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Assessing the sustainability of small hydropower sites in the Citarum Watershed, Indonesia employing CA-Markov and SWAT models

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ABSTRACT

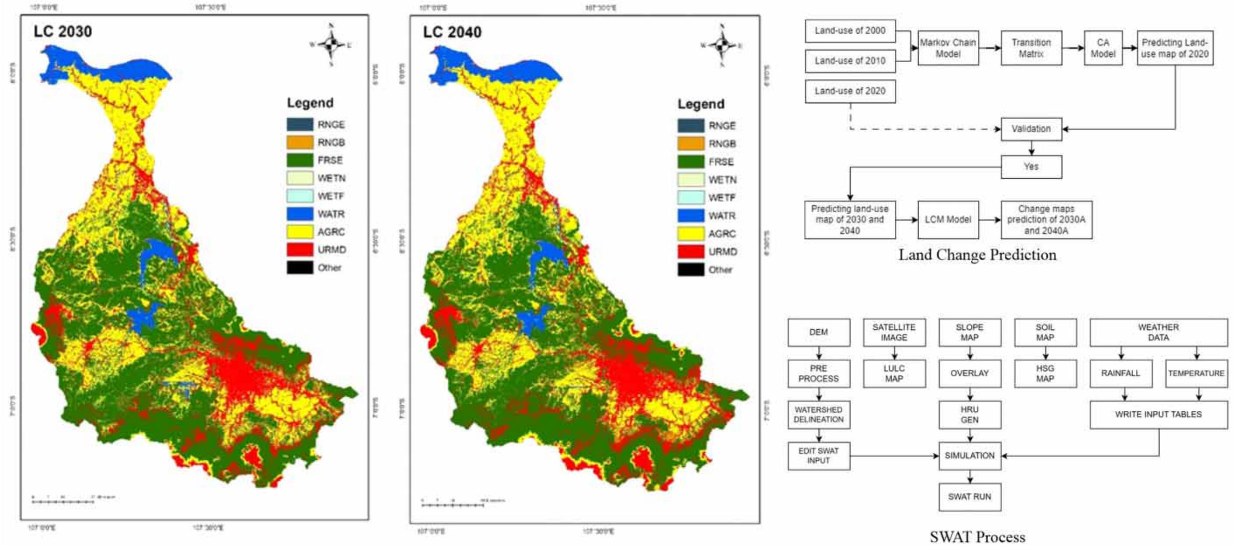
This study investigates the sustainability of potential small hydropower sites within the Citarum Watershed in West Java, Indonesia. The Citarum River, with a catchment area of 6,090 km^2, plays a crucial role in regional water supply and hydroelectric power generation. However, environmental challenges such as deforestation, land use changes, and sedimentation pose significant risks. We employed the CA-Markov model integrated with IDRISI TerrSet software and the Soil and Water Assessment Tool to predict future land use changes and assess water supply, soil erosion, and sedimentation impacts for 2030 and 2040. The analysis revealed diverse trends in water yield across different catchment areas, with some regions showing increased water availability and others facing declines. High erosion and sedimentation rates were identified as critical issues affecting hydropower efficiency. The study highlights the need for comprehensive watershed management strategies, including reforestation, sustainable land management practices, and sediment management, to enhance the sustainability of small hydropower projects. Our findings underscore the importance of integrating environmental considerations into hydropower development to ensure the ecological integrity of the Citarum Watershed.

Key words: catchment area, Citarum, erosion, sedimentation, sustainability, water supply

HIGHLIGHTS

- Environmental challenges in the watershed, including deforestation, land use changes, and sedimentation.
- Use of the CA-Markov model and IDRISI TerrSet software for land use prediction.
- Application of the Soil and Water Assessment Tool for assessing water supply, soil erosion, and sedimentation.
- High erosion and sedimentation rates are identified as major challenges for hydropower efficiency.
- Prediction of significant land use changes by 2030 and 2040, with notable declines in forest areas.

GRAPHICAL ABSTRACT



Land Change Prediction

SWAT Process

1. INTRODUCTION

In the context of the United Nations Sustainable Development Goals, particularly those focusing on clean water and energy (Goals 6 and 7), the assessment of small hydropower potential in ecologically sensitive areas like the Citarum Watershed in West Java, Indonesia, gains global significance. The Citarum Watershed in West Java, Indonesia, is a critical area for both environmental and human activities. Home to approximately 25 million people, the population is densely concentrated along the river and in urban areas, particularly in the west-northwest and southwest regions, while the downstream and upstream areas have lower densities (Mayasari & Nugraha 2021). The watershed supplies about 7,650 million cubic meters of water per year, but increasing population and industrial activities have led to a 47% rise in water demand between 2000 and 2020 (Satgas DAS Citarum 2024). Surface water levels follow a seasonal pattern, with higher levels during the monsoon season, which corresponds to groundwater recharge (Monash University 2021). Approximately 78% of the extracted water is used for irrigation, supporting hundreds of thousands of hectares of rice fields, crucial for maintaining agricultural productivity in the region (Nahib *et al.* 2023). Industrial activities and electricity generation consume about 14% of the water, while 8% is used for domestic consumption (Nahib *et al.* 2023). Additionally, the river supports fisheries, provides raw water for drinking, and is used for hydroelectric power plants (Islahuddin *et al.* 2015). Despite the large water supply, the watershed experiences water shortages due to high demand and inefficient water management (Satgas DAS Citarum 2024). The Citarum River is heavily polluted due to industrial waste and human activities (Mayasari & Nugraha 2021). Various initiatives, including government programs and community-based efforts, have been undertaken to clean up the river and improve water quality (Habibie *et al.* 2024). These efforts are crucial to addressing the environmental and social challenges the watershed faces and ensuring its sustainability for future generations.

Diverse geographical conditions within the watershed impact its water resources and environment. The upper regions, for example, have experienced deforestation, influencing streamflow and environmental state (Nurfatriani *et al.* 2023). Additionally, human activities like urbanization and agricultural expansion significantly degrade water quality and ecological balance in river systems, exacerbating soil erosion, sedimentation, and pollution (Wang *et al.* 2015). This degradation is evident in the Mekong River delta, where rapid erosion and coastal subsidence are linked to construction and power plant operations (Anthony *et al.* 2015). Sediment management is crucial in mitigating these effects, as dams trap sediment and disrupt sediment transport, impacting channel morphology and aquatic habitats (Kondolf *et al.* 2014). In East Africa, human-induced sedimentation in hydropower reservoirs reduces water storage capacity and affects hydropower production (Amasi *et al.* 2021). Addressing soil erosion and sedimentation involves implementing erosion control measures and land use planning strategies. Afforestation and check-dam construction trap sediment and reduce erosion, supporting sustainable land management (Li *et al.* 2019). Evaluating best management practices in vulnerable watersheds is essential for reducing sediment yield and preserving ecosystem health (Demissie *et al.* 2013). The detrimental effects of human activities on soil erosion, sedimentation, and water quality underscore the urgent need for sustainable sediment management practices to promote the long-term health and resilience of river ecosystems.

