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Exploring Ecosystem Service Trade-Offs and Synergies for Sustainable Urban Watershed Management in Indonesia – A Case Study of the Citarum River Basin, West Java, Indonesia

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ABSTRACT

Understanding the relationships among ecosystem services (ESs) are crucial for sustainable watershed management. Current studies on ESs often focus on mapping individual services, but there is limited research on the trade-offs and synergies degree (TSD) among them. The objectives of this study are: (i) to map multi-year data for three Ess: water yield (WY), carbon stock (CS), and soil conservation (SC); (ii) to examine the TSD among these ESs; and (iii) to identify the variables that influence TSD. The Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model was used to map WY, SC, and CS in the Citarum Watershed, Indonesia. Multiscale geographically weighted regression (MGWR) model was employed to explore the relationships between the factors influencing TSD. The results indicate that (1) both WY and CS experienced similar downward trends, decreasing by 18.37% and 2.89% from 2000 to 2010, and by 15.01% and 4.98% from 2010 to 2020, respectively. In contrast, SC increased by 10.60% from 2000 to 2010 and by 12.03% from 2010 to 2020. (2) The TSD analysis revealed significant variations in trade-offs and synergies within the Citarum watershed, with the most prominent TSD occurring between WY and SC (approximately 64%). (3) The driving factors of TSD include vegetation, topography, climate, and social factors, contributing 34.51%, 31.99%, 20.92%, and 11.58%, respectively, to the WY-SC trade-off. The novelty of this research lies in its integration of TSD with the MGWR model, providing valuable insights into the complex spatial relationships between TSD and its driving factors. These findings offer important contributions to sustainable watershed management.

Keywords: carbon storage, water yield, InVEST model, MGWR model, heterogeneity analysis, ecological, spatio-temporal, sustainability.

INTRODUCTION

The interaction of ESs can impact the natural environment, human well-being, and the socio-economic sphere (Turner et al., 2014). ESs exhibit trade-offs when the improvement of a specific service aligns with a decrease in others, and synergistic effects arise when multiple ESs concurrently rise or fall together (Goldstein et al., 2012). Global change deeply affects the provision of global ESs by influencing ecosystem structure and function, endangering human habitats, and affecting the sustainable progress of societies and economies (Fahad et al., 2021). Among these factors, alterations in climate and land use stand out as primary drivers dictating the extent and trajectory of changes in ESs (Fahad et al., 2019).

Ecosystem management should involve the progress of individual ESs and the meticulous adjustment the interplay between various ESs to optimize overall advantages and foster sustainable development at a regional level. The need to comprehend the intricate relationships among multiple ESs has become widely acknowledged by ecosystem managers and researchers. (Groot et al., 2018). Various environmental and socio-economic factors can impact the intricate processes governing ES dynamics and their interconnected mechanisms for trade-off and synergy. Previous studies have frequently investigated the relationships between factors impacting these dynamics and the resulting trade-offs or synergies using qualitative methods, like scenario comparisons (He et al., 2020). The ability of the ESs to recognize and measure the benefits and values of natural spaces gives planners and decision-makers new perspectives on how to best utilize particular locations throughout the landscape (Infield et al., 2018).

Correlation analysis is one of the contemporary approaches frequently utilized to examine the dynamics of trade-offs and synergies amongst ESs (Huang et al., 2022), and scenario simulation (Asadolahi et al., 2018). Before implementing efficient and focused regional planning and it is essential to understand how these factors influence ESs, as well as their trade-offs and synergies. (Locatelli et al., 2014). Finding the factors influencing interactions between various ESs is essential to balancing trade-offs and enhancing synergy (Zhang et al., 2020).

According to McDonnell et al. (2007), watersheds display the temporal and spatial diversity of landscape characteristics and their responses to complicated climatic conditions. Therefore, watersheds are important for planning in natural resource management (De Steiguer et al., 2003). The Citarum watershed is one of 15 critical and priority watershed for rehabilitation in Indonesia. The watershed is also very interesting for studying ESs dynamics, because of the high level of human activity in this watershed, which is characterized by changes of some land cover classes into residential and industrial. The Citarum watershed's alterations in land use and land cover (LULC) raise the surface runoff coefficient, which increases the danger of flooding (Yulianto et al., 2022). At the same time, this can also reduce water infiltration, thereby negatively impacting land degradation and erosion (Xue et al., 2022).

ESs dynamics are strongly influenced by various driving forces (Liu et al., 2019). These factors that exert influence can differ based on the research scale. For instance, on a global level , climate change seems to be the primary factor driving changes in Ess. (Wang et al., 2016). Natural factors like terrain, vegetation cover, and soil conditions influence ESs dynamics at the regional scalelevel (Rao Enming et al., 2013). Human-related factors also play a role, encompassing land-use alterations, policy shifts, population dynamics, and human activities (Fu and Zhang, 2014). Exploring how ESs respond to various driving factors is a crucial step towards achieving the sustainability of ecosystems.

Several studies have explored scenarios of Ess trade-offs and synergies worldwide, including in China and Indonesia. Study in China, focusing on three ESs: water yield (WY), soil conservation (SC), and carbon storage. The trade-off and synergy analysis of ESs in the Luanhe River Basin (X. Feng et al., 2022). Additionally, (Lang and Song, 2018) investigated trade-offs and synergies in Southern China's Karst region, focusing on soil conservation, water ield, and net primary productivity (NPP). However, there are limited studies that contribute to comprehending the intricate dynamics of ESs within the context of changing landscapes and human activities.

However, research related to correlation multi ESs in Indonesia has not been or is very limited. Moreover, ESs assessments have predominantly been conducted at a global scale, whereas local assessments in tropical regions, such as Indonesia, are relatively scarce. ESs assessments in Indonesia often focus on individual services, neglecting the interconnectedness and trade-offs among them. This gap is particularly evident in tropical regions, where local assessments are limited. Recent studies highlight the need for integrated evaluations of multiple ES to inform conservation strategies effectively (IPBES, 2019). Previous research in Indonesia, has indeed highlighted the importance of assessing both trade-offs and synergies within ESs. However, comprehensive studies addressing all aspects of these relationships : trade-offs, synergies, and their driving factors are still limited.

Several studies conducted in Indonesia include: study at the Cisadane watershed revealed significant declines in ecosystem service values (ESsV) due to land use changes, emphasizing the importance of assessing multiple services simultaneously to understand their interactions (Nahib et al., 2024b). While, participatory mapping in West Kalimantan demonstrated that diverse ES uses are linked to specific land cover types, underscoring the need for place-based assessments that reflect local community values (Mathys et al., 2023). Meanwhile, some studies that explore trade-offs and synergies in the marine sector include: coastal ESs and their conditions for policy management plans in East Nusa Tenggara (Tussadiah et al., 2021).

To address the gap in current knowledge, further research should aim to integrate methodologies that comprehensively examine the interplay between various ESs. Techniques such as the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model could help in evaluating nutrient retention, water production, and carbon storage while identifying critical drivers behind these interactions (Wang et al., 2022) Such holistic approaches would enhance our understanding of managing ecosystems sustainably in Indonesia. The integration of trade-offs and synergies with their driving factors using the multiscale geographically weighted regression (MGWR) model. Thus, this research fills the research gap on trade-offs and synergies by considering three ESs (WY, SC, CS) in Indonesia. The objectives of this study are: (i) to map multi-year data for three ESs: water yield (WY), carbon stock (CS), and soil conservation (SC); (ii) to examine the TSD among these ESs; and (iii) to identify the variables that influence TSD. The integration of trade-offs and synergies through the MGWR model offers a robust framework for understanding complex spatial relationships. By accommodating varying scales for different predictors, MGWR enhances our ability to analyze and interpret spatial data effectively, making it an invaluable tool for researchers across diverse disciplines. As applications continue to expand, MGWR is poised to significantly advance our understanding of spatial dynamics in both natural and built environments.

