Journal of Infrastructure, Policy and Development 2024, 8(15), 9375.
https://doi.org/10.24294/jipd9375

Article

Assessment of dynamic water yield using multi scenario of LULC in Cisadane Watershed West Java, Indonesia

Turmudi Turmudi[1], Irmadi Nahib[1,2], Wiwin Ambarwulan[1], Jaka Suryanta[1,*], Nawa Suwedi[1], Yatin Suwarno[1], Reni Sulistyowati[1], Darmawan Listya Cahya[1], Lena Sumargana[1], Bambang Winarno[1], Fanny Meliani[3], Ilvi Fauziyah Cahyaningtiyas[1], Teguh Arif Pianto[1], Harun Idham Akbar[1,4], Yulianingsani Yulianingsani[1]

[1] Research Center for Limnology and Water Resources, National Research and Innovation Agency (BRIN), Cibinong 16910, Indonesia
[2] Study Program of Natural Resources Environmental Management, Graduate School of IPB University, Bogor 16680, Indonesia
[3] Research Center for Geoinformatics, National Research and Innovation Agency of Indonesia (BRIN), Bandung 40135, Indonesia
[4] Study Program of Tropical Ocean Economics, Faculty of Economics and Management, IPB University, Bogor 16680, Indonesia
*** Corresponding author:** Jaka Suryanta, jaka008@brin.go.id

CITATION

Turmudi T, Nahib I, Ambarwulan W, et al. (2024). Assessment of dynamic water yield using multi scenario of LULC in Cisadane Watershed West Java, Indonesia. Journal of Infrastructure, Policy and Development. 8(15): 9375. https://doi.org/10.24294/jipd9375

ARTICLE INFO

Received: 29 September 2024
Accepted: 21 October 2024
Available online: 16 December 2024

Abstract: Uncontrolled economic development often leads to land degradation, a decline in ecosystem services, and negative impacts on community welfare. This study employs water yield (WY) modeling as a method for environmental management, aiming to provide a comprehensive understanding of the relationship between Land Use Land Cover (LULC), Land Use Intensity (LUI), and WY to support sustainable natural resource management in the Cisadane Watershed, Indonesia. The objectives include: (1) analyzing changes in WY for 2010, 2015, and 2021; (2) predicting WY for 2030 and 2050 under two scenarios—Business as Usual (BAU) and Protected Forest Area (PFA); (3) assessing the impacts of LULC and climate change on WY; and (4) exploring the relationship between LUI and WY. The Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model calculates actual and predicted WY conditions, while the Coupling Coordination Degree (CCD) analyzes the LULC-WY relationship. Results indicate that the annual WY in 2021 was 215.8 × 108 m^3, reflecting a 30.42% increase from 2010. Predictions show an increasing trend in WY under both scenarios for 2030 and 2050 with different magnitudes. Rainfall contributes 88.99% more dominantly to WY than LULC. Additionally, around 50% of districts exhibited unbalanced coordination between LUI and WY in 2010 and 2020. This study reveals the importance of ESs in sustainable watershed management amidst increasing demand for natural resources due to population growth.

Keywords: coupling coordination degree model; InVEST; land use intensity; prediction

1. Introduction

A watershed is a complex and dynamic ecosystem characterized by human interaction with nature and involves natural resources and socio-economic components. Many watersheds in the world are currently experiencing degradation due to exploitation and aggressive human activities, exceeding the carrying capacity of the watershed (Sriyana et al., 2020). Watershed quality decline occurs in various places, including flooding, land degradation, and erosion (Ambarwulan et al., 2021), driven by human activities and climate change.

Watersheds, which encompass a variety of ecosystems services (ES), provide numerous benefits, including water and habitat provisioning, water treatment, carbon storage, climate regulation, and cultural services such as recreation (Rose et al., 2015). These services support essential sectors, including agriculture, fisheries, industry, transportation, and tourism. Strassburg et al. (2020) reported that uncontrolled economic development is leading to further degradation of global and regional ecosystem functions. Meanwhile, Jew et al. (2019) stated that Land Use Land Cover (LULC) changes account for 60% of the decline in ES provision. Therefore, the assessment of ES is important for sustainable ecosystem management.

Currently, the important role of ES is increasingly considered in decision-making for sustainable watershed management. Regional development planning needs to consider changes in ES resulting from changes in LULC (Gomes et al., 2021). Changes in LULC can cause land degradation, hinder the provision of ES in certain areas, and undermine sustainable ecosystem development. LULC changes encompass modifications in land use types and adjustments in the intensity and spatial arrangements of land (Fu et al., 2015). Therefore, ES should be mapped to identify risks, impacts, and potential trade-offs associated with predicted environmental changes (Malinga et al., 2015). Thus, ES conservation is urgent to be implemented to ensure human well-being.

Water yield (WY) refers to the amount of water flowing from land to rivers and available for human use (Zhou et al., 2015). It is an important component of hydrological ES, and the most valuable ecological indicators (Wang et al., 2022). Some indicators influence the WY, such as rainfall received (P), evapotranspiration (ET), and LULC (Zhang et al., 2021). Lu et al. (2024) stated that the most important thing about WY is that it will affect other ES such as carbon cycle, biomass, irrigated agriculture, domestic water production and use, and socio-economic development.

The influence of LULC changes on WY has been discussed by many researchers worldwide. Historical studies on WY proved that WY was affected by both LULC and climate change (Muhammed et al., 2021). Thus, understanding WY dynamics and its driving mechanisms is urgently needed, as it will provide scientific guidance for regional ecological protection and restoration. A comprehensive WY model will be useful for decision makers and environmentalists focused on sustainable development. Several models have been used to assess WY, including the Soil and Water Assessment Tool (SWAT) model (Chen et al., 2020; Lepcha et al., 2024), and Hydrological Simulation Program-Fortran (Guan et al., 2023). One of the effective techniques for monitoring and evaluating WY is the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) Model. This model has been applied by many researchers and has proven to be very useful for improving ES performance including WY. The advantages of the InVEST model are easy-to-obtain data input, strong spatial analysis, and easy to use (Dennedy-Frank et al., 2016). Thus, the InVEST model for WY has been carried out in various watersheds in the world (Balist et al., 2022; Liang et al., 2021; Zhang et al., 2021) and several locations in Indonesia, such as the Citarum Watershed (Nahib et al., 2021, 2023). Zheng et al. (2022) conducted a study focusing on the relationship between changes in LUI and ES. Variations in LUI also have an impact on ES and functions (Wen et al., 2019). At the same time, Xu et al. (2016) discussed the correlation technique of the relationship between LUI and ES services and community welfare. They found that increasing LUI levels would increase food security, Soil Conservation, and climate regulation control (Xu et al., 2016). The results of Felipe-Lucia et al. (2020) showed that ES and its functions can be augmented at moderate LUI levels, and the positive correlation between ES and its functions decreases at high LUI level.

Indonesia has 17,088 watersheds and 108 watersheds are designated as critical watersheds and require priority handling. However, there are 15 watersheds including Cisadane Watershed that are very critical and need to be restored immediately. The Cisadane Watershed is facing some problems such as flooding, water pollution, erosion and sedimentation. Cisadane Watershed experiences a very large LULC conversion problem due to urbanization and population growth. Research related to LULC changes and their predictions in the Cisadane Watershed has been conducted by (Ambarwulan et al., 2023). The research found that built-up area increased, paddy field and forest was decreasing significantly. The research on impact the LULC changes on ES in the Cisadane Watershed has conducted by (Nahib et al., 2024). They discovered that a substantial reduction in forest and rice field areas caused a decrease in ES of $196.37 billion from 2010 to 2021.

Several studies on WY have been conducted. However, the impact of LULC and the correlation between LUI and ES remain limited globally, including in Indonesia (Fang et al., 2022). Therefore, this study aims to fill the gap in the literature regarding the effects of changes in LULC and the correlation between LUI and ES. Specifically, this research analyzed the relationship between LULC and WY using the InVEST model and examined the correlation between LUI and WY. To achieve this goal, four specific objectives were set, namely (1) calculating changes in WY for the years 2010, 2015, and 2021; (2) predicting WY for 2030 under two scenarios: Business as Usual (BAU) and Protecting Forest Areas (PFA), (3) analyzing the impact of LULC and climate change on WY, and (4) investigating the relationship between LUI and WY. The results are expected to be useful as a reference for regional planners, and decision-makers for sustainable watershed management.