The watershed's social and economic fabric is interwoven with its environmental state. Agricultural activities sustained by the watershed benefit from government-led social forestry initiatives to enhance farmers' incomes and forest conservation. The health of the watershed and the effects of converting traditional home gardens into commercial entities underscore the intricate balance between environmental sustainability and livelihoods. The main research problem lies in the Citarum Watershed's environmental challenges, including the impact of land use/land cover (LULC) changes on water resources, flooding, and sedimentation. These issues are compounded by the need for sustainable management strategies that can balance the watershed's ecological integrity with its role in supporting the region's hydroelectric power and water supply (Siswanto & Francés 2019; Rahmad & Wirda 2021; Marselina & Putri 2022).

A general solution is to employ models like the CA-Markov model integrated with IDRISI TerrSet software, which predicts future land use based on historical data, offering insights into land use trends and their implications for water resources and environmental sustainability (Chen *et al.* 2018; Leta *et al.* 2021).

Employing the Soil and Water Assessment Tool (SWAT) for assessing the sustainability of potential locations for small hydropower in the watershed presents a specific solution. The SWAT can evaluate future water supply, soil erosion, and sedimentation in catchment areas under various future climate and land use scenarios. This methodology incorporates the understanding of water and sediment dynamics crucial for the sustainable implementation of small hydropower projects (Sudarningsih *et al.* 2017; Belinawati *et al.* 2018; Sapan *et al.* 2022).

Despite the comprehensive studies on the Citarum Watershed, there remains a gap in the specific assessment of small hydropower potential concerning sustainability. Current research primarily focuses on general water resource management and environmental impacts. The integration of the SWAT for small hydropower sustainability assessment concerning future climate and land use scenarios is not extensively explored. This gap indicates the need for detailed studies focusing on the intricate balance between hydropower development and environmental sustainability within the Citarum Watershed.

The objective of this study is to assess the sustainability of potential locations for small hydropower in the Citarum Watershed, focusing on future water supply, erosion, and sedimentation. The novelty lies in the application of the CA-Markov model with IDRISI TerrSet software alongside the SWAT to predict and evaluate the implications of land use changes on hydropower sustainability. This approach is novel in its comprehensive integration of land use prediction models and hydrological tools to assess small hydropower's environmental impact. The scope of the study is confined to the Citarum Watershed, considering its diverse geographical, climatic, and socio-economic characteristics, and aiming to provide insights into sustainable hydropower development strategies in similar regions worldwide.

2. MATERIALS AND METHODS

2.1. Defining small hydropower potential location in the Citarum Watershed

A watershed is a geographic area defined by ridges or divides, draining into a common water body like a main river, lake, or ocean. Watersheds can range in size from a few to thousands of square kilometers, encompassing entire river basins. Within a watershed, a catchment area is a more localized region where all precipitation flows to a specific outlet, such as a river, lake, or reservoir. Following the (2015) approach, we use watersheds to show the overall drainage basin of the river and catchment/sub-catchment for a more localized context crucial for detailed water management and planning.

The Citarum Watershed is characterized by its significant role in water supply and power generation, along with facing environmental challenges like sedimentation and erosion. Data Collection for Geographical Analysis: Geographic data, head elevation value, dependable discharge (Q90), and potential power capacity as small hydropower class category (1–10 MW), were collected for the entire watershed area. Figure 1 shows there are four potential locations for small hydropower, projects. The basis for identifying potential sites for small hydropower projects is based on research conducted by Pranoto *et al.* (2021) that has been processed and filtered to highlight viable sites.

2.2. Land use prediction in 2030 and 2040 using the CA-Markov – land change model (LCM)

Data collection: Land use data from 2000, 2010, and 2020 were gathered from The GLAD Global Land Cover and Land Use 2000 and 2020 (storage.googleapis.com). Potapov *et al.* (2022) measure changes in forest area and height, cropland, built-up land, surface water, and perennial snow and ice area from 2000 to 2020 at a spatial resolution of 30 m. This global dataset is

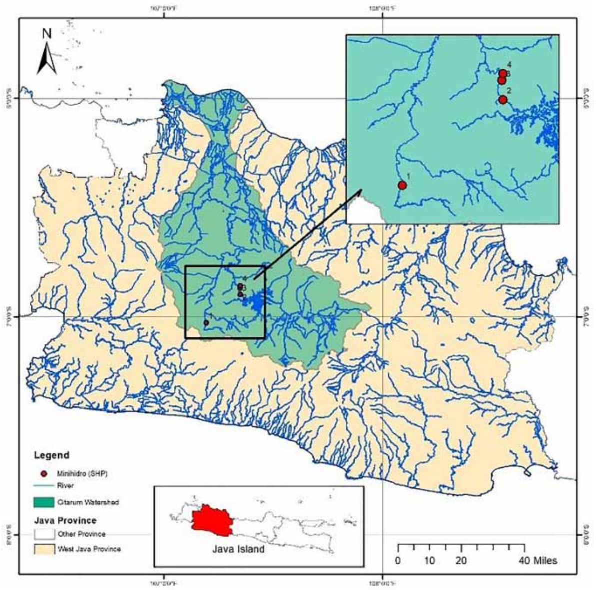


Figure 1 | Potential small hydropower in the Citarum Watershed (Pranoto *et al.* 2021).

derived from GLAD Landsat Analysis Ready Data. Each thematic product was created independently using locally and regionally calibrated machine learning tools.

Land classification adjustments are made to approach the classification in the SWAT database, Table 1 is a land class adjustment based on the definition approach of each source and Figure 2 reclassifies land use maps in the years 2000, 2010, and 2020.

After reclassifying the land use data for the years 2000 and 2010, the Markov chain model is employed to calculate transition matrices for each land use class. These matrices are subsequently utilized within a cellular automata (CA-Markov) model to forecast the land use patterns for the year 2020. Figure 2 shows the method for forecasting future land use.

The CA-Markov model was initialized and calibrated using land use data from 2000 to 2010, ensuring an accurate representation of historical land use changes. The model was validated against actual land use data for 2020 to assess its predictive accuracy, as per Wijayasari *et al.* (2023).