MATERIALS AND METHODS

Study area and data sources

The study was conducted in the Citarum watershed, Indonesia (Figure 1). The watershed is spread throughout eight regencies in West Java Province, and cover 690,916 hectares. Geographycally, the watershed is located between latitudes 106°51′36″ and 107°51′ E and longitudes

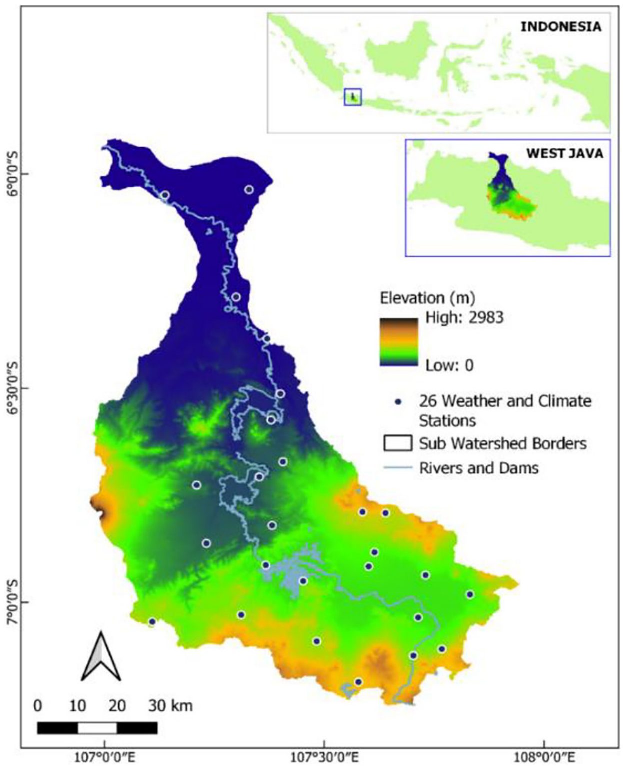

Figure 1. Location and overview of Citarum watershed, West Java

7°19′ and 6°24′ S. The area has a three-monthly dry climate with 2,358 millimeters (mm) of annual rainfall on average. Three large dams : Saguling, Cirata, and Jatiluhur—bridge the Citarum River, which flows through the watershed and is essential to many West Javans' freshwater, agriculture, and electricity. The region's topography is varied, with hills and volcanic formations among its topography. Variations in slope can be found at the base (5 to 15%), on mountain slopes (15 to 30%), and at the peaks (30 to 90%). The Citarum tributary's upstream plains have modest volcanic relief features, whereas the upstream mountains are between 750 and 2,300 meters above sea level (Citaum org., 2012).

The Citarum watershed is divided into three regions based on landforms: upstream, middle, and downstream. The Bandung Basin, the upstream part, is 625 and 2,600 meters above sea level. Its geological makeup primarily comprises lapilli, breccia, tuff, and lava. The upper region's highland and mountainous areas have an average annual rainfall of 4,000 mm and a minimum temperature of 15.3 °C. Latosol (35.7%), Andosol (30.76%), Alluvial (24.75%), Red Yel-low Podzolic (7.72%), and Regosol (0.86%) are the different soil types found in the upper watershed (Khairunnisa et al., 2020). Middle portion: The middle portion has various topography, including plains at 250 to 400 meters, rolling hills at 200 to 800 meters, steep slopes at 1,400 to 2,400 meters, and volcanic formations. The geological structure consists of volcanic sediments, ancient lake-floor deposits, and alluvial sediments in narrow valleys along the major river. Volcanic elements include tuffaceous sandstones, tuff shale, tuff breccias,

and agglomerates, whereas lake-floor sediments comprise tuff clay, tuff sandstones, tuff gravel, and tuff conglomerate. The alluvium consists of clay, silt, sandstone, and gravel formed during tertiary deposits and ancient volcanic eruptions. Middle-range temperatures span from 15.3 °C to 27 °C, while yearly precipitation varies from 1,000 mm to 4,000 mm.

Sector Downstream: t 200 to 1,200 meters above sea level, plains undulating hills distinguish the downstream sector and sharp slopes. The Citarum river empties into the Java Sea to the north, with its tributaries flowing from Mount Barangrang, Tunggul Hill, and Canggah to the north. Tertiary sediments and old volcanic deposits make up the majority of the geological deposits in this area. The average yearly rainfall in the mountainous upper basin is 1,000 mm, while the minimum temperature in the coastal and downstream lowland sections is often 27 °C. Alluvial varieties like entisol and inceptisol are found in the riverbank soil, frequently refilled by floods (Khairunnisa et al., 2020).

Data sources

The data used in this study, including remote sensing and secondary data, are based on Nahib's research conducted in 2022 (Nahib et al., 2022) and in 2024 ((Nahib et al., 2024a). Various software tools were utilized for data processing in this study. These included ArcGIS 10.8, the InVEST model, R Studio, and MGWR (Qiao et al., 2019; RDC, 2009; Sharp et al., 2020). The InVEST model, a spatial analysis tool, was used to assess the impact of soil erosion on ESs. The management and analysis of spatial data were facilitated using a geographic information system (GIS). For InVEST model inputs, the WGS84 datum was used, and the data was transformed from vector to raster format with a spatial resolution of 30 meters.

Research methodology

The research was carried out in three stages, with a flowchart depicting the process shown in Figure 2. The first stage,assessed the characteristics and variations of three specific ESs: WY, SC, and CS, within the Citarum watershed for 2000, 2010, and 2020. This assessment used the InVEST model to measure ESs and their temporal transformations. The second stage, the study investigated the intricate trade-offs and synergies among ESs within the Citarum watershed. Pearson correlation analysis and the product-moment correlation coefficient method were employed, uncovering the complex relationships between these services. Meanwhile, the last phase, the research focused on deciphering the mechanisms driving ESs within the Citarum watershed. The Multiscale Geographically Weighted Regression approach was employed, illuminating the diverse factors contributing to the dynamics of ESs. Ultimately, the study proposed techniques and recommendations for ecological management and control, drawing on insights from the research findings.