2. Materials and methods

2.1. Study area

This research was carried out in the Cisadane Watershed, Indonesia (**Figure 1**). The Cisadane Watershed has an area of 151,126 Ha which is crossed by the main river (Cisadane River) and 10 tributaries. The Cisadane River flows water from the Gede-Pangrango and Halimun-Salak mountains as far as 126 km to the Java Sea. This watershed is located at an altitude of 2958 m above sea level.

This watershed is included in the administrative areas of West Java Province and Banten Province. This watershed is very important because it is a source of clean water for residents and industrial activities in the province. The morphological conditions of this watershed are grouped into 3 types (trees): 1) flat areas (0%–8%) are found in the downstream area; 2) wavy topography (8%–40%) is found in the middle of the watershed; 3) topography (> 40%) is found in the upstream part of the watershed. The dominant vegetation in this watershed is the built-up area in the downstream part of the watershed, agriculture and rice fields in the middle part of the watershed, and forests in the upstream part of the watershed (Ambarwulan et al., 2023). The research area has a tropical climate with a rainfall range of 2000–5000 mm/year with an average temperature in the downstream of 25.73 ℃ and in the upstream 21.23 ℃.

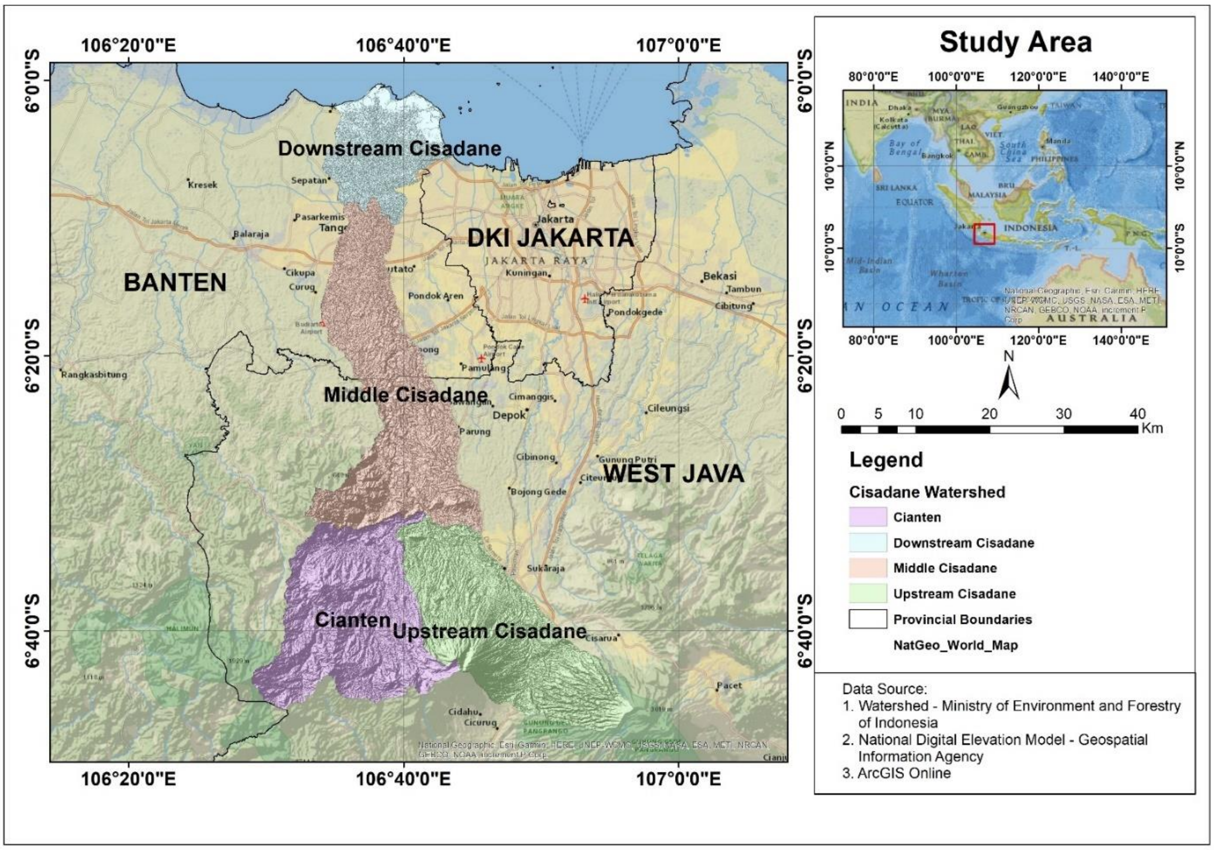


Figure 1. Research location, Cisadane Watershed, Indonesia.

2.2. Sources of dataset

The study utilized some thematical data for estimating WY dynamic and predictions using the InVEST annual WY modeling (**Table 1**). The InVEST model is a spatial-based software in raster format, so all input data was standardized into raster format with a spatial resolution of 30 m × 30 m and the World Geodetic System (WGS) 84 coordinate system.

Table 1. Summary of data inputs for InVEST annual water yield.

Parameter/Data	Description	Data and Value	Source
Precipitation or Rainfall (mm)	Map of average annual rainfall	Annual Average Rainfall (mm) Raster	JAXA Global Rainfall Watch website https://sharaku.eorc.jaxa.jp/ GSMaP/)
Reference Evapotranspiration (mm)	The amount of water that vaporizes from land into the air over a given period. It is the sum of evaporation (directly off of soil, bodies of water, and other surfaces) and transpiration (through plants)	Global Potential Average Evapotranspiration (mm) Raster	MODIS Terra Yearly L4 Global (https://earthexplorer.usgs.gov/)
Root Restricting Layer Depth (mm)	The soil depth at which root penetration is strongly inhibited because of physical or chemical characteristics.	Raster (mm)	Harmonized World Soil Database (HWSD) https://www.fao.org/soils-portal/en/data-hub/soil-map-data-base
Plant Available Water Content (PAWC)	The difference between the fraction of volumetric field capacity and permanent wilting point.	Raster (0 to 1)	Harmonized World Soil Database (HWSD) https://www.fao.org/soils-portal/en/data-hub/soil-map-data-base
LULC: 2010, 2015, 2021	Describes the physical properties of the land and/or how people are using it	Raster—Coded Land Use/Land Cover	Ambarwulan et al. (2023)

Table 1. (*Continued*).

Parameter/Data	Description	Data and Value	Source
Boundary Shapefile (Watershed)	Map of watershed boundaries	Integer (ws_id) from one to n. Vector file (.shp)	College of Forestry, Environment and Resources Management; Ministry of Environment and Forestry, Republic of Indonesia
Biophysical Table		CSV File (Values assigned per Land Use/Land Cover	
LULC Vegetation (AET Equation)	Indicating whether the LULC class is vegetated for AET		InVEST Guide
Root Depth	Depth at which 95% of root biomass occurs		Rooting depths

2.3. Methods

Broadly speaking, this research has been divided into four main steps, namely (1) preparing input data, (2) calculating and predicting WY, (3) impact of climate and LULC on WY, and (4) calculating the relationship between LUI and WY. The framework of this research is shown in **Figure 2**.