Table 1 | Reclassify from GLAD class to SWAT class

GLAD class	Range value	SWAT code	Reclass
True desert (terra firma)	0–18	Grasslands/herbaceous/RNGE	1
Dense short vegetation (terra firma)	19–24	Range shrubland/RNGB	2
Stable tree cover (terra firma)	25–48	Evergreen forest/FRSE	3
Sparse vegetation, dense short vegetation (wetland)	102–124	Emergent/herbaceous wetlands/WETN	4
Stable tree cover (wetland)	125–148	Woody Wetlands/WETF	5
Open surface water	200–211	Open Water/WATR	6
Cropland	244–247	Small Grains/AGRC	7
Built-up	250–254	Urban medium density/URMD	8
Other	49–101, 149–199, 212–243, 248–249	Others (undefined)	9

RNGE: range-grasses or herbaceous range land.

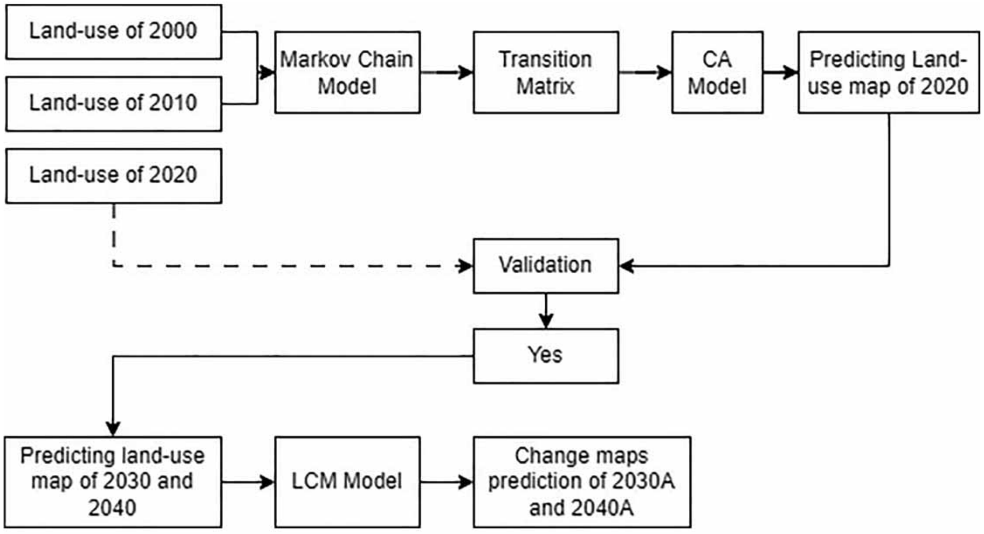


Figure 2 | Prediction change map method.

The LCM, commonly employed for promoting ecological sustainability, was incorporated into IDRISI Selva software and is additionally accessible as an add-on in ArcGIS software. This tool is frequently utilized to tackle the urgent issue of rapid land conversion (Aburas *et al.* 2015). Hence, in this study, the LCM was utilized to assess urban transformation within the Citarum Watershed. Future land use scenarios for 2030 and 2040 were developed, considering potential changes in land use drivers such as elevation, slope, urban distance, street distance, and river distance. The model was run using these scenarios to simulate future land use changes.

2.3. Assessing water supply, erosion, and sedimentation using the SWAT

The SWAT is a widely used ecohydrological model for simulating the impacts of land use, management systems, and climate on hydrology and water quality. It has been applied extensively for a broad range of hydrologic and environmental problems. The SWAT model has proven to be an effective tool for assessing water resource and nonpoint pollution problems for a wide range of scales and environmental conditions across the globe (Tan *et al.* 2019).

Data collection and preprocessing: Spatial data, including digital elevation models (DEMs), LULCs, soil maps, and meteorological data, were collected and preprocessed for compatibility with the SWAT model integrated with ArcGIS (ArcSWAT) (Betrie *et al.* 2011; Yang & Lu 2018). Figure 3 shows the SWAT process from input to output results.

Watershed delineation in the SWAT involves processing a DEM to identify watershed boundaries, subdivide the watershed into sub-basins, and delineate stream networks. This process begins with preprocessing steps to ensure DEM accuracy, followed by watershed delineation using flow accumulation principles. The SWAT then divides the watershed into sub-basins based on flow accumulation thresholds, facilitating spatial representation of hydrological processes. Within each sub-basin, SWAT delineates stream networks into reaches, forming the basis for subsequent hydrological modeling to simulate rainfall-runoff, sediment transport, and nutrient cycling within the watershed, essential for assessing land use and management impacts on water resources (Ruttoh *et al.* 2022). The hydrologic cycle as simulated by the SWAT is based on the water balance equation:

$$\mathrm{SW}_t = \mathrm{SW}_o + \sum_{i=1}^{t} (R_{\mathrm{day}} - Q_{\mathrm{surf}} - E_{\mathrm{a}} - w_{\mathrm{seep}} - Q_{\mathrm{gw}}) \quad (1)$$

where SW_t is the final soil water content (mm H_2O), SW_o is the initial soil water content (mm H_2O), t is the time in days, R_{day} is the amount of precipitation on day i (mm H_2O), Q_{surf} is the amount of surface runoff on day i (mm H_2O), E_{a} is the amount of evapotranspiration on day i (mm H_2O), w_{seep} is the amount of percolation and bypass exiting the soil profile bottom on day i (mm H_2O), and Q_{gw} is the amount of return flow on day i (mm H_2O).