ESs calculation

Three specific ESs: WY,SC, and CS were quantitatively evaluated using the InVEST Model

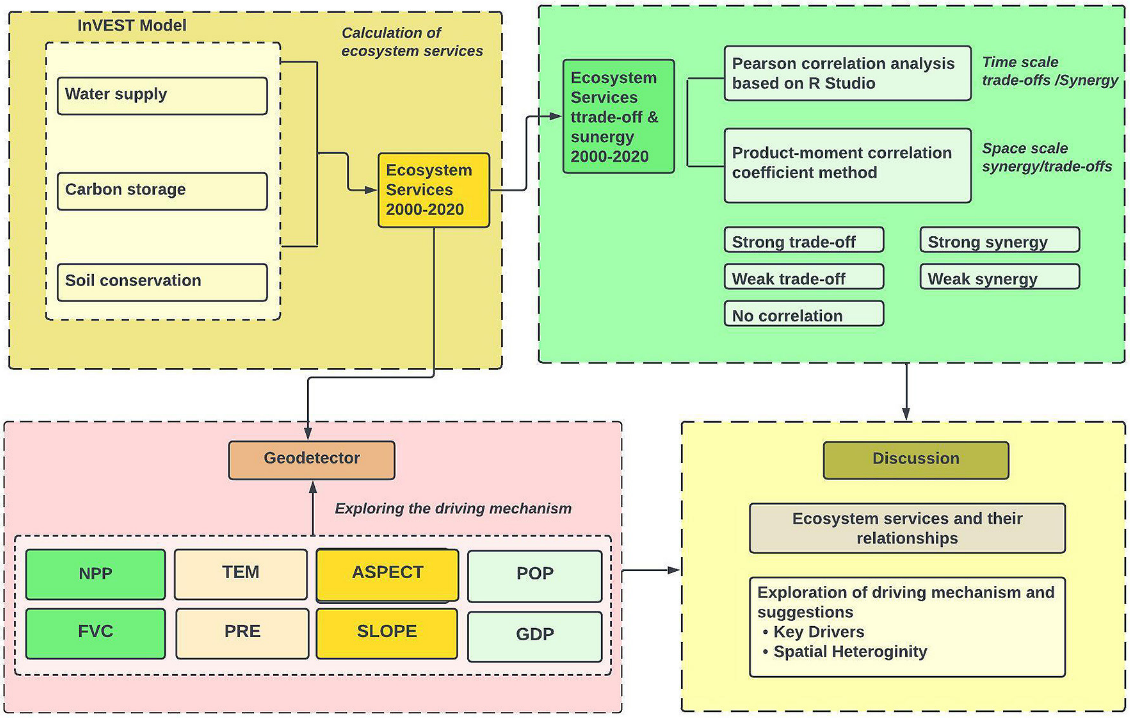

Figure 2. The research framework

in the Citarum watershed in 2000, 2010, and 2020. The methodology and mathematical formulas employed in this evaluation were derived from Sharp et al. (2020).

Trade-off and synergy analysis of ESs

Trade-offs happen when boosting one ecosystem service leads to a reduction in another. For instance, draining wetlands can improve agricultural output but at the cost of reducing biodiversity and water filtration capabilities. On the other hand, synergies arise when enhancing one service also benefits another. For example, afforestation in semiarid regions can simultaneously improve soil conservation and support biodiversity (Dade et al., 2019).

We examined the trade-off and synergy patterns across three ESs in the Citarum watershed from 2000 to 2020 using the Pearson product-moment correlation coefficient technique using Python. According to (Wang et al., 2017), this approach interpreted positive and negative correlations in the correlation coefficients to capture the trade-off and synergy links. The intricate relationships between these ESs were accurately portrayed by this method. The equation for the pixel-by-pixel Pearson product-moment correlation analysis is as follow :

$$\mathrm{R}_{xy} = \frac{\sum_{i=1}^{n}(ES1_i - \overline{ES1})(ES2_i - \overline{ES2})}{\sqrt{\sum_{i=1}^{n}(ES1_i - \overline{ES1})^2 \sum_{i=1}^{n}(ES2_i - \overline{ES2})^2}} \quad (1)$$

where: $ES1_i$ and $ES2_i$ stand for the values of the i-$_{th}$ pixel for the two ESs, $\overline{ES1}$ and $\overline{ES2}$ are the mean values of the two ESs, and n is the total number of samples. Additionally, the correlation coefficient between two ESs is represented by Rxy. Rxy=0 denotes no correlation, Rxy<0 denotes a trade-off relationship, and Rxy>0 denotes a synergistic relationship between the two ESs. $ES1_i$ and $ES2_i$ denote the i-$_{th}$ raster values of the ESs.

The correlation coefficients were categorized into five levels: weak synergy ($0.3 < r < 0.7$); strong synergy ($0.7 < r < 1$); no relationship ($-0.3 < r < 0.3$); moderate trade-off ($-0.7 < r < -0.3$); and strong trade-off ($-1 < r < -0.7$) (Zhao and Li, 2022).

Influencing factors of trade-offs and synergies

The study aims to establish the relationship between trade-offs and synergies with their driving factors by converting raster data from various independent variables into tabular data summarized at the district level using ArcGIS 10.8.

These variables include topography, climatic factors, vegetation attributes, and socio-economic indicators. The relationships between the dependent variables (TSD) and the independent variables: slope (SLO, X_1), elevation (ELE, X_2), change in annual average temperature (Δ Temp, X_3), change in annual average precipitation (Δ Precip, X_4), change in net primary production (Δ NPP, X_5), change in fractional vegetation cover (Δ FVC, X_6), and change in income per capita (Δ GDRI, X_7) were examined.

The connection between TSD (the dependent variable) and the independent variables was analyzed using Multiple Linear Regression (MLR) in R Studio. Key steps included identifying significant variables, removing unnecessary ones, and checking for multicollinearity using the Variance Inflation Factor (VIF). The Kolmogorov-Smirnov and Shapiro-Wilk tests were used to determine whether the sample distribution was normal. The objective was to develop a robust regression model to elucidate the study's associations and then identify the most relevant elements using a variable ranking method. The spatial relationship was evaluated using a MGWR model. This model utilizes adaptive bandwidth selection, examines key drivers at multiple spatial scales, and represents the latest version of geographically weighted regression models (Fotheringham et al., 2017). An MGWR model is illustrated as follows:

$$y_i = \sum_{j=1}^{k} \beta_{bwj}(\mu_i, \gamma_i)\, x_{ij} + \epsilon_i \tag{2}$$

In this study, y_i represents the trade-off synergy degree, bwj refers to the bandwidth utilized by the regression coefficient for variable j, and (ui,vi) indicates the spatial geographic coordinates of location i. The term βbwj corresponds to the regression coefficient for the jth variable, while xij denotes the value of the jth independent variable at location i. Lastly, εi represents the model's error term at location i. The MGWR model applied in this research was developed using the MGWR 2.2 software by Oshan et al. (Oshan et al., 2019).

By comparing the residual sum of squares (*RSS*) values between the MLR results with all variables (*RSS i*) and without the variable whose contribution was calculated (*RSS j*), we were able to compute the contribution rate finally. The total of these values as overall predictors was 100 because of the relative nature of the contribution rate values. The following is the formula used to determine the contribution rate (CR):

$$CR\ (\%)\ j = \frac{RSSj - RSSi}{RSSj} \times 100 \tag{3}$$

A simple model was developed to examine the impact of determining factors on the TSD between water WY and SC, as presented below

$$Y = \beta 1X1 + \beta 2X2 + ... + \beta ijXi + \varepsilon \tag{4}$$

where: Xi is the represents variable between 2000 and 2020, βi reprensents the model coefficient, $\beta 0$ is the intercept, and ε is the error term. Y represents TSD WY-SC at the district level in this case.

RESULTS

Analysis of ESs heterogeneity

Figure 3 and Table 1 present the spatial distribution and changes of three ESs within the Citarum watershed over the 20 years from 2000, 2010 and 2020. These visual tools provide important insights into the evolving dynamics and spatial patterns of ESs in the study area.