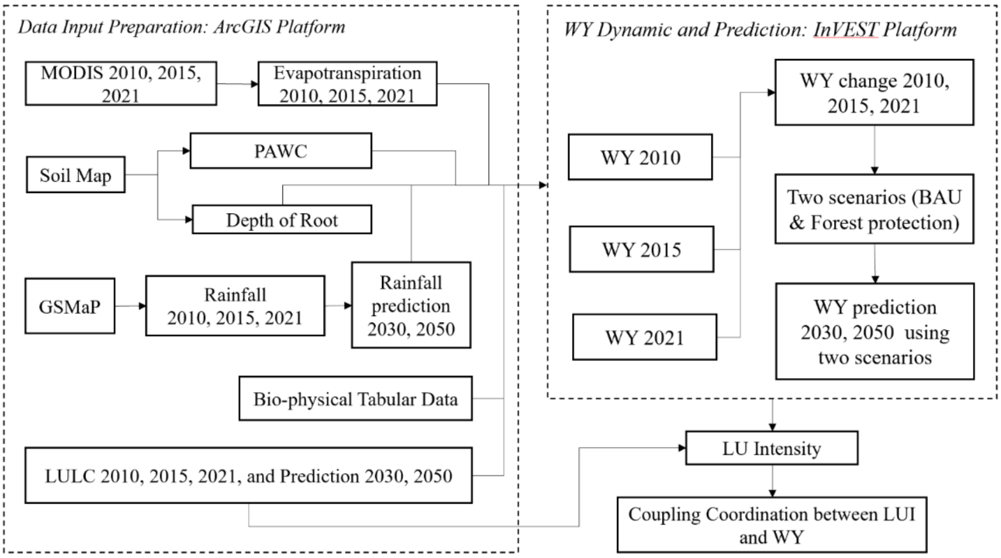


Figure 2. Research flowchart.

2.3.1. Preparing data input

a) Multi Years LULC

The LULC maps of 2010, 2015, 2021 are not part of this research because they have been processed and published (Ambarwulan et al., 2023). The LULC of 2010, 2015, and 2021 used in this research come from Landsat 5 imagery in 2010, Landsat 8 in 2015, and Sentinel-2 MSI in 2021 which were processed using Google Earth Engine. The LULC classification system used was supervised classification, Machine Learning, and a Random Forest algorithm. The LULC classification consists of eight LULC classes, namely the built-up land (BUL), dryland farming (DF), paddy field (PF), plantation (PLT), forest (FRT), pond (PO), and water body (WB) classes. The accuracy assessment has been carried out using the Kappa value, the research found that the Kappa value was above 83% for the three LULCs (Ambarwulan et al., 2023).

Additionally, LULC prediction was done using Land Change Modeller (LCM).

b) Rainfall

Many sources of rainfall data are available, both from field measurement observations and from global satellite data such as the Global Satellite Mapping of Precipitation (GSMaP) and the Tropical Rainfall Measuring Mission (TRMM). This study has been used daily rainfall data from the global satellite GSMaP downloaded from the JAXA Global Rainfall Watch website (https://sharaku.eorc.jaxa.jp/GSMaP/) with 10 km spatial resolution. This study utilizes satellite rainfall data because it has broader coverage area compared to using point data from the Meteorological, Climatological, and Geophysical Agency (BMKG) stations, and it has a good performance to estimate daily rainfall data over the Indonesia (Fatkhuroyan and TrinahWati, 2018). Over the Cisadane Watershed, there are only 2 rain-gauge BMKG meteorological station, while the satellite data has 77 gridded rainfall data. Furthermore, the satellite data is in grid format which enhances the detail results from the models that also use land use inputs. Consequently, the simulation results from the InVEST model, which employs grid-based rainfall data, are expected to be more detail and accurate. The rainfall data used is the average annual rainfall spatialized and resampling to 30 m resolution by using the Kriging interpolation technique. In the rainfall change scenario, it has been assumed: (1) that rainfall in the Cisadane Watershed increased gradually by 5% in 2030 and 10% in 2050 from the 2021 rainfall data baseline, and (2) evapotranspiration data was assumed to be constant.

c) Evapotranspiration

Evapotranspiration (ET) is the integration of evaporation and transpiration, which is the process of water transfer from the land surface and vegetation to the atmosphere. ET is one of the components that plays an important role in the WY model. The variability of WY is influenced by ET and rainfall which is divided into infiltration and runoff. These processes have an impact on water availability and ecosystem dynamics in various landscapes. ET values are obtained from the Annual Evapotranspiration (AET) of the Moderate Resolution Imaging Spectroradiometer (MODIS) Terra Level 4 which has a spatial resolution of 500 m and is downloaded from the site https://earthexplorer.usgs.gov/. The MODIS data used are data in 2010, 2015 and 2021 (**Table 2**). The algorithm used is based on the Penman-Monteith equation which includes daily meteorological reanalysis data, vegetation, albedo and land cover. The ET data, originally at 500 m resolution, was resampled to 30 m using the cubic technique and then adjusted to match the original values.

Table 2. The AET of Cisadane watershed derived from MODIS Terra.

Year	Max	Mean	Min	X	Y	StD
2010	65534	19852.2	1825	1	1	18881.2
2015	65534	19511.1	1825	1	1	19171.9
2021	65534	19954.7	1825	1	1	18861.4

2.3.2. Calculating and prediction WY multi years

InVEST software (https://naturalcapitalproject.stanford.edu/software/InVEST, accessed on 18 May 2024) has been used to calculate the annual WY in the Cisadane

Watershed. The input data include LULC, annual rainfall, annual ET, and soil solum depth. The calculation of WY was carried out using Equation (1) (Budyko and Miller, 1974).

$$Y_{(x)} = \left(1 - \frac{\mathrm{AET}_{(x)}}{P_{(x)}}\right) \times P_{(x)} \tag{1}$$

where $Y_{(x)}$ is the annual rainfall on pixel x and $AET_{(x)}$ is the actual annual ET for pixel x.

The actual AET is quite impossible to measure on a broad scale. AET was calculated using potential evapotranspiration (PET) in the InVEST model. Based on PET, calculating AET was simple, which was calculated by multiplying the reference ET by the crop coefficient for each grid square. The AET was calculated using Equations (2) and (3) (Fu, 1981).

$$\frac{AET_{(x)}}{P_{(x)}} = 1 + \frac{PET_{(x)}}{P_{(x)}} - \left[1 + \left(\frac{PET_{(x)}}{P_{(x)}}\right)^{\omega}\right]^{\frac{1}{\omega}} \tag{2}$$

$$\omega_{(x)} = Z\frac{AWC_{(x)}}{P_{(x)}} + 1.25 \tag{3}$$

where $\boldsymbol{\omega}_{(x)}$ is calculated based on the plant's available water content (AWC), the empirical constant *Z*, and rainfall (Sharp et al., 2020). *Z* is an empirical constant ranging from 1 to 30, reflecting regional hydrogeological characteristics. AWC, or available vegetation water content, is determined by the effective soil depth and texture. The detail of WY calculating can be found in (Nahib et al., 2023; Sharp et al., 2020).

The available water capacity of soil refers to its ability to hold water that plants can use. It is represented as the AWC(x) where (x) denotes the specific pixel or location. This metric is calculated using PAWC, minimum depth of the root limiting layer (Root1), and the vegetation's root depth (Root2). The Equation (4) is used to perform the calculation.

$$\mathrm{AWC(x)} = \min\,(\mathrm{Root1}, \mathrm{Root2})\cdot\mathrm{PAWC} \tag{4}$$

The ET of reference plants ETo(x) in the particular location reflects the local meteorological conditions, whereas Kc(x) is influenced mostly by the land use and plant cover features unique to each pixel. The AET in non-vegetated LULC regions, such as water bodies or settlements, is directly calculated based on the reference ET. The quantity of rainfall determines the upper limit of ETo(x), and the estimate approach using Equation (5):

$$\mathrm{AET(x)} = \min\,(\mathrm{Kc(x)}\cdot\mathrm{ETo(x)}, \mathrm{P(x)}) \tag{5}$$

The modified Hargreaves equation (BIG, 2021) was used to compute reference evapotranspiration, ETo(x) (mm/day). When the following data are provided, this method is thought to produce more accurate findings than Penman–Monteith method using Equation (6).

$$ETo_{(x)} = 0.0013 \cdot 0.408Ra \left[\left(\frac{T_{max} + T_{min}}{2}\right) + 17\right] [(T_{max} - T_{min}) - 0.0123P]^{0.76} \tag{6}$$

where: *Ra* = extra-terrestrial solar radiation (MJ·m−2·d−1), $T_{\max}$ = average maximum daily air temperature (°C), $T_{\min}$ = average minimum daily air temperature (°C), *P* = monthly rainfall (mm/day).