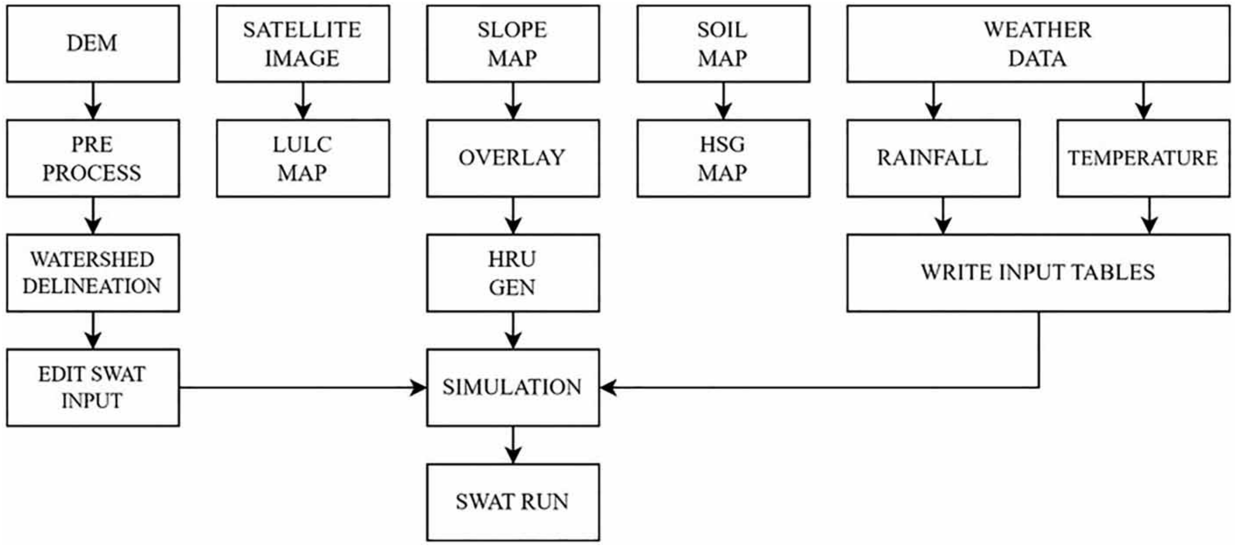


Figure 3 | SWAT process.

Erosion predicted using the USLE (Universal Soil Loss Equation) model using the equation as follows:

$$A = R.K.\mathrm{LS}.C.P \tag{2}$$

where A is the average annual soil loss per unit area (t ha^{-1} year^{-1}), R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1}), K is the soil erodibility factor (t h MJ^{-1} mm^{-1}), LS is the slope length and steepness factor, C is the cover and management factor, and P is the support factor and conservation practices.

Sediment on the model SWAT was calculated using the equation below:

$$\mathrm{Sed} = 11.8\,(Q_{\mathrm{surf}}.Q_{\mathrm{peak}}.\mathrm{Area}_{\mathrm{hru}})^{0.56}.K_{\mathrm{usle}}.C_{\mathrm{usle}}.P_{\mathrm{usle}}.\mathrm{LS}_{\mathrm{usle}}.\mathrm{CFRG} \tag{3}$$

where Sed is the sediment yield on a given day (metric tons); Q_{surf} is the surface runoff volume (mm H_2O/ha); q_{peak} is the peak runoff rate (m^3/s); Area$_{\mathrm{hru}}$ is the area of the Hydrologic Response Units (HRU) (ha); K_{usle} is the USLE soil erodibility factor, C_{usle} is the USLE cover and management factor; P_{usle} is the USLE support practice factor; LS$_{\mathrm{usle}}$ is the USLE topographic factor and CFRG is the coarse fragment factor.

Model outputs were analyzed to predict changes in water supply, erosion, and sedimentation under different future scenarios. The spatial distribution of these changes and their potential impacts on the catchment area were assessed. The spatial distribution maps were analyzed to identify change hotspots, such as regions experiencing high erosion rates or significant changes in water yield. The potential impacts on the catchment area were assessed by overlaying the spatial distribution maps with other relevant data layers, such as land use types, slope, and proximity to water bodies. This helped to understand the implications of the changes on different land uses and ecosystems. Specific attention was given to areas where increased sedimentation could impact hydropower efficiency, water quality, and agricultural productivity. By combining the predictive capabilities of the SWAT model with detailed spatial analysis in a Geographic Information System (GIS) environment, we could comprehensively assess the spatial distribution of changes in water yield, soil erosion, and sedimentation and their potential impacts on the catchment area. This integrated approach provided a robust framework for understanding the complex interactions between land use changes, hydrological processes, and environmental impacts within the Citarum Watershed.

3. RESULTS AND DISCUSSION

3.1. Defining catchment area of potential location

The analysis of geographic data revealed four potential locations for small hydropower projects in the middle portion, and their catchment area is upstream of the Citarum Watershed. The Citarum Watershed is divided into three regions based on landforms: upstream, middle, and downstream. The middle portion of the Citarum Watershed exhibits diverse topography ranging from plains at 250–400 m above sea level to rolling hills extending up to 800 m, along with steeper slopes rising to 1,400–2,400 m. This region is characterized by volcanic formations and geological structures comprising volcanic sediments, ancient lake-floor deposits, and alluvial sediments concentrated in narrow valleys along major rivers. The volcanic elements include tuffaceous sandstones, tuff shale, tuff breccias, and agglomerates, while lake-floor sediments consist of tuff clay, tuff sandstones, tuff gravel, and tuff conglomerate. Alluvial deposits, formed during tertiary deposits and ancient volcanic activities, contribute clay, silt, sandstone, and gravel to the landscape. The climate in the middle portion ranges from temperate to tropical, with temperatures varying between 15.3 and 27°C annually. Precipitation levels fluctuate significantly, ranging from 1,000 to 4,000 mm per year, influencing water availability crucial for reservoirs' functionality. The geological makeup and topographical diversity make this area suitable for reservoir construction, requiring careful consideration of factors such as lithology, fault development, and slope stability to ensure the sustainable development of hydropower projects.

The portion upstream is situated between 625 and 2,600 m above sea level. Lappilli, breccia, tuff, and lava comprise most of its geological composition. The highland and mountainous portions of the upper region receive an average of 4,000 mm of rainfall annually and experience a low temperature of 15.3°C. The various soil types present in the upper watershed are Latosol (35.7%), Andosol (30.76%), Alluvial (24.75%), Red Yel-low Podzolic (7.72%), and Regosol (0.86%) (Khairunnisa *et al.* 2020). Figure 4 shows the catchment area (CA) for small hydropower potential.

3.2. Land use prediction for 2030 and 2040

In the reclassification process, the author used an overlay of the government's LULC map to help identify land classification to minimize errors in land type interpretation. One of the weaknesses of the government LULC map is that mapping is not

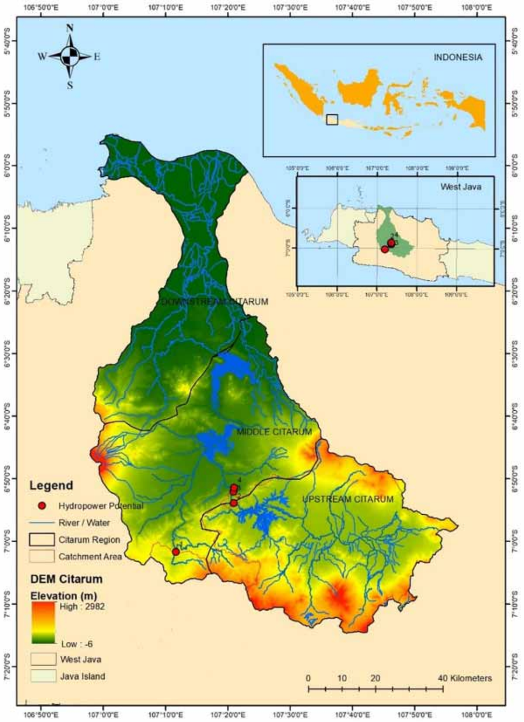


Figure 4 | Catchment area (CA) for small hydropower potential.