Water yield

Table 1 reveals an overall decrease in WYand CS within the Citarum watershed from 2000 to 2020, while SC increased during the same period. These trends reflect the changing ecological conditions in the Citarum watershed over the two decades. In 2000, 2010, and 2020, water yields were 112.34×10^8 m³, 91.70×10^8 m³, and 77.93×10^8 m³, respectively, indicating a continuous decline. The total WY in 2020 decreased by 34.40×10^8 m³ (30.60%) compared to 2000, and by 13.8×10^8 m³ (15.00%) compared to 2010. 2020 had a notable spatial variation in WY, with the middle stream having the highest unit WY, followed by the downstream and the upstream with the lowest.

Declines in WY were seen across all sub-watersheds in both 2000–2010 and 2010–2020. In the first decade, water discharge decreased by 15.77% upstream, 17.64% in the middle area, and 21.49% downstream. In the second decade, the decrease was generally smaller except for the downstream area, with reductions of 9.74% upstream, 11.44% in the middle, and 24.75% downstream. These patterns highlight the shifting water availability within the Citarum watershed over the two periods.

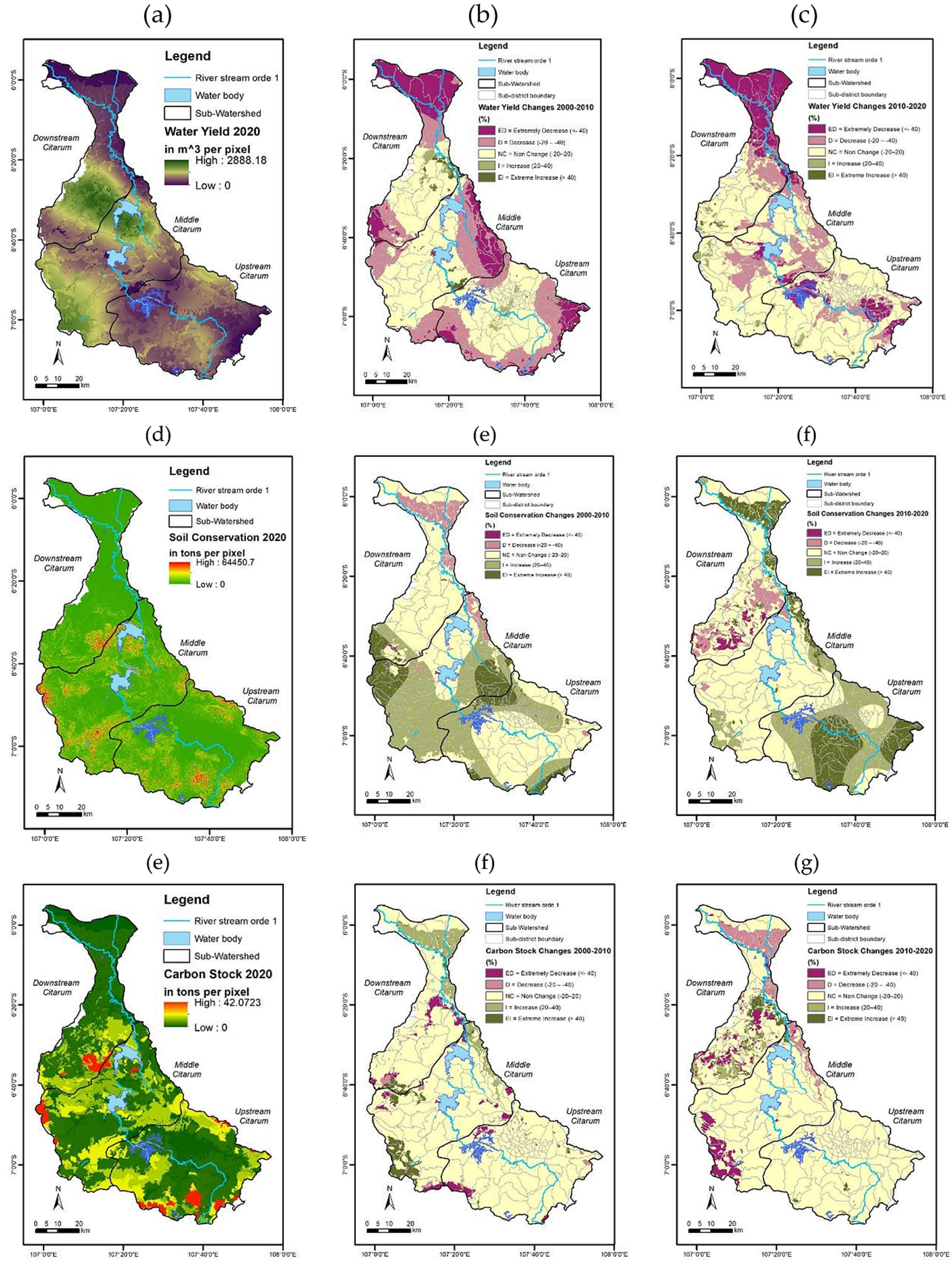

Figure 3 The grid-scale spatial distribution of ESs, including (a) Mean WY in 2020, (b) Changes in WY from 2000 to 2010 (c) Changes in WY from 2010 to 2020 (d) mean SC in 2020 (e) Changes in SC from 2000 to 2010 (f) Changes in SC from 2010 to 2020 (g) Mean CS in 2020 (h) Changes in CS from 2000 to 2010 (i) Changes in CS from 2010 to 2020

The "no change" classification, shown in yellow, is the most significant category across the three sub-watersheds–north-northwest (downstream Citarum), west-southwest (middle Citarum), and east-southeast (upstream Citarum) – according to an analysis of the spatial distribution from 2000 to 2010 (Figure 3b). This category is fairly evenly spread among the sub-watersheds. There is a notable decrease in the downstream Citarum area (depicted in purple), while

Table 1. The total amount of ESs in the Citarum Watershed in 2000, 2010 and 2020.

Name sub watershed	Area (ha)	WY		SC		CS	
		Mean (m^3 10^3 ha^{-1})	Total (m^3 10^8)	Mean (tons $10^3 ha^{-1}$)	Total (10^8 tons)	Mean (tons/ha)	Total mg 10^6
Year 2000							
Upstream	245,413	11.85	28.60	3.20	7.78	56.88	13.83
Middle	251,373	19.53	48.48	4.42	11.07	52.45	13.15
Downstream	194,130	19.23	35.26	2.25	4.11	39.26	7.31
	690,916	16.87	112.34		22.96		34.30
Year 2010							
Upstream	245,413	10.02	24.09	3.74	9.09	51.55	12.54
Middle	251,373	16.13	39.93	5.61	14.04	53.68	13.46
Downstream	194,130	15.07	27.68	2.50	4.56	39.24	7.31
	690,916	13.74	91.70	3.95	27.69		33.31
Year 2020							
Upstream	245,413	9.01	21.74	4.89	11.89	51.79	12.60
Middle	251,373	14.25	35.36	6.11	15.29	49.47	12.40
Downstream	194,130	11.36	20.83	2.10	3.84	35.69	6.65
	690,916	11.54	77.93	-	31.02		31.65
Change 2000-2010		(10^8 m^3)	-20.64	(10^8 tons)	4.73	10^6 tons	-0.99
		(%)	-18.37	(%)	20.60	(%)	-2.89
Change 2010-2020		(10^8 m^3)	-13.76	(10^8 tons)	3.33	10^6 tons	-1.66
		(%)	-15.01	(%)	12.03	(%)	-4.98

Note: Image analysis results

a substantial increase is evident in the middle Citarum region (illustrated in dark green). The change distribution is as follows: 52.64% for "no change", 26.53% for "D" (indicating a decrease), and 16.45% for "ED" (an extreme decrease). For the 2010–2020 period (Figure 3c), the distribution pattern remains similar to that of 2000–2010, but the proportions are higher but the proportions are higher: 62.64% for "no change", 18.84% for "D," and 16.61% for "ED". These visualizations highlight the evolving patterns of change and stability within the sub-watersheds over these two decades.