The InVEST model validity was assessed by comparing it to the whole Wyoming dataset received from (Liu et al., 2017). Linear regression analysis was used to compare the observed data to the estimated data generated by the model. Several statistical analyses were performed using the R program during the model validation phase depending on the study findings. The InVEST model validity was assessed by comparing it to the whole Wyoming dataset received from (Liu et al., 2017). Linear regression analysis was used to compare the observed data to the estimated data generated by the model. Several statistical analyses were performed using the R program during the model validation phase depending on the study findings. The determination coefficient (R^2), Pearson correlation (r), and root mean square error (*RMSE*) were all calculated as part of these investigation.

2.3.3. Impact of changes in climate and LULC on the WY

To assess the impact and contribution of various parameters to fluctuations in WY volume, we examined three scenarios in the WY modeling: (1) baseline: no changes in climate or LULC, (2) climate change and LULC remaining constant, and (3) LULC change and climate conditions remaining constant. By calculating WY variability across these scenarios, we quantified the influence of both climate and LULC changes on WY variability using Equations (7) and (8) (Wei et al., 2021).

$$Z_C = \frac{\Delta\text{Climate}}{\Delta\text{Climate} + \Delta\text{LULC}} \times 100\% \tag{7}$$

$$Z_L = \frac{\Delta\text{LULC}}{\Delta\text{LULC} + \Delta\text{Climate}} \times 100\% \tag{8}$$

In this context, Z_C represents the climatic rate’s contribution to changes in WY without LULC alterations, while Z_L indicates the rate at which LULC changes impact WY without climate change. Δ Climate shows the variation in the annual mean WY between 2010–2015 and 2015–2021 under a scenario with no LULC changes. Similarly, Δ LULC reflects the difference in the mean annual WY between 2010–2015 and 2015–2021 under a scenario with no climate change.

2.3.4. Calculating and relationship between LUI and WY

Regarding Land Use Intensity (LUI), it’s categorized into four classes: (i) unutilized land and bare land (class 1), (ii) water bodies, lake, paddy field, forests (virgin forest and plantation forest), shrub and grasslands (class 2), (iii) agricultural land: estate crop plantation, dry farming (class 3), and (iv) construction land: settlement area and airport (class 4). LUI reflects, to some extent, the intensity of anthropogenic disturbances. The LUI index was calculated using Equation (9) (Zhu et al., 2022).

$$\mathrm{LUI} = 100 \times \sum_{i=1}^{n} A_i \times C_i \tag{9}$$

where LUI means the comprehensive index of land use degree; A_i indicates the index of the land use degree classification of level i; and C_i is the percentage of the area of the land use degree classification of level i.

The interconnected relationships between LUI and total ecosystem services (TES) were inspired by a concept found in physics literature (Zhu et al., 2022). This concept highlights that when two or more systems interact, they can mutually benefit from a positive dynamic relationship (Dong and Li, 2021). Drawing upon this theory of coupling in physics, we developed a model to calculate the coupling between ES and LULC, as depicted at Equation (10).

$$C = 2\sqrt{(LUI_x \times TES_x)/(LUI_x + TES_x)^2} \tag{10}$$

In this context, C denotes the degree of coupling between LUI and TES, ranging from 0 to 1. LUI represents the assessment value for LUI, while TES indicates the comprehensive assessment for TES. Higher values of C indicate stronger interactions between LUI and TES.

However, it’s essential to recognize that the coupling degree solely reflects the level of correlation between the two systems, rather than their actual developmental status. It’s plausible for both systems to have low values yet exhibit high coupling degrees. Hence, it’s crucial to distinguish between a high coupling value and high horizontal coupling. To quantify the level of coordination between LUI and TES, the CCD model was employed, utilizing the Equations (11) and (12).

$$D = \sqrt{C \times T} \tag{11}$$

$$T = \alpha LUI_x + \beta TES_x \tag{12}$$

In this scenario, D represents the coordination coefficient of LUI and TES ecosystem. T signifies the collective synergy effect expressed in the comprehensive evaluation index of both systems. α and β denote the weight coefficients assigned to the two systems, typically ranging between 0 and 1. For this study, it is assumed that urbanization and the ecosystem hold equal significance. Hence, both α and β were assigned the same value of 0.5 (Zhang and Li, 2020). Recent studies categorize the CCD into different levels of imbalance and coordination: severe imbalance ($0 \leq D < 0.2$), moderate imbalance ($0.2 \leq D < 0.4$), essential coordination ($0.4 \leq D < 0.6$), reasonable coordination ($0.6 \leq D < 0.8$), and high coordination ($0.8 \leq D \leq 1$) (Zhang et al., 2022).

3. Result and discussion

In order to provide a comprehensive understanding of the relationship between LULC, LUI and WY in the Cisadane Watershed, the InVEST model and CCD have been applied. The result and discussions will be included: (1) Actual and predicted WY; (2) Impact of climate change and LULC changes on the WY; and (3) Relationships between LUI and WY.

3.1. Water yield actual and prediction

The annual WY for the Cisadane Watershed in 2010, 2015 and 2021 are presented in **Table 3** and illustrated in **Figure 3**. As shown in **Figure 3**, the WY distribution pattern in the Cisadane Watershed from 2010 to 2021 s relatively consistent. The downstream area exhibits a low WY class (brown), while the Cianten area falls into the medium class, and the upstream Cisadane area is classified as high class.

Table 3. Annual WY from 2010–2021 and prediction for 2030 and 2050 based on two scenarios (BAU and PFA).

Sub watershed	**Area (Ha)**	**WY Actual**									
		2010		**2015**		**2021**		**2010–2015**		**2015–2021**	
		Mean (mm)	**Volume***	**Mean (mm)**	**Volume***	**Mean (mm)**	**Volume***	**%**	**(%/year)**	**%**	**(%/year)**
Cisadane Downstream	201.60	298.00	5.51	342.00	6.33	531.00	9.81	12.95	2.59	43.83	3.98
Middle Cisadane	473.50	787.38	36.87	1,086.00	50.88	1,197.00	56.09	27.54	5.51	34.27	3.12
Cisadane Upstream	426.24	1223.00	51.90	1,382.00	58.70	1,670.00	70.95	11.58	2.32	26.85	2.44
Cianten	423.68	1282.00	54.21	1,188.00	51.60	1,813.00	76.60	−5.06	−1.01	29.23	2.66
Cisadane Watershed	151,576.65	897.60	150.22	1,105.00	167.51	1,424.28	215.88	10.32	2.06	30.42	2.77

Sub Watershed	WY Prediction*								
	Baseline	Scenario BAU		Scenario PFA		Change BAU		Change PFA	
	2021	2030	2050	2030	2050	2030	2050	2030	2050
Cisadane Downstream	9.81	11.81	14.52	11.2	14.52	2.00	4.71	1.39	4.71
Middle Cisadane	70.95	61.13	71.22	60.97	71.1	−9.82	0.27	−9.98	0.15
Cisadane Upstream	70.95	76.8	91.57	76.97	88.46	5.85	20.62	6.02	17.51
Cianten	76.65	82.18	98.1	83.35	93.7	5.53	21.45	6.7	17.05
Cisadane Watershed	215.8	234.5	278.4	235.1	270.7	18.7	62.6	19.3	54.9

Notes: * = 108 m^{3}.