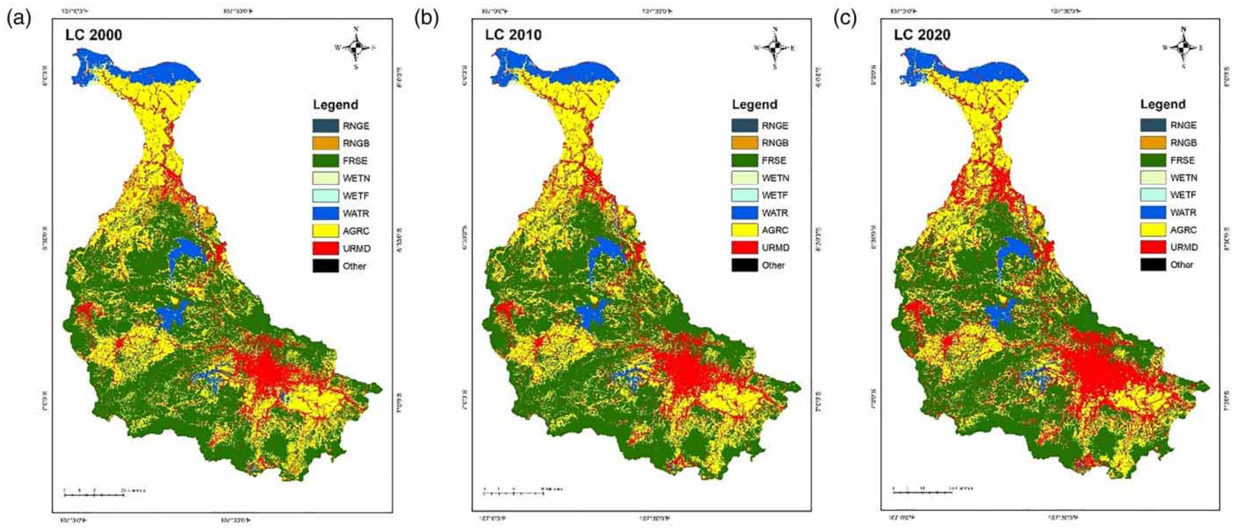


Figure 5 | Reclassify land use of the Citarum Watershed from GLAD (Potapov *et al.* 2022) to SWAT Code, (a) Year 2000; (b) Year 2010; (c) Year 2020.

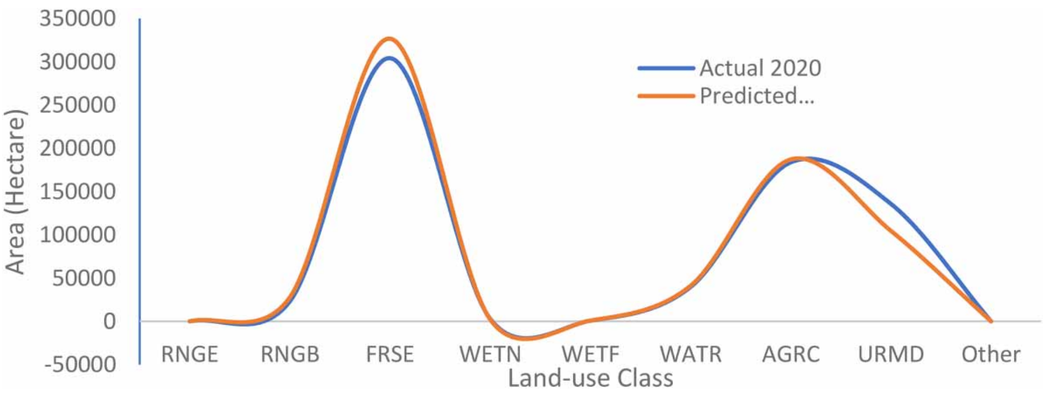


Figure 6 | Actual and predicted land use map of 2020.

done every year so it is difficult to get a time series LULC map. Figure 5 shows the reclassified map from the GLAD class to the SWAT class.

The IDRISI CA-Markov model, calibrated with data from 2000 to 2010 (see Figure 5), successfully predicted land use changes for 2020, showing high accuracy. This validates the model's reliability in forecasting future land use patterns. To evaluate the model's accuracy, the land-cover map projected for 2020 was compared to the actual map using Kappa index statistics, which assess its validity in terms of both quantity and spatial distribution (refer to Figure 6). The results of model validation affirm that the simulated accuracy meets the study's requirements. Specifically, the validation findings show prediction accuracies of 0.87, 0.87, and 0.81 for the Kappa value, Kappa location, and Kappa standards, respectively. Analysis of historical and simulated land-cover maps suggests that changes in land development processes will potentially impact the sustainability of forest lands (FRSE) (Figure 6).

The CA-Markov chain model forecasts a forest (FRSE) decline in lands within the Citarum region, projecting a reduction of 3,810 hectares by 2030 and 5,655 hectares by 2040 (see Table 2). This is a significant decrease from the 970 hectares recorded in 2010. The primary factors contributing to this reduction are the expansion of urban (URMD) and agricultural (AGRC) areas, driven by rapid population and economic growth. This expansion is negatively impacting the sustainability of forest lands in the Citarum Watershed. Additionally, these forest lands are often situated on flat surfaces, making them prime targets

Table 2 | Land use change Citarum Watershed

	Area (Hectare)				
Land use/Year	**2000**	**2010**	**2020**	**2030**	**2040**
Grasslands/herbaceous/RNGE	43.74	31.23	58.41	31.23	31.23
Range shrubland/RNGB	42,197.76	33,720.39	23,322.69	23,649.3	20,714.58
Evergreen forest/FRSE	328,870.2	327,899.8	304,146.2	325,060.5	323,215.1
Herbaceous wetlands/WETN	4,491.99	3,195.36	2,800.44	1,872.81	1,727.55
Woody wetlands/WETF	1,095.57	891.45	783.36	891.45	891.45
Open water/WATR	41,214.51	41,337.63	39,757.77	40,279.41	39,325.05
Small grains/AGRC	192,117.9	190,052.7	183,806.5	183,340.8	179,103.6
Urban medium density/URMD	80,432.19	93,298.86	135,827.9	115,302	125,418.9
Others (undefined)	99.99	136.35	60.57	136.35	136.35