Soil conservation

The improvement of soil conservation in the Citarum Watershed means increasing efforts to protect and preserve the soil in the area. This can be achieved through practices such as contour farming, terracing, and the use of organic materials to enhance soil structure and reduce erosion. The Citarum watershed's trend for soil protection is rising (Table 1). Between 2000 and 2010, there was an increase in SC in the Citarum watershed. The overall soil conservation in the Citarum watershed increased from 22.96×10^8 tons in 2000 to 27.685×10^8 tons in 2010. Soil conservation increased by 4.73×10^8 tons (20.60%) in ten years. This issue persisted from 2010 to 2020 as well. In the Citarum watershed, total soil conservation was 27.68×10^8 tons in 2010 and will reach 31.05×10^8 tons in 2020. Soil conservation increased by 3.33×10^8 tons (12.05%) in ten years.

From 2000 to 2010 (Figure 3e), the "no change" category, depicted in yellow, is the dominant class across all three sub-watersheds: downstream (north-northwest), middle (west-southwest), and upstream (east-southeast) Citarum. A noticeable decrease in purple is particularly evident in the downstream Citarum area. Meanwhile, the spatial distribution for the 2010–2020 period (Figure 3f) remains largely similar to the previous decade, though the proportions shift slightly: "no change" at 59.69%, "Increased" at 18.34%, and "Extremely Increased" at 16.35%. Notably, the upstream sub-watershed is characterized by increased conditions, the central sub-watershed by stability, and the downstream sub-watershed by a mix of stability and decline. These patterns offer crucial insights into the evolving dynamics within the Citarum watershed over the two decades.

Carbon storage

Table 1 indicates a declining trend in the carbon storage of the Citarum watershed, with values of 34.30×10^8 tons, 31.31×10^8 tons, and 31.65×10^8 tons in 2000, 2010, and 2020, respectively. However, the overall rate of decrease was rather gradual. In 10 years (2000–2010), there was a decrease in carbon storage of 0.99×10^8 tons (2.89%). The same condition also occurred from 2010 to 2020. Meanwhile, from 2010 to 2020, there was a decrease in carbon storage of 1.66 ×10^8 tons (4.98%).

When examining the spatial distribution for 2000–2010 (Figure 3h), yellow represents "no change", the dominant change category. The distribution proportions are as follows: 86.67% for "no change", 5.28% for "I" (increase), 3.70% for "ED" (extreme decrease), and 3.58% for "EI" (extreme increase). In contrast, the spatial distribution for 2010–2020 (Figure 3i) shows significant differences compared to 2000–2010. Specifically, the "no change" category decreased to 62.64%, while the "I" (increase) and "EI" (extreme increase) categories rose to 18.84% and 16.35%, respectively. These distinct spatial distributions provide valuable insights into the evolving patterns within the different sub-watersheds of the Citarum watershed over the specified time intervals.

Ecosystem changes in the Citarum watershed using sub-district boundaries are presented in Table 2. Changes in WY based on districts show that: (a) in the period 2000–2010, the decreasing trend in CS from 2000 to 2010, the majority of districts (98 out of 174 districts), Decreased (49 districts), and ED (21 districts). Meanwhile, in 2010–2020, it is the dominant class of change, the same as the 2000-2010 period with higher values, namely NC (112 districts), D decreased (35 districts), and relatively constant ED (20 districts)

Alterations in trade-off/synergy relationships for ESs

Table 3 summarizes the temporal dynamics and changes in the interactions among ESs within the Citarum watershed from 2000 to 2020, derived through Pearson correlation analysis of three ESs.

Table 3 reveals significant positive correlations among ESs within the Citarum watershed. The strongest correlations were between WY –SC (-0.90), SC – CS (0.60), and WY – CS (-0.53). These robust positive relationships remained fairly consistent from 2000 to 2020, indicating these interactions' enduring nature and significance. An analysis was carried out using the Python platform to investigate the spatial distribution of trade-offs and synergies across ESs – specifically WY, SC, and CS – in the Citarum watershed using a large time series dataset spanning from 2000 to 2020. This analysis highlighted how these services interacted spatially over the examined period. Furthermore, the ArcGIS platform was utilized to generate spatial maps that visually illustrated the

Table 2. Changes in the value of ESs in the Citarum watershed by district from 2010 to 2020 (%)

Class of change	Water supply				Carbon stock				Soil conservation			
	2000–2010		2010–2020		2000–2010		2010–2020		2000–2010		2010–2020	
	N	P	N	P	N	P	N	P	N	P	N	P
ED (< 40%)	21	12.21	20	11.63	5	2.91	8	4.65	0	0.00	0.	0.00
D (-20% – -40%).	49	28.49	35	20.35	5	2.91	13	7.56	9	5.23	2	1.16
NC (-20% – 20%)	98	56.98	112	65.12	142	82.56	151	87.79	92	53.49	77	44.77
I (20 – 40%).	4	2.33	3	1.74	4	2.33	0	0.00	51	29.65	52	30.23
EI (> 40%).	0	0.00	2	1.16	16	9.3	0	0.00	20	11.63	41	23.84

Note: N – number, p – percentage

Table 3. Pearson correlation of ESs in Citarum watershed

Ecosystem service relationships	Year		
	2000	2010	2020
Water supply – soil coservation	-0.9055	-0.9089	-0.9259
Water supply– carbon stroage	0.6170	0.5672	0.6222
Soil conservation – carbon stroge	-0.5749	-0.5237	-0.5871

outcomes of this analysis. These maps are presented in Figure 4, providing a comprehensive visual depiction of the trade-offs and synergies inherent in the specified ESs within the Citarum watershed. Through the integration of these two platforms, the study effectively delivered valuable insights into the spatial dynamics governing interactions among ESs over two decades.

These visual depictions offer a comprehensive overview of the evolving interactions between distinct ESs, particularly trade-offs and synergies, from 2000 to 2020 within the Citarum watershed. They offer valuable insights into the complex relationships among these services and their spatial distributions within the study area.

The research reveals significant patterns in the relationship between soil conservation and water yield, as shown in Figure 4. This relationship predominantly showcases a strong trade-off pattern, particularly concentrated across most sub-watershed areas within the Citarum watershed. However, there are areas of strong synergy relationships, notably observed in the downstream sub-watersheds and the central region of the upstream sub-basin. The spatial distribution of negative TSD values for the water yield and soil conservation relationship is widespread, covering nearly all aCitarum watershed areas. In contrast, the downstream sub-basins exhibit a predominant trend of strong synergy relationships. These findings offer a thorough understanding of the varied dynamics of trade-offs and synergies between water yield and soil conservation in different regions of the Citarum watershed.