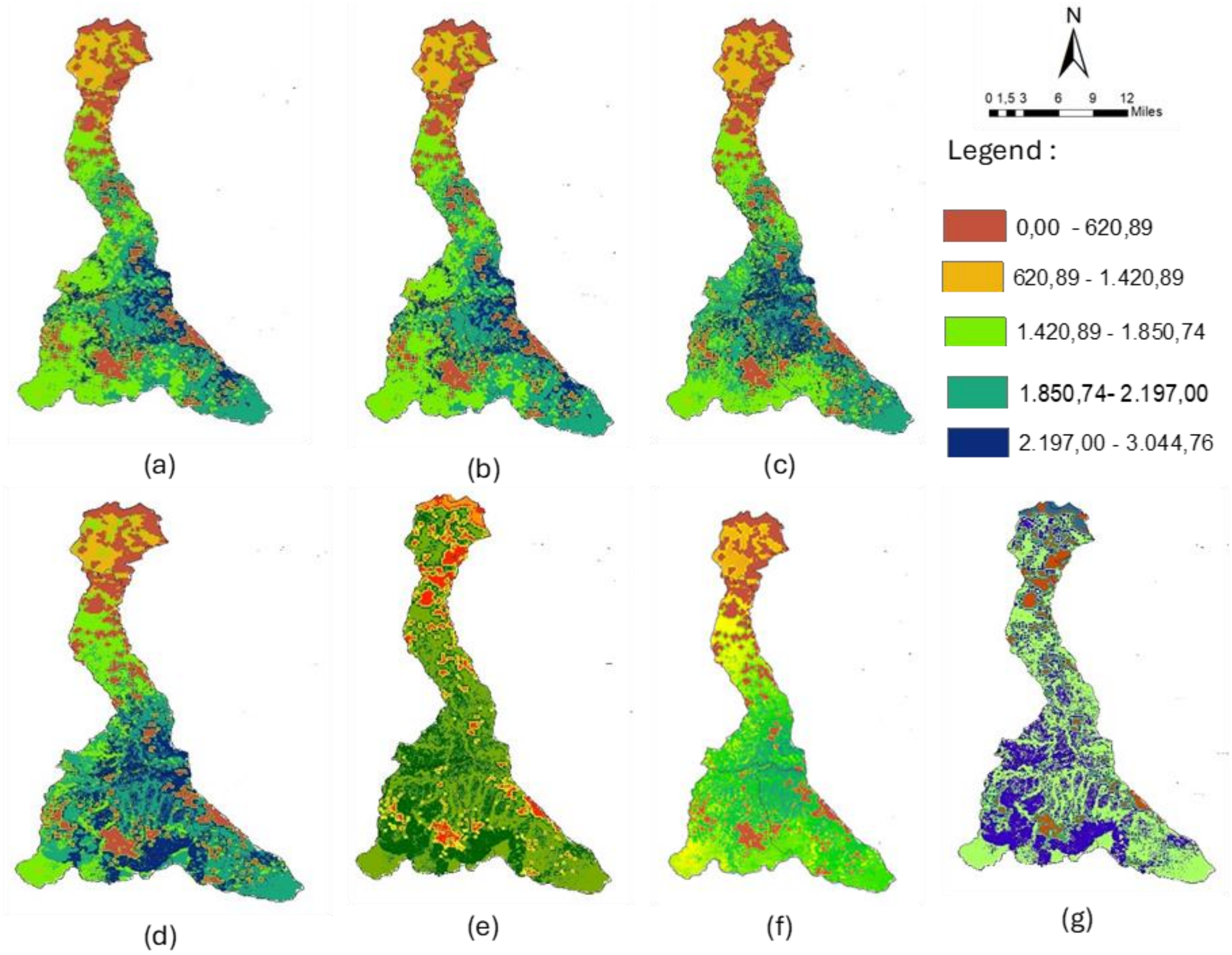


Figure 3. Spatial distribution (in mm/year) of WY in Cisadane Watershed on. **(a)** 2010; **(b)** 2015; **(c)** 2021; and WY prediction on; **(d)** 2030 (BAU); **(e)** 2050 (BAU); **(f)** 2030 (PFA), and; **(g)** 2050 (PFA).

Referring to **Table 3**, the overall WY condition in the Cisadane Watershed in 2021 increased about one percent per year relative to 2010. The highest average WY was observed in the Cisadane Upstream, Cianten, and Middle Cisadane sub-watersheds. Conversely, the region with the lowest average WY was in the downstream areas. The most significant increase in WY occurred in the Middle Cisadane sub-watershed, with an increase of 4.93×10^8 m^3 (9.68%) during the period 2010–2015 and 5.65×10^8 m^3 (11.10%) during the period 2010–2021. The smallest increase was in the Cisadane Downstream sub-watershed, with an increase of 10×10^8 m^3 (1.57%) during the period 2010–2015 and 20×10^8 m^3 (3.15%) during the period 2010–2021. It can be seen from **Table 3** and **Figure 3** that there was high WY in the upstream area (Cisadane Upstream sub-watershed and Cianten sub-watershed) and decreases to downstream sub-watersheds. For the entire Cisadane Watershed, WY from 2010 to 2021 experienced an average increase of 2.77% per year, where WY in 2010 was 897.60 mm and in 2021 it increased to 1424.28 mm. Although the WY of Cisadane Watershed, for the 2010–2021 period, increased by 2.66% per year, the WY for the Cianten sub-watershed, in the 2010–2015 period, decreased from 1282 mm to 1188 mm. In other words, WY in the Cianten sub-watershed, for the 2010–2015 period, experienced a decline of 1.01% per year.

Using LULC predictions (BAU and PFA) and rainfall predictions for 2030 and 2050, the volume of WY in the Cisadane Watershed for 2030 is presented in **Table 3** and illustrated in **Figure 3**. The WY for 2030 and 2050 under both scenarios (BAU and PFA) shows a general increased. **Figure 3** illustrated that this increase in WY was observed in almost all sub-watersheds of Cisadane Watershed for both conditions. Detailed observations from **Table 3**, in BAU conditions, from 2021, 2030 and 2050 WY always experiences an increase. Where the volume of WY in Cisadane Watershed in 2021, 2030, and 2050 is 215.8 × 10^8 m^3, 234.5 × 10^8 m^3, and 278.4 × 10^8 m^3, respectively. However, the WY value of the Middle Cisadane sub-watershed in 2030 experienced a decrease of 9.82 × 10^8 m^3, while in 2050 it rose again to reach 0.27 × 10^8 m^3 if compared with WY in 2021. The WY from Middle Cisadane in 2021, 2030, and 2050 respectively is 70.95 × 10^8 m^3, 61.13 × 10^8 m^3, and 71.22 × 10^8 m^3. The increase of WY in Cisadane Watershed can also be seen in PFA conditions, wherein 2021, 2030, and 2050 are 215 × 10^8 m^3, 235.1 × 10^8 m^3, and 270.7 × 10^8 m^3, respectively. However, the Middle Cisadane sub-watershed looks different compared to other sub-watersheds. The Middle Cisadane sub-watershed in 2030 decreased by 9.98 × 10^8 m^3 (to 60.97 × 10^8 m^3) and in 2050 it increased again to 71.1 × 10^8 m^3. With the BAU scenario, WY in Cisadane Watershed for 2030 is estimated to increase by 18.7 × 10^8 m^3, while with the PFA scenario, it is estimated to increase by 19.3 × 10^8 m^3.

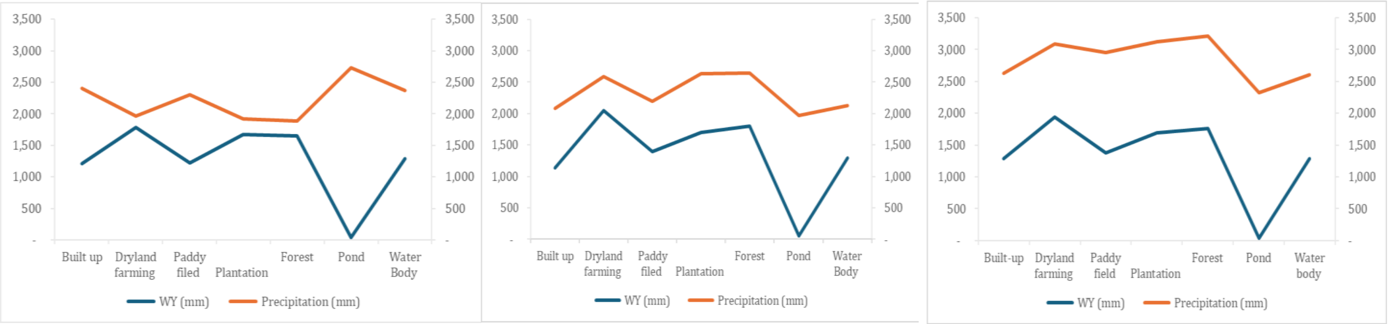
In the Middle Cisadane and Downstream Cisadane sub watersheds, for 2030, the WY results from the PFA scenario were lower compared to the results from the BAU scenario. Meanwhile for other sub-watersheds, the situation was opposite. In 2050, for almost all sub-watersheds, the WY resulting from the PFA scenario was lower than the WY resulting from the BAU scenario. However, this was not the case for the Downstream Cisadane sub-watershed, where the WY resulting from the BAU scenario was the same as the WY resulting from the PFA scenario.