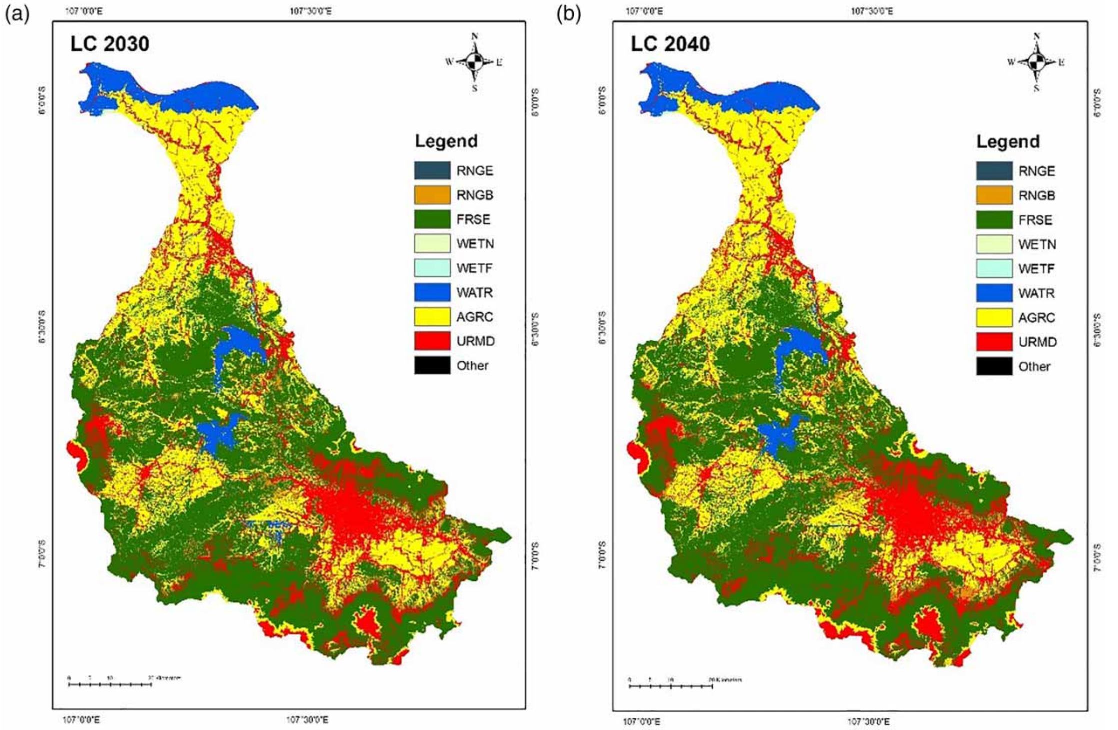


Figure 7 | Land use prediction for 2030 and 2040.

for urban development projects (Aburas *et al.* 2018). In contrast, urban areas are predicted to expand significantly, with an increase of 34,870 hectares by 2030 and 44,987 hectares by 2040.

Figure 7 presents the projected land use changes in the Citarum Watershed for the years 2030 and 2040, based on the CA-Markov model. The projections indicate a significant decline in forest areas (FRSE), with an anticipated reduction of 3,810 hectares by 2030 and 5,655 hectares by 2040, compared to the baseline year of 2010. This trend is largely driven by the expansion of urban (URMD) and agricultural (AGRC) areas, reflecting the pressures of rapid population growth and economic development. Urban areas are expected to increase substantially, with a projected expansion of 34,870 hectares by 2030 and 44,987 hectares by 2040. This urban sprawl poses a threat to the sustainability of forest ecosystems and the overall health of the watershed. The predicted decrease in herbaceous wetlands (WETN) and range shrubland (RNGB) further emphasizes the need for strategic land management and conservation efforts to mitigate the adverse effects of land conversion. The results underscore the critical importance of implementing proactive measures such as reforestation, sustainable urban planning, and agricultural practices to preserve the ecological integrity of the Citarum Watershed and ensure the viability of its water resources and hydropower potential.

Table 2's analysis of LULC changes between 2000 and 2040 reveals significant transformations within the watershed area. Comparisons with the Citarum Watershed in Indonesia, as discussed by Dan-Jumbo *et al.* (2018), Pitaloka *et al.* (2020), Yulianto *et al.* (2022), Suryanta *et al.* (2022a), and Sapan *et al.* (2022), underscore these findings.

Grasslands/Herbaceous/RNGE and Range Shrubland/RNGB exhibit fluctuations, with grasslands peaking in 2020 at 58.41 hectares before reverting to 2010 levels. Range shrubland consistently decreased from 42,197.76 hectares in 2000 to 20,714.58 hectares in 2040, likely due to land conversion for agriculture or urban development, echoing trends in the Citarum Watershed as noted by Dan-Jumbo *et al.* (2018) and Pitaloka *et al.* (2020).

Evergreen forest areas decreased from 328,870.2 hectares in 2000 to 304,146.2 hectares in 2020, then recovered by 2030 and 2040, suggesting efforts toward conservation and reforestation. This pattern aligns with Pitaloka *et al.* (2020).

Urban medium density (URMD) areas grew from 80,432.19 hectares in 2000 to 135,827.9 hectares in 2020, reflecting ongoing urban expansion, a trend also seen in the Citarum Watershed, as highlighted by Yulianto *et al.* (2022) and Suryanta *et al.* (2022a).

Open water areas (WATR) remained relatively stable, emphasizing the need for effective land cover management to maintain water resources, as discussed by Sapan *et al.* (2022).

Agricultural land decreased gradually, indicating a shift toward urbanization, with potential impacts on the local economy and food security, paralleling observations in the Citarum Watershed.

The decline in forested areas and rise in urban zones could exacerbate erosion and sedimentation, as suggested by Suryanta *et al.* (2022a), highlighting the need for comprehensive conservation strategies advocated by Sapan *et al.* (2022) to maintain ecological balance in the watershed.

From the above information, it is noted that despite a decrease in forested areas from 2000 to 2020, a predicted increase by 2040 is based on several factors considered in the CA-Markov and SWAT models. These models assume positive impacts from reforestation programs, conservation policies, and sustainable land management practices. Effective policy interventions to control urban sprawl and promote green infrastructure, along with advances in sustainable agriculture and urban planning technologies, are expected to support forest recovery.