Meanwhile, the relationships between WY and CS and SC and CS are dominated by noncorrelation. Furthermore, only the trade-offs and synergies between water yield and soil conservation are analyzed for their driving factors. The results of the trade-off and synergy analysis (Wei et al. 2022) are based on polygons for each district. The summary is presented in Table 4 which shows that during the 2000–2020 period, the trade-offs and synergies are mostly traded for (WY-SC) by

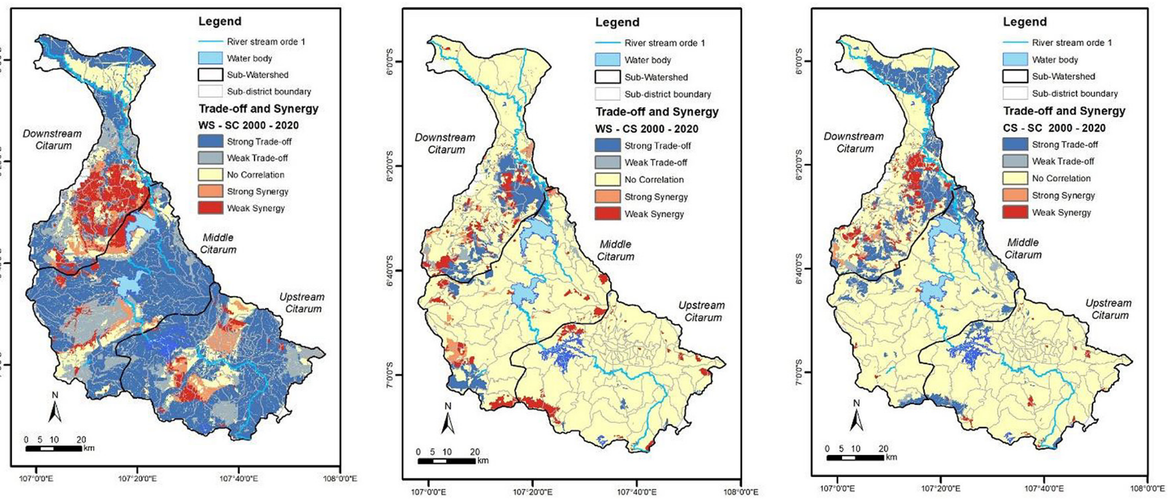

Figure 4. The spatial distribution depicting the trade-offs and synergies among ESs within the Citarum watershed: (a) Water yield - soil conservation (2000–2020), (b) Water yield - carbon storage (2000–2020), (c) Soil conservation - carbon storage (2000–2020)

Table 4. Trade of and synergy of each ESs during the 2000–2020

Class of trade-off synergistic	WY-SC		WY-CS		CS-SC	
	N	P	N	P	N	P
Strong synergy	3	-1,72	0	0.00	3	-1.72
Weaks synergy	18	-10.34	0	0.00	3	-1.72
No corelation	42	-24.14	150	-86.21	165	-94.83
Weaks trade of	53	-30,46	16	-9.2	3	-1.72
Strong trade of	58	(33.33)	8	-4.6	0	0.00

Note: N – number, p – percentage

64%. Meanwhile, the trade of synergy for WY-SC and SC-SC is noncorrelation (around 80%)

Influencing factors of trade-offs and synergies

According to the findings of the R^2 determination and multicollinearity tests, all variables can be used to predict the dependent variable (TSD ecosystem). The MGWR model surpasses the OLS and GWR models in effectively explaining the spatial distribution and driving factors of TSD within the Citarum watershed. This superiority is reflected in the higher R^2 values: 0.673 for the relationship between water yield (WY) and sediment concentration (SC), 0.557 for the relationship between WY and soil conservation (CS), and 0.491 for SC and CS. These R^2 values represent the proportion of variability in the dependent variable that can be explained by the independent variables in the model. Higher R^2 values suggest a stronger fit of the model in capturing the spatial distribution and the underlying factors influencing the relationships among ESs within the Citarum watershed.

The ArcGIS geographic distribution module was used to visually study the correlation coefficients for each driving component using the MGWR data. This analysis is represented in both Table 5 and Figure 5.

As illustrated in Figure 5 and condensed in Table 5, the Slope coefficient values exhibit a spectrum spanning from -0.176 to 0.064, with an average value of -0.08694. The distribution of these Slope coefficient values across different regions displays a distinct pattern. Specifically, within the Upper Sub watershed and Middle Sub-watersheds, the coefficient values exceed those observed in the Downstream Sub-watersheds. This differential distribution of coefficient values across these sub-watersheds indicates varying strengths of influence between the driving factors and the trade-off/synergy intensity of the WY-CS ecosystem service relationship.

Conversely, the elevation coefficient values demonstrate a range from -0.2509 to 0.06040, with an average value of -0.104. The elevation coefficients' distribution pattern contrasts with the slope coefficients. Specifically, in the upstream sub-watershed, the coefficient value is lesser than the elevation coefficient value observed in both the Middle sub-watershed and downstream sub-watershed. These details can be gleaned from Figure 5 and Table 5 for further insights into the coefficient values of other variables. This comprehensive analysis of various coefficient values offers a deeper understanding of the relationships between driving factors and the trade-off/synergy intensity of the studied ecosystem service relationship.

The outcomes of the multiple regression analysis conducted using the MGWR software have indicated that seven variables have made noteworthy and statistically significant contributions to TSD of the WY-SC ecosystem service relationship. These significant variables are documented and elaborated upon in Table 6. This analysis underscores the importance of these variables in influencing the trade-off and synergy dynamics between water yield and soil conservation within the study area.

In Table 6, based on the regression coefficient, the variables that most dominantly affect TRD WY-SC are FVC (0.29), Slope (-0.111), and Precip (0.089). The variable regression coefficient is positive, which indicates that the higher the variable's value, the more significant its contribution to the increase in WY-SC TSD is. Furthermore, based on the level of contribution of the independent variables to the total TSD WY-SC, the most dominant variable is the FVC variable, with a contribution of 27.37% (MGWR). In contrast, the elevation and rainfall variables are the following dominant variables. There are differences in the amount of contribution for each variable.

DISCUSSION

Spatial heterogeneity analysis of ESs

The primary factors that impact the delivery of ESs, intricately tied to human well-being, are changes in LULC and climate conditions, as emphasized by (Yan and Li, 2023). The alterations in ESs observed within the Citarum watershed are primarily attributed to the consequences of shifts in LULC patterns and climatic fluctuations, particularly changes in rainfall and temperature.

Table 5. The average MGWR coefficients between driving variables and TSD WY-CS.