Under the PFA scenario in 2030, the predicted annual WY will reach 235.1 × 10^8 m^3, while the BAU scenario for the same year predicts 234.5 × 10^8 m^3. This represents an increase of approximately 0.25% compared to the BAU scenario, or an increase of 187.0 × 10^8 m^3 (8.66%) compared to the WY conditions in 2021.

In 2050, the PFA scenario projects a WY of 278.4 × 10^8 m^3, whereas the BAU scenario predicts 235.1 × 10^8 m^3. This indicates an increase of about 2.84% compared to the BAU scenario in 2050, or an increase of 626.0 × 10^8 m^3 (29.91%) compared to the WY conditions in 2021. The findings show, changes in LULC over 21 years mainly involves forest loss due to agricultural land expansion losses for residential development. Other research in Heilongjiang Province China in 2024, specifically from 2000 to 2020, changes in rainfall increased and contributed 99.58% to WY, while changes in land use type only contributed 0.42% to the trend in WY which increases even though residential growth increases.

Research conducted by Astuti et al. (2019) in the upper Brantas River Basin, East Java showed that changes in LULC between 1995 and 2015 impact on the hydrological processes. The model used is the Soil and Water Assessment Tool (SWAT) with data from 2003–2008 for calibration, while for validation in 2009–2019 with $R^2 > 0.91$. The model predicts that in the long term there will be changes in WY (+0.28%), runoff (+8%), groundwater (−1.8%), and ET (−1.15%) (Astuti et al., 2019). Similarly, a study was carried out by Soplanit and Silahooy (2012) in Batugajah River Basin, Ambon City. In 1998–2010, forest areas decreased by 28.73%, settlements increased by 29.06%, and village areas increased by 12.12%. Land use change resulted in WY increased from 210.48 mm to 220.56 mm, annual discharge increased from 2525.81 mm to 2646.70 mm; surface flow increased from 2288.35 mm to 2291.35 mm; subsurface flow also increased from 103.382 mm to 244.99 mm, while base flow decreased from 141.07 mm to 110.35 mm (Soplanit and Silahooy, 2018). Meanwhile, the analysis of annual WY using the InVEST model was also conducted by Ningrum et al. (2022) in Tesso Nilo National Park, Riau in 2018 and obtained an annual WY of 2729.52 mm. The WY is significantly influenced by actual ET, mean annual rainfall and land cover (Ningrum et al., 2022). Studied in by Hou et al. (2022) in the Yiluo River Basin, China with the aim of detecting the evolution and attribution of WY coefficients in the past and future. The results obtained were that the WY increased by 8.53% from 2000–2020, with agricultural land increasing by 10.47% and forest land decreasing by 8.93% (Hou et al., 2022). While Li et al. (2018) used the InVEST model to investigate the spatial-temporal variation of WY due to LULC changes. In northern China, the Beijing-Tianjin-Hebei region from 1990 to 2015, there was an increase in built-up area of 35.66%, while vegetation land decreased resulting in an increase in total WY of 5.1% (Li et al., 2018). In addition, climate change and LULC have an impact on WY in Heilongjiang Province, China. Research conducted by (Liu et al., 2024) in 2000, 2010 and 2020, the results obtained were WY of 105.03 mm, 162.46 mm, and 269.34 mm. From 2000 to 2020, the WY increased by 164.31 mm (156.44%). Climate change contributed 99.58% to the WY, while LULC change contributed 0.42% (Liu et al., 2024).

Referring to several studies of WY on the island of Java, including by Nahib et al. (2021) in the Citarum watershed the average was 935.26 mm/year, while in Central Citarum by Suryanta et al. (2024) the average WY was 1636.44 mm /year. Another research conducted by Ridwansyah et al. (2014) in the Cisadane Watershed the averaged WY was 1373.05 mm/year. subsequent research by Nugroho (2017) in the Rawapening watershed, the WY value was 1137.00 mm/year. WY’s current research in 2024 in the Cisadane Watershed between 2010 and 2021 apparently shows results ranging from 997 mm/year—1317 mm/year. Referring to research on the average WY on Java Island of 1401.28 mm/year, the current research results are acceptable for further WY trend analysis and further simulations for the management of the Cisadane Watershed itself. Based on the relationship between rainfall and WY as influenced by LULC type, which is presented in the **Figures 4** and **5**.



(a) Year 2010 **(b)** Year 2015 **(c)** Year 2021

Figure 4. Relationship between Rainfall with WY on the years of 2010, 2015 and 2021.

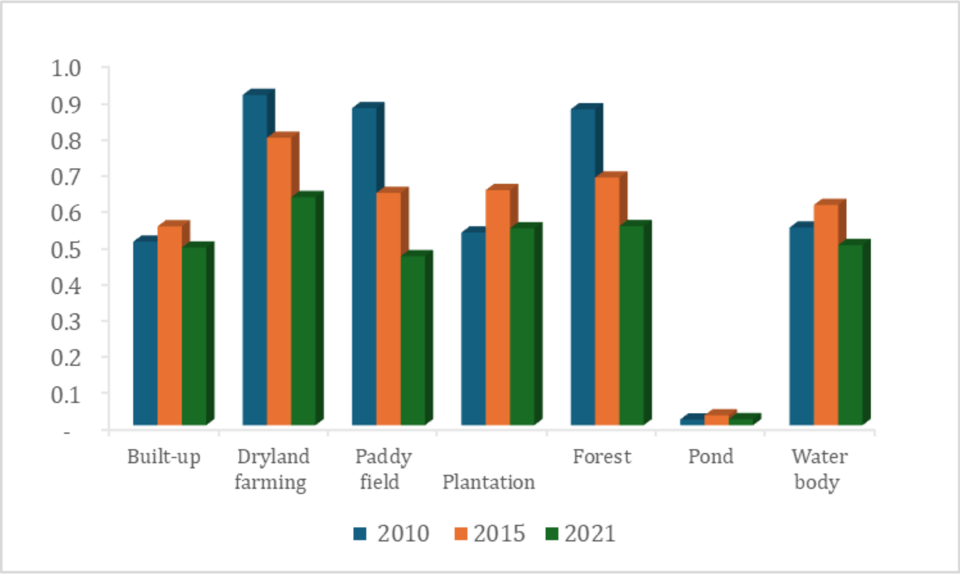


Figure 5. Water Yield (WY) Coefficient base on LULC.

Referring to the **Figure 5**, the WY coefficient analyzed base on LULC tends to show a similar pattern in 2010, 2015, and 2021. The highest WY coefficient is observed in Dryland (0.62–0.90) and Forest (0.54–0.86), while the lowest coefficient is found in Pond Farming (0.01–0.02). For land cover types such as built-up areas, the WY coefficient is higher compared to Pond Farming.

The relationship between rainfall and WY (see **Figure 4**) is affected by various factors. Typically, more rainfall leads to increased WY as more water is available to flow into rivers, lakes, or reservoirs. However, this relationship can vary depending on several factors. First, vegetation, such as forests or crops, can absorb rainwater and influence water flow. Dense vegetation usually increases infiltration and reduces direct surface runoff, thereby enhancing WY and improving soil health. Second, urbanization, deforestation, and other land use changes can impact WY by altering water absorption and flow. Urban areas often have impervious surfaces that reduce infiltration and increase surface runoff, leading to lower WY. Conversely, reforestation efforts can enhance infiltration and reduce runoff, thereby increasing WY. While higher rainfall generally increases WY, the effectiveness of this relationship is significantly influenced by soil conditions, vegetation cover, topography, and land use practices. The WY coefficient represents the proportion of rainfall that contributes to WY. One limitation of the InVEST model is its inability to distinguish between groundwater and surface water. This limitation explains why the WY coefficient is higher in built-up areas compared to pond farming (Nahib et al., 2021). Effective water conservation and management practices are crucial to maintaining the watershed's health and ensuring sustainable water resources. Integrated watershed management programs are essential to address the challenges posed by land use changes and pollution.