The certainty of these long-term predictions involves inherent uncertainties due to the dynamic nature of human activities and climate change. To address this, the CA-Markov and SWAT models were calibrated and validated using historical data and compared against actual 2020 data. They incorporate different scenarios, including varying degrees of policy implementation and technological adoption, to capture a range of possible futures. Adaptive management, through continuous monitoring and real-time data updates, helps improve prediction accuracy. Sensitivity analysis identifies the most influential factors, ensuring robust model outputs. The CA-Markov and SWAT models may not fully capture the dynamic interactions between human activities and climate change, leading to potential deviations such as accelerated urbanization due to socio-economic factors, causing greater-than-anticipated land cover changes; enhanced erosion and sedimentation from extreme weather events, impacting water quality and hydropower efficiency; shifts in agricultural practices in response to climate changes, altering land use patterns and irrigation demands; and variability in forest degradation and reforestation efforts, depending on the effectiveness of conservation policies and initiatives. These factors highlight the need for adaptive management and continuous monitoring to address the uncertainties in LULC predictions.

The predicted increase in forested areas by 2040 reflects the potential positive outcomes of effective environmental management and policy interventions, although the certainty of these predictions remains subject to long-term environmental and socio-economic uncertainties.

3.3. Assessing water yield, soil erosion, and sedimentation using the SWAT

Table 3 illustrates the dynamic changes in water yield, soil erosion, and sedimentation across different catchment areas (CA) within the Citarum Watershed from 2000 to 2040. The data are segmented into three categories: water yield, soil erosion, and sedimentation. The water yield, measured in millimeters, shows variations in annual water availability across the catchment areas, with some regions experiencing fluctuations over the years. Soil erosion rates, expressed in tons per hectare, indicate

Table 3 | Water yield, soil erosion, and sedimentation dynamic change

CA No	2000	2010	2020	2030	2040
	(a) Water yield (mm)				
1	4,920	4,838	4,901	4,897	4,901
2	5,206	5,171	5,156	5,187	5,221
3	4,908	4,883	4,850	4,822	4,850
4	3,809	3,814	3,809	3,814	3,817
	(b) Soil erosion (ton per hectare)				
1	1.58	3.26	1.88	1.57	1.84
2	2.62	2.51	8.3	1.2	1.26
3	2.06	2.03	7.5	6.35	5.91
4	17.51	59.41	19.68	59.41	53.83
	(c) Sedimentation (ton per hectare)				
1	2.39	4.51	2.73	2.4	2.71
2	2.69	2.65	8.87	1.34	1.36
3	2.18	2.17	8.84	8.8	8.82
4	12.92	50.48	13.2	50.48	52.43

significant changes, highlighting periods of increased erosion that could impact soil quality and land stability. Sedimentation rates, also in tons per hectare, reflect the accumulation of sediment within the catchment areas, which can affect water quality and hydropower efficiency. These trends underscore the importance of understanding and managing the impacts of land use changes on the sustainability of hydropower sites and the watershed's overall health.

3.3.1. Water yield

Water, erosion, and sedimentation calculations were carried out in each catchment area in each decade to see the trend of value changes. To comprehensively analyze water yield data in the catchment area, this study systematically reviews trends across five decades: 2000, 2010, 2020, 2030, and 2040 in Table 3a. This investigation critically examines the implications of these trends, considering various influencing factors.

Table 3a presents water yield data across five decades (2000, 2010, 2020, 2030, and 2040) for four catchment areas (CA Nos. 1, 2, 3, and 4), illustrating trends over time with corresponding slopes. CA No. 1 demonstrates a relatively stable water yield, with a slight increase as indicated by a positive slope of 0.211, suggesting effective water management and balanced runoff dynamics rather than solely consistent precipitation. Similarly, CA No. 2 shows a stable increase in water yields (slope of 0.456), likely due to effective land and water management practices that enhance hydrological stability. In contrast, CA No. 3 displays a declining trend with a negative slope of -1.771, where factors such as land use changes, soil degradation, and localized anthropogenic activities likely play more significant roles than broad climatic variations. CA No. 4 maintains remarkable stability with minimal fluctuations (slope of 0.149), indicating a well-managed hydrological environment. These observations underline the significant impact of localized environmental management and land use changes on water yields across the CAs. While stable trends in CAs 1, 2, and 4 reflect successful management practices, the decline in CA No. 3 highlights the need for targeted interventions to address specific challenges such as deforestation and urbanization. This analysis emphasizes the importance of comprehensive land and water management strategies over merely climatic factors in sustaining water yields and points to the necessity for proactive measures in catchment areas showing declining trends to secure future water resource sustainability.

3.3.2. Soil erosion

Table 3b presents soil erosion data in tons per hectare for four catchment areas (CAs 1, 2, 3, and 4) within the Citarum Watershed from 2000 to 2040. These data reveal significant variations and trends with implications for land management and conservation.

In CA 1, soil erosion fluctuated modestly, peaking at 3.26 tons per hectare in 2010 before stabilizing. This suggests interventions or natural stabilization post-2010. CA 2 shows a dramatic increase to 8.30 tons per hectare in 2020, likely due to intense agricultural activity or deforestation, with stabilization in the following decades indicating remedial actions. CA 3 exhibited a similar spike in 2020 and sustained high levels, highlighting ongoing issues needing robust intervention. CA 4 has extreme variability, with erosion rates skyrocketing to 59.41 tons per hectare in 2010, dipping, then rising again, indicating severe and recurrent erosion problems driven by anthropogenic activities.

Comparing these trends with scientific literature, such as Borrelli *et al.* (2021) and Montgomery (2007), shows that land use changes, climate variability, and the effectiveness of conservation measures significantly impact soil erosion. Studies suggest areas with deforestation or inadequate erosion control face higher erosion rates, while regions with sustainable practices see reduced erosion.

The data underscores the importance of consistent soil conservation practices. Dramatic spikes in erosion suggest sporadic interventions are inadequate. Comprehensive strategies, including sustainable agriculture, reforestation, and ongoing monitoring, are crucial for reducing erosion and preserving watershed health. Insights from studies by Ambarwulan *et al.* (2021), Suryanta *et al.* (2022b), and others provide a comprehensive framework for understanding soil erosion complexities in the Citarum Watershed.

3.3.3. Sedimentation

Table 3c shows sedimentation rates (tons per hectare) for four catchment areas (CAs 1–4) within the Citarum Watershed over 10-year intervals from 2000 to 2040, highlighting the interconnectedness of sedimentation and soil erosion and their implications for watershed management.

In CA 1, sedimentation rates fluctuated modestly, peaking at 4.51 tons per hectare in 2010 before stabilizing around 2.40–2.73. This pattern mirrors soil erosion trends, suggesting a direct correlation between periods of higher soil erosion and increased sedimentation, as eroded soil particles are transported downstream.