Variable	Slope	Elev	ΔPrecip	Δ Temp	Δ FVC	ΔNPP	Δ GDRI
WYS-SC	-0.086	-0.104	0.003	0.007	0.155	-0.126	-0.091

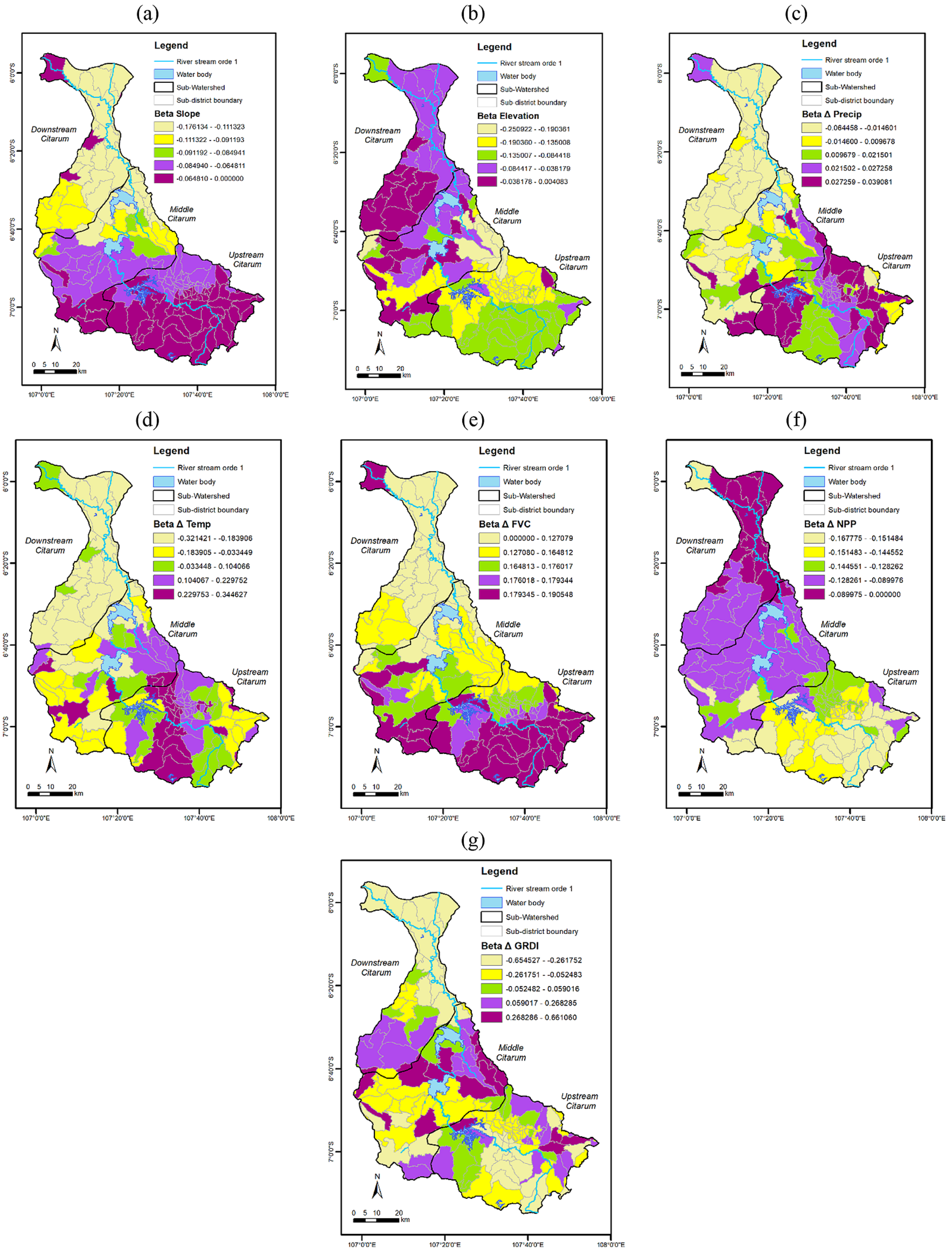

Figure 5. Spatial distribution characteristics of different drivers of TSD WY-SC

For instance, the rainfall in the Citarum watershed during 2000, 2010, and 2020 has been recorded at 2,310 mm, 1,783 mm, and 1,679 mm, respectively, with a consistent declining trend. Correspondingly, the potential evaporation has also decreased, measured at 1,419 mm, 1,297 mm, and 1,679 mm, respectively. This period also witnessed spatial heterogeneity in ESs. The diminishing trend in rainfall and potential evapotranspiration can be primarily attributed to their close connection, as rainfall significantly influences potential evapotranspiration. The interplay between these factors underscores the intricate relationship between climatic conditions and ESs,

Table 6. OLS and contributor rate of TSD WY-CS estimates and p-values for various drivers

Driving factors	WY-SC			
	B	P value	Contributor rate (%)	
			OLS	MGWR
Topograpghy				
Slope	-0.111	0.165	5.87	6.58
Elev	0.043	0.111	18.14	25.41
Sub total			24.01	31.99
Climate				
∆ PRECIP	-0.089	0.084	14.44	19.47
∆ Temp	0.060	0.078	5.35	3.45
Sub total			19.79	20.92
Vegetation				
∆ FVC	0.290	0.159	42.29	27.37
∆ NPP	-0.080	0.083	11.78	17.14
			54.06	34.51
Socio-economic				
∆ GRDI	-0.041	0.102	2.13	11.58
Sub Total			2.13	11.58

contributing to the changing dynamics observed in the Citarum watershed from 2000 to 2020.

Moreover, the strength of land use intensity and the specific spatial distribution of soil attributes contribute significantly to the pronounced spatial heterogeneity of water yields. A combination of landform, climate, and hydrology shapes the dynamics of water yields. These factors collectively determine the volume of water generated within a given area. The intricate interplay between land use, soil characteristics, and environmental conditions creates variations in water yields across different spatial locations, highlighting the complexity of ecosystem dynamics and their relationship with hydrological processes.

The observations align closely with the outcomes of the study conducted by Yan and Li in 2023, as highlighted in their research (Yan and Li, 2023). They concluded that two primary factors, namely LULC and climate change, significantly influence the provisioning of ESs, subsequently impacting human well-being. These findings are further substantiated by research conducted by Zhang in 2023 in China that emphasized the dominance of temperature, rainfall, and fractional vegetation cover as key factors affecting ESs, focusing on water yield and soil conservatio (Zhang et al., 2023). This convergence of research findings underscores the critical role of climatic variables and land use patterns in shaping ESs and their subsequent impacts on human welfare.

Geng's research in 2023, specifically focused on the Yellow River Basin in China, revealed distinctive insights into the factors influencing changes in water yield, soil conservation, and food production (Geng et al., 2022). The study highlighted that alterations in rainfall emerged as the primary driver for changes in water yield. On the other hand, shifts in soil conservation and food production were shaped by a combination of factors, including rainfall, temperature, and the specific type of land use. Notably, no single factor exhibited a dominant influence over these variables. The research indicated a spatial synergy between soil conservation and water yields, with the relationship between these two factors being particularly noteworthy. It is worth mentioning that the study acknowledged certain limitations, such as data imprecision and potential biases in assessing ESs rainfall (Geng et al., 2022). The research further disclosed that soil conservation is influenced by the interaction of slope and land use type, while rainfall primarily affects water yield. Other studies, such as highlighted that a combination of rainfall and slope influences water yield. These collective findings underscore the complex interplay of multiple factors influencing ESs within specific geographical contexts (Wei et al., 2022a).