3.2. Impact of climate change and LULC changes on the water yield

We calculated the contribution level of each parameter included in the scenarios, namely LULC and climate change. Equations (7) and (8) were used to determine the contribution levels in **Table 4**. Referring to **Table 4**, it can be seen that the largest contribution to changes in WY comes from rainfall (climate factors), with an average of 88.99%, while changes in LULC contribute only an average of 11.01%. The contribution patterns of climate and LULC are similar, with climate contributing more significantly than LULC.

Table 4. The contribution of climate change and LULC on actual WY (×10^8 m^3).

Actual 2010	**WT CLIM**	**WT LULC**	**Climate (ΔC)**	**LULC (ΔL)**	**ΔL+ΔC**	**ZC (%)**	**ZL (%)**
150.22	2015 179.51	2015 154.50	29.29	4.28	33.57	87.25	12.75
150.22	2021 227.80	2021 158.15	77.58	7.93	85.51	90.73	9.27
Average			53.44	6.11	59.54	88.99	11.01
Actual 2021	WT CLIM	WT LULC	Climate (ΔC)	LULC (ΔL)	ΔL+ΔC	ZC (%)	ZL (%)
215.88	BAU 2030 234.96	BAU 2030 215.43	19.08	0.45	19.53	97.70	2.30
215.88	BAU 2050 273.55	BAU 2050 220.71	57.67	4.83	62.5	92.27	7.73
215.88	PAF 2030 234.96	PAF 2030 234.26	19.08	3.38	22.46	84.95	15.05
215.88	PAF 2050 273.55	PAF 2050 213.19	57.67	2.69	60.36	95.40	4.60
Average			38.37	2.77	41.15	92.52	7.48

Based on **Table 4**, the pattern of climate and LULC contributions to WY predictions aligns with actual WY conditions. The contribution pattern indicates that climate has a more significant impact than LULC. It is evident that the largest contribution to changes in WY comes from rainfall (climate factors), averaging 92.52%, while changes in LULC contribute only 7.48% on average. The impact of LULC changes on WY predictions for 2030 and 2050 ranges from 2.30% to 15.05%, while the impact of climate factors is between 84.95% and 97.70%. This pattern is consistent with the contribution of LULC and climate to the actual WY in 2015 and 2021. This condition is in accordance with the research findings of Nahib et al. (2023) in the Citarum Watershed that the contribution of LULC changes to variations in WY during the 2000–2018 period ranged from 5.8% to 10.42%. In contrast, climate change had a much larger impact, contributing between 89.57% and 94.19% (Nahib et al., 2023). Meanwhile research on WY by Bai et al. (2019) also shows the greater impact of climate change than water retention on land use change at the state scale of Kentucky USA, but on soil retention, nitrogen and phosphorus export, land use change contributes more.

In Jin-Jing-Jin, China, changes in LULC, such as the reduction of cropland, grassland, and swamp areas and the increase in built-up areas, have led to a significant increase in WY by 5.1% (Li et al., 2018). Research conducted in the alpine regions of the Qinghai-Tibet Plateau (QTP) using the InVEST model showed that the model accurately predicts WY. The study found that in the Shule River Basin, climate change had a much larger impact (90.56%) on WY compared to LULC change (9.44%), highlighting the model's effectiveness (Wei et al., 2021). For more details, refer to Balist et al. (2022) which discusses the combined effects of LULC and climate change on WY. The study shows that climatic factors have a more significant impact on WY compared to LULC changes. Specifically, the results indicate that climatic factors influence WY three times more than LULC factors (Balist et al., 2022). Clerici et al. (2019) found out that the effect on WY and supply of climate change scenarios greater than LUCC change scenarios, however in rural forest and shrubland areas the carbon sequestration is greater than from Bogota. Decreasing WY could be the result of reduced ET due to strong decay in rainfall, or primarily results of agriculture and pasture's urbanization, increasing human, industrial consumption, etc. Coupled of the increasing temperature and reduced rainfall was characterized the climate change results, implies increasing urbanization at the expense of pasture-cultivated areas and forest cover to a lesser degree, on the scenarios of economic development and land use policies assumption will be continued in the past decades. On the other hand, increasing WY will have the most discernible effect from urbanization. The modelling approach of InVEST was unable to estimate the temporal variations of WY during the tropical dry and rainy season, in the dry season monthly WY will be decreasing in term of annual balance.

The influence of rainfall on water production is more significant than LULC change effect. In the Yellow River Basin, China, from 1995 to 2018, the WY increased by 20,106 million m^3. The LULC change and climate change contribution to water production from 1995 to 2005 were 3.32% and 96.68%, and from 1995 to 2018 were −0.48% and 100.48% respectively (Yang et al., 2021). Another study in the Dongjiang Lake Basin also showed that the WY of all LULC types also increased by 21.15% in 2010–2020, and the average annual rainfall increased by 18.29%. Thus, the WY of the watershed is significantly affected by climate change, especially rainfall, which has a positive correlation with WY (Mo et al., 2021). Research conducted in the Yellow River Basin in Henan Province, with simulations of changes in LULC and climate change from 2000–2030 shows that the interaction between meteorological factors (rainfall, potential ET) and changes in LULC types (such as rainfall and population) also has high driving force, which indicates that meteorological factors are the most important for air production in the study area (Ma et al., 2024). Lepcha et al. (2024) research in the upstream Teesta River basin simulates hydrological components and sediment yield for the historical (1990 to 2019) and near-future (2020 to 2059). LULC change affects decreased actual ET, streamflow, base flow, and WY (approximately 4%), while lateral flow and sediment yield increase (approximately 36%), both in the historical and near-future. Meanwhile, climate change has shown a significant increase in WY and sediment yield during the historical and near future. In historical, annual WY increased by around 12%.

3.3. Relationships between land use intensity (LUI) and water yield

Model Coordinated Coupling Degree (CCD) is used to assess the relationship between LUI and various ES, including WY. The model reveals that the integration of LUI and ES is primarily at a basic level and is nearly uncoordinated, indicating that the two significantly constrain each other. One of the main factors contributing to this low level of coordination is uncontrolled land use, which disrupts the balance necessary for sustainable environmental management. By assessing the CCD between LUI and WY, it is possible to measure how well LUI interacts with WY, a critical factor in sustainable land management (Li et al., 2024). LUI can have direct and indirect impacts on biodiversity, potentially leading to biodiversity loss, land degradation, decreased WY, increased carbon emissions, and other adverse environmental effects.

The CCD model was used to reveal the spatial distribution of the degree of coordinated development of LUI and WY in Cisadane Watershed, from 2010 to 2021 based on district presented in **Figure 6** and **Table 5**. **Table 5** summarizes the CCD between LUI and WY in the Cisadane Watershed at the district level from 2010 to 2021. The results of the study found that: severe imbalance decreased from 5 districts in 2010 into 4 districts in 2021, while moderate imbalance increased from 16 districts in 2010 into 18 districts in 2021, and reasonable coordination decreased from 7 districts in 2010 to 6 districts in 2021. Meanwhile, the number of districts with essential coordination and high coordination remained constant. Most districts (51.22%–53.66%) were in the unbalanced category, while the remaining districts (46.34%–48.78%) were in the coordination category. Overall, the distribution of districts across different CCD categories changed, with an increase in moderate imbalance and decreases in severe and reasonable coordination categories.

Table 5. Coupling coordination between LUI and WY in the Cisadane Watershed (District Scale) 2010–2021.

