin, we provided the following specific management countermeasures in the upstream and downstream areas.

At present, the hydropower development of the Yalong river is concentrated in the downstream areas. Attention should be paid to restoring the damaged natural vegetation after the engineering construction is finished to ensure that the loss of ESs can be restored. Although there is no hydropower in the Anning river sub-basin, the expansion of towns and cultivated land will lead to regional changes in nitrogen and phosphorus services (Maavara et al., 2015), which may trigger water pollution problems. Therefore, it is necessary to consider comprehensive farmland management and centralized waste treatment to reduce the pollution risk (Fang et al., 2020b).

The upstream area is very close to a National Nature Reserve, where the ecosystem is particularly valuable and relatively fragile. More consideration should be given to the impact of ESs in future hydropower construction, especially in ecologically fragile areas. Future hydropower construction should be carried out with a stage-development schedule according to the ecological carrying capacity. After completing a stage of hydropower development, it is necessary to set forbidden development periods with forest replanting and ecological cultivation to restore ecological capacity. And through long-term ecological assessment, to detect the regional ecosystem pattern and changes of ESs to determine whether the next stage of hydropower development can be started, to ensure that the ecology of the whole basin is safe and sustainable.

4.3. Limitations and research forward

This study devised an ES-based hydroelectric ecological impact assessment framework to allow trade-offs between hydropower production and other ESs to be fully considered. This framework can provide a good platform for hydropower lifecycle assessment and research on withdrawal mechanisms in China and elsewhere. However, we are also fully aware that ESs assessments that rely on the InVEST model may not be sufficient to characterize the ecosystem services fully. ESs within rivers, as opposed to ESs within the basin, are challenging to assess due to model and data limitations. Due to the lack of long-term tracking data, we could not evaluate the economic costs of ESs compensation or ecological restoration measures, nor could we analyze the effectiveness of aquatic ecological protection measures on aquatic biodiversity. Furthermore, this study used large quantity samples in the ESs comparison analysis, which helped to exclude the possibility of inferring non-significant ESs change due to insufficient samples. These large quantity samples, however, may reduce the credibility of significant differences in hydropower production. It is, essentially, a trade-off at the method level, which also reflects the complexity of ESs change characteristics.

There are many ecological reserves in the Yalong river basin, its economic development depends on the hydropower industry, and many human activities are also generated around the hydropower industry. So, in this study, we attribute the change of LULC to hydropower development. Although hydropower development often has spatial independence, composite factors may lead to LULC changes in other areas. This needs to be divided by spatial identification before more accurate analysis can be carried out on the dam reservoir area to eliminate interference factors.

5. Conclusion

This study proposed an ES-based multi-stage evaluation framework to study spatio-temporal correlations among four types of ESs closely related to hydropower development over different periods in the Yalong River Hydropower Base in Southwest China. Hydropower development was found to have negative impacts on ESs, but sustainable ecological restoration measures were found to improve these during the hydropower operation period. The key message from our evaluation of the Yalong river basin is that we may achieve a win-win situation of hydropower and ecological benefits through long-term ecological management. Moreover, the spatial evaluation of ESs based on biophysical processes (such as InVEST used in this study) can provide a decision-making basis for more accurate ecological spatial management and control. This framework is not static but can be further expanded as needed. It is considered to introduce the health assessment of the river ecosystem and discuss the survival of aquatic organisms in future research. This study proposes a systematic framework to evaluate ESs changes and provides evidence that win-win outcomes, improving economic and other ESs benefits, can be achieved in relation to hydropower development.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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