Indeed, human activities and various environmental factors profoundly impact soil conservation. Research by Ren et al. from 2022 emphasizes that population density and elevation have observable spatial differentiation effects on water yields and carbon storage services (Ren et al., 2022). The correlation between soil conservation and slope and forest proportion emerges as notably significant in influencing these services. The intricate relationship between these variables shapes the spatial distribution of ESs and their subsequent impacts. The multifaceted nature of soil conservation is reflected in its response to various factors. As Geng et al. (2022) highlighted, changes in soil conservation are influenced by a combination of factors, including rainfall, temperature, and the type of land use. However, none of these factors singularly exert a dominant influence, emphasizing the intricate interplay of multiple drivers in shaping soil conservation dynamics. This factor underscores the complexity of understanding ESs and the need to consider a holistic range of factors to comprehend their intricate patterns and relationships. Indeed, alterations in water yield are primarily driven by changes in rainfall patterns. Geng et al.'s study in 2022 underscores that the correlation between water yield and rainfall is of paramount significance influence (Geng et al., 2022).

Changes in ecosystem service trade-off/synergy relationships

Based on the data presented in Figure 4a and Table 4, a moderate to strong correlation exists between WY-SC within the Citarum watershed. This observation mirrors research findings from the West Sichuan Plateau in China. Although the Pearson correlation values are similar, there are slight differences in the actual figures. For example, the West Sichuan Plateau study reports a correlation of 0.82 between WY-SC, 0.62 between WY-CS, and 0.59 between SC and CS. Additionally, the trade-off between WY and SC is apparent in about 66% of the Citarum watershed area. This aligns with research from the West Sichuan Plateaus (Wei et al., 2022a) and the Henan Section of the Yellow River Basin in China (Niu et al., 2022), highlighting the trade-off between these ESs. This pattern suggests that improving one service could potentially compromise the other, emphasizing the need to consider such trade-offs in ecological management decisions (Niu et al., 2022; Wei et al., 2022b)

The relationship between WY and SC is complex and influenced by various factors. The search results show no definite relationship pattern between WY and soil retention; some are trade-offs, and some are synergistic. The search results show that the relationship between water yield and soil retention is not always clear and can vary depending on the specific context. The results of Wang's research are studies on simulating the impacts of future climate change and ecological responses, the authors found that water yield and soil conservation have a synergistic relationship in some regions, but there are also areas where there is a trade-off between water yield and soil conservation (Wang et al., 2020).

Wang's research on ESs also found that the relationship between WY and SC is a trade-off, where in the past 15 years, WY decreased by 3.38%, and SC was increased by 1.45%. Trade-offs occur primarily among WY and other ESs (Wang et al., 2023). Meanwhile, the relationship between WY and SC is a trade-off, as stated by Ren et al., 2022 who researched the Assessment of ESs in Hainan Province, China. The relationship between WY and SC services shows a trade-off, meaning that enhancing WY capabilities tends to reduce SC. There is generally also strong CS in regions with high WY vegetation, indicating a strong synergistic relationship between WY and CS services. However, the correlation between WY services and SC services in water did not pass the significance test. This lack of clear correlation is because water storage does not directly involve carbon fixation (Ren et al., 2022).

In contrast, Huang's 2023 study in the Wujiang Basin, Guizhou Province, discovered a synergistic relationship between WY and SC (Huang et al., 2023). Similarly, the Taohe River Basin, characterized by a significant proportion of agricultural land, forest, and grassland, shows a synergistic interaction (Zhou et al., 2023), the Jiulianshan National Nature Reserve in Jiangxi Province, China (J. Feng et al., 2022), and the Loess Plateau in China (Feng et al., 2017).

Influencing factors of ESs

The model evaluation results underscore the MGWR model's superior suitability for the analysis, as indicated by larger R^2 values and smaller Akaike information criterion (AICc) values. This observation is by the findings from Nahib's study in 2023, which also emphasized the superiority of the Geographically Weighted Regression (GWR) model in explaining location-specific influences on changes in water yields when compared to the broader coefficients provided by ordinary least squares (OLS)

(Nahib et al., 2023). Moreover, non-stationary spatial interactions are effectively addressed by the MGWR model, which is an improvement over the GWR. This is achieved by considering the ideal bandwidth for several independent variables, which fixes the limitations found in previous modeling techniques (Li and Fotheringham, 2020). The adoption of the MGWR model aligns with capturing the intricate spatial dynamics of ESs relationships more comprehensively and precisely.

On a larger temporal and spatial scale, land use and climate change are the primary factors driving changes and variations in ESs (Su and Fu, 2013). Changes in LULC types can profoundly impact the ecosystem of the Citarum watershed, influencing water yield, carbon storage, and soil conservation. The findings of Nahib's research further corroborate this notion, revealing shifts in land use and cover within the Citarum watershed between 2000 and 2018. Nahib's study documented significant changes in various land use and cover categories within the Citarum watershed over this period: A decline of 35.87% in virgin forests, A decrease of 13.87% in plantation forests, A substantial reduction of 77.97% in shrub cover, A decrease of 20.24% in plantation areas A decline of 24.56% in vacant land A decrease of 6.57% in rice fields Conversely, there was an increase in settlement areas by 4.23%, Pure Dry Agriculture by 64.85%, and Mixed Dry Agriculture by 64.85%. These alterations underscore the significant impact of land use changes on the overall ESs within the Citarum watershed (Nahib et al., 2023). Upon examining Table 8, it becomes apparent that the most impactful variables are fractional vegetation cover (FVC), elevation, and rainfall. This aligns with the findings of a study by Zhou et al. in 2023. Their research demonstrated that rainfall, digital elevation model (DEM), and the coefficient of Rainfall-Runoff process (CROP) are the key contributing factors influencing the synergistic relationship between WY and SC. This correlation supports the idea that FVC, elevation, and rainfall are critical drivers influencing the dynamics of ESs within the context of water yield and soil conservation (Zhou et al., 2023).

Climatic factors, such as temperature and rainfall, substantially shape WY and soil retention within ecosystems. Among these factors, rainfall is particularly influential, displaying a strong and positive correlation with ESs. In contrast, the connection between temperature and ESs is comparatively less pronounced (Yan and Li, 2023). The study conducted by Yan and Li in 2023 underscores that the transformation of vacant land into pasture and agricultural land, coupled with the enhancement of forested areas, yields positive outcomes in terms of bolstering ESs.

CONCLUSIONS

Our study focused on monitoring changes over time and space in three pivotal ESs: WY, SC, and CS within the Citarum watershed, spanning 2000 to 2020. Ultimately, we explored the underlying drivers of these ESs. This was achieved by integrating geographic detectors with the MGWR model, allowing us to discern spatial discrepancies in the primary influencing factors.

The results revealed that WY and CS decreased by 18.37% and 2.89%, respectively, from 2000 to 2010, while SC increased by 10.60%. Meanwhile, from 2010 to 2020, WY and CS decreased by 15.01% and 4.98%, respectively, while SC increased by 12.03%. The utilization of the TSD indicator reveals that trade-off and synergy relationships, along with their intensities, exhibit significant spatial heterogeneity throughout the Citarum watershed. This discovery enhances comprehension of the intricate interplay between various ESs and the mechanisms dictating these trade-offs and synergy dynamics. This study enriches our understanding of how ESs interact and the factors underpinning these interactions by uncovering spatial disparities in trade-offs and synergy patterns.

The coefficients of topography, climate, vegetation, and socio-economic factors obtained from the MGWR model show that the impact on trade-off/synergy varies spatiotemporally. TRD WY-SC is influenced by vegetation (34.51%), topography (31.99%), climate (20.92%), and socio-economic factors (11.58%). The trade-off/synergy analysis results provide decision-makers with invaluable insights for crafting effective regional plans and strategies for ecological management that promote sustainable development.

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