No		**2010**		**2021**		**Change 2010–2021**	
		Number	**%**	**Number**	**%**	**Number**	**%**
1	Severe imbalance ($0 \leq U < 0.2$)	5.00	12.20	4.00	9.76	(1.00)	(25.00)
2	Moderate imbalance ($0.2 \leq U < 0.4$)	16.00	39.02	18.00	43.90	2.00	11.11
3	Essential coordination ($0.4 \leq U < 0.6$)	9.00	21.95	9.00	21.95	0.00	0.00
4	Reasonable coordination ($0.6 \leq U < 0.8$)	7.00	17.07	6.00	14.63	(1.00)	(16.67)
5	High coordination ($0.8 \leq U \leq 1$)	4.00	9.76	4.00	9.76	0.00	0.00
	Total	41.00	100.00	41.00	100.00		

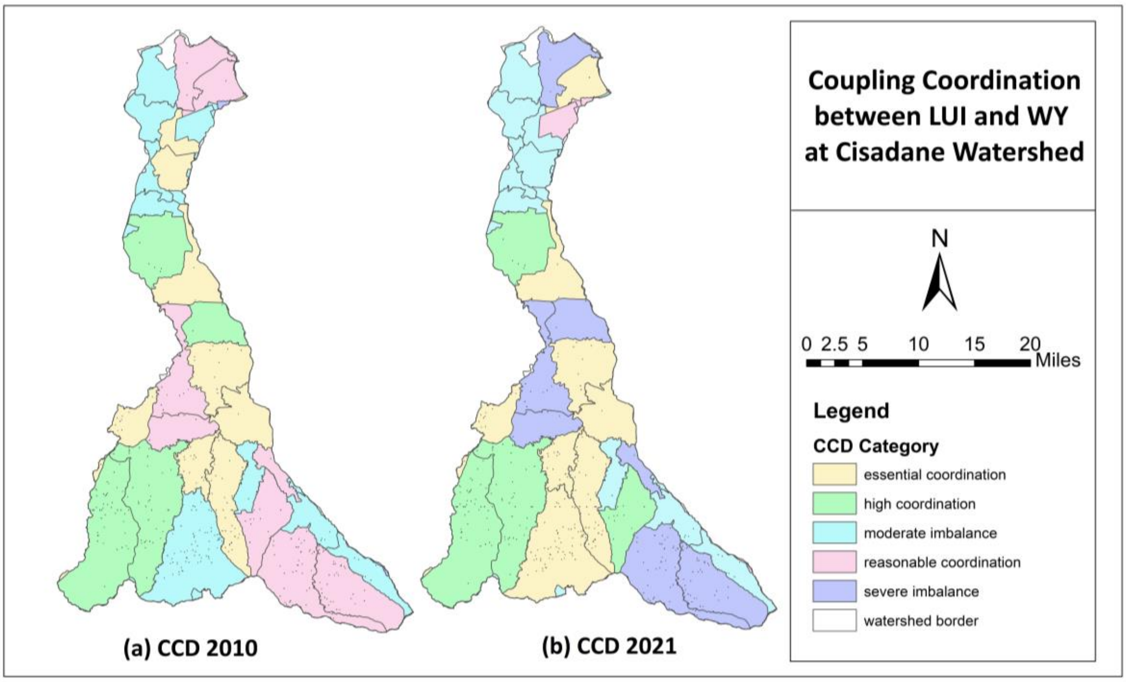


Figure 6. Spatial distribution of coupling coordination between LUI and WY on the district scale.

This particularly highlights the need for better coordination in regions where LUI and WY are not well aligned. Such coordination is essential for improving WY and promoting sustainable land use practices. The gap between water availability and demand can negatively impact ecosystem performance and regional economies, emphasizing the importance of optimizing land use to address this issue.

Several studies have highlighted that LULC changes and climate change significantly impact WY. Research using the GMOP-PLUS and InVEST models in the Xinjiang region shows that while land-use changes can increase water availability by enhancing plant water absorption, a deficit in water availability remains (Liu et al., 2023). Furthermore, climate change has a more substantial impact on WY than LULC changes, underscoring the need for coordinated strategies that address both factors. This coordination is crucial for managing the relationship between land development and WY services, particularly in key water resource areas (Wang et al., 2022).

Increased LUI typically leads to greater trade-offs among ES. For instance, while intensive agriculture can boost food production, it often comes at the cost of other services, such as water quality and biodiversity. In systems with high LUI, sustaining both food production and regulatory services is often only feasible on smaller farms, whereas, in low-intensity systems, these services can be maintained across larger farms.

Changes in LULC, such as urbanization, agricultural expansion, and deforestation, can either raise or lower WY. For example, in India, converting rice paddies to dryland crops increased surface water availability but decreased groundwater recharge (Reheman et al., 2023). Similarly, in Malaysia, forest degradation and urban expansion resulted in higher WY, underscoring the direct link between land-use changes and water resources (Baiya and Hashim, 2020). These observations highlight the critical need to consider land-use practices when managing water resources and planning for sustainable development. In regions where CCD is imbalanced, more effective land-use planning and management are essential. This approach can enhance LUI, which in turn can improve water retention and reduce evapotranspiration, thereby increasing WY and availability for various purposes, including agriculture, urban consumption, and environmental needs (Qi et al., 2023). Effective land-use planning can also boost soil infiltration rates, reduce runoff, and mitigate flood risks by ensuring that water is absorbed into the soil rather than flowing across the surface (Balist et al., 2022). Aligning LUI with WY can promote sustainable ecosystem services by maintaining healthy vegetation cover, which aids in soil conservation, reduces erosion, and supports biodiversity (Xu et al., 2016).

Conversely, in regions with a high Coordination Coupling Level, strategies should aim to optimize the balanced development of various subsystems. This can be accomplished through several methods. First, encouraging the adoption of environmentally friendly agricultural practices and conservation technologies to reduce water consumption and enhance soil health. Second, regularly monitoring and evaluating CCD to ensure the effectiveness of these strategies (Fan et al., 2023). Third, policies to local conditions to foster coordinated and sustainable development (Ge et al., 2023). Lastly, educating communities on water conservation and sustainable land-use practices. Actions that can improve the coordination and connection between LUI and WY include developing an index system to evaluate urban development intensity and water environmental carrying capacity (Deng et al., 2023), and assessing efficiency and coordinating linkages across different systems, such as those in high-tech industries (Deng et al., 2023). Integrating water resource management into land-use planning, as practiced in Greece, can significantly contribute to environmental conservation and sustainable development. This approach fosters collaboration between land-use authorities and water management entities through strategic planning, stakeholder involvement, adaptive management, and continuous monitoring to tackle water management issues and enhance environmental protection (Wang and Zhang, 2023).

4. Conclusion

This study employs a combination of the InVEST Model and CCD to assess WY. The InVEST Model evaluates WY for the years 2010, 2015, 2021, and forecasts future WY for 2030 and 2050. Meanwhile, the CCD method was applied to examine the relationship between LUI and WY. The findings are anticipated to support in managing land resources and optimizing WY.

The findings revealed the annual WY increased from 150.2×10^8 m^3/year in the year 2010 to 215.8×10^8 m^3/year in 2021; which represents an increase of approximately 6.56×10^8 m^3 (30.42%). The annual predicted for WY based on the PFA scenario in 2030 is 235.1×10^8 m^3, while the WY for the BAU scenario is 234.5×10^8 m^3, reaches 0.6×10^8 m^3 (about 0.25%) compared to the BAU scenario in 2030. Additionally, the PFA scenario shows an increase to 187.0×10^8 m^3, reflecting an increase of around 8.66% compared to the WY in 2021. The main contribution to the changes in WY comes from rainfall (climate factors), accounting for about 88.99%, while changes in LULC contribute less than 11%. The relationship between LUI and

WY was analysed using CCD for 2010 and 2020. Each category of LUI and WY exhibited the same pattern. Most districts (51.22%–53.66%) fell into the unbalanced category, where an increase in LUI usually leads to greater trade-offs with WY. The remaining districts (46.34%–48.78%) were in the coordination category. This study is expected to serve as a reference for decision makers in sustainable watershed management based on ES.

Author contributions: Conceptualization, IN, WA and JS; methodology, TT, IN and YS; software, JS, NS, FM and HIA; validation, TT, NS, RS and DLC; formal analysis, IN, NS, YS and JS; investigation, RS, LS, HIA and YY; resources, BW, FM, TAP and HIA; data curation, DLC, LS, IFC and BW; writing—original draft preparation, YS, FM, IFC and TAP; writing—review and editing, TT, WA, RS and LS; visualization, IFC, TAP and YY; supervision, WA; project administration, BW; funding acquisition, DLC and YY. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: We acknowledge the effective collaboration between the National Research and Innovation Agency (BRIN), the provincial governments of West Java and Banten, and the Ciliwung-Cisadane River Basin Organization (BBWSCC). We also extend our gratitude to the Japan Aerospace Exploration Agency (JAXA) for providing GSMaP data. Additionally, we would like to thank BRIN for its continued support.

Conflict of interest: The authors declare no conflict of interest.

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