CA 2 saw a notable spike to 8.87 tons per hectare in 2020, corresponding with increased soil erosion, likely due to land disturbances or agricultural activities. The stabilization to around 1.34–2.69 tons per hectare in other decades indicates successful interventions or natural recovery processes.

CA 3 shows a consistent rise from 2.18 tons per hectare in 2000 to about 8.80–8.84 from 2020 onwards, paralleling high soil erosion rates and highlighting persistent land management or climatic issues.

CA 4 exhibits extreme variability, starting at 12.92 tons per hectare in 2000, peaking at 50.48 in 2010, dipping to 13.20 in 2020, and rising again to around 50.48–52.43 in 2030 and 2040. These fluctuations reflect episodic interventions or environmental changes and severe land disturbances.

Comparing these sedimentation rates with soil erosion data underscores the direct relationship between the two processes, with high erosion rates typically leading to increased sedimentation. Effective watershed management must address both erosion and sedimentation through integrated land use planning, reforestation, and sustainable agricultural practices. The trends and correlations observed emphasize the need for comprehensive soil conservation techniques, reforestation, and continuous monitoring to reduce erosion and sedimentation, preserve soil health, and maintain ecological balance within the Citarum Watershed.

3.4. Dynamic erosion and sedimentation

Table 3 shows that while the water yield in Catchment Area 4 (CA4) remains consistent from 2000 to 2040, soil erosion and sedimentation rates fluctuate due to various independent factors. Localized land use changes within CA4, such as deforestation or agricultural expansion, significantly impact soil erosion and sediment transport, even with stable water yield. Temporary shifts in land management practices, like altering agricultural methods, applying erosion control, or construction activities, also temporarily affect erosion and sedimentation. Soil characteristics and topography are crucial; highly erodible soils and steep slopes are more prone to erosion. Extreme weather events, like heavy rainfall or droughts, further contribute to fluctuations by increasing runoff or reducing vegetation cover, respectively. Human activities, including construction, urbanization, and mining, disrupt soil stability, increasing erosion and sedimentation. Despite stable water yield, soil erosion and sedimentation in CA 4 vary due to localized land use, soil and topographical features, extreme weather, and human activities. Continuous monitoring and adaptive land management are essential for mitigating these fluctuations and ensuring watershed sustainability.

3.5. The impact of a potential small hydropower location

The impact of a potential small hydropower location within the Citarum Watershed, based on the analyses in Table 3 involves several key environmental and sustainability considerations. The hydropower potential in the region can be significantly influenced by the water yield, soil erosion, and sedimentation rates observed across different catchment areas.

From Table 3a, the water yield trends indicate relatively stable hydrological conditions in some catchment areas (e.g., CA Nos. 1 and 2), which are favorable for hydropower generation. These stable water yields ensure a consistent flow rate necessary for reliable energy production. However, CA No. 3 shows a declining water yield, suggesting potential challenges in maintaining a steady power supply. The decline in water yield, potentially caused by factors such as deforestation and climate change (Siswanto & Francés 2019), can lead to reduced hydropower capacity. This affects the long-term viability of these systems and raises concerns about their ability to consistently meet energy demands. In contrast, CA No. 4, despite stable water yield trends, may face challenges due to severe soil erosion and sedimentation.

Table 3b and 3c reveal critical environmental issues related to soil erosion and sedimentation that can impact the sustainability of hydropower projects. As observed in CA Nos. 3 and 4, high erosion rates can lead to significant sedimentation in reservoirs, reducing their capacity and efficiency over time, damaging hydropower turbines and reducing operational efficiency. These irregular patterns, as noted by Borrelli *et al.* (2021) and Montgomery (2007), may arise from climatic events or land management practices, including agricultural activities. This sedimentation can increase maintenance costs, reduce the lifespan of hydropower infrastructure, and potentially lead to environmental degradation downstream. CA No. 4, with its extreme and variable soil erosion and sedimentation rates, highlights the risk of severe land degradation, which can undermine the long-term viability of hydropower projects in this area.

Moreover, the correlation between soil erosion and sedimentation suggests that areas experiencing high erosion rates will likely face corresponding sedimentation challenges. Effective soil conservation and land management practices are crucial to mitigate these impacts. For instance, catchment areas with moderate and controlled soil erosion and sedimentation rates (e.g., CA Nos. 1 and 2) are better suited for small hydropower projects as they present fewer environmental risks and maintenance challenges. Kayastha *et al.* (2022) emphasize the need for effective sediment management strategies to address these issues, thereby supporting sustainable hydropower operations.

Small hydropower projects in the Citarum Watershed have the potential to contribute to renewable energy generation, their success and sustainability depend heavily on addressing the environmental impacts of soil erosion and sedimentation. Comprehensive land management strategies, including soil conservation and reforestation, are essential to mitigate these issues and ensure the long-term viability of hydropower projects. Careful selection of sites with stable water yields and lower erosion and sedimentation risks will be crucial in maximizing the benefits and minimizing the environmental impact of small hydropower installations.

3.6. Hydropower sustainability and watershed integrity: a nexus approach

To ensure the sustainability of small hydropower projects in the Citarum Watershed, a holistic approach that integrates water, energy, and food systems is essential. Sediment trapping is essential for maintaining the efficiency and longevity of hydropower facilities by preventing blockages in turbines and associated equipment (Deng *et al.* 2023). Strategies such as the use of traps and structures to prevent sediment transport through turbines are crucial for ensuring the uninterrupted operation of hydropower plants (Prajapati *et al.* 2024). Effective sediment trapping mechanisms help minimize the risk of turbine erosion, mechanical vibrations, and energy loss due to sediment abrasion (Bajracharya *et al.* 2022). Sediment trapping can also have significant downstream impacts on agriculture by reducing nutrient supply and affecting irrigation systems, ultimately leading to decreased soil fertility and increased fertilizer costs (Oliveira *et al.* 2020). While upstream water quality may improve, downstream ecosystems and habitats may suffer, affecting biodiversity and fisheries (Kondolf *et al.* 2014). To address these challenges, sustainable land management practices such as agroforestry and conservation tillage can help mitigate the impacts of sediment trapping by reducing soil erosion and enhancing soil fertility (Oliveira *et al.* 2020).

Implementing sediment management practices like bypass systems and controlled sediment release is crucial to balance hydropower needs with downstream requirements (Hauer *et al.* 2020). Holistic policies integrating water, energy, and food considerations are necessary to ensure equitable resource distribution and foster collaboration among sectors (Zhang *et al.* 2021). Monitoring sediment transport, water quality, and ecosystem health is vital for adaptive management and timely corrective measures (Hauer *et al.* 2020). By adopting an integrated approach that balances energy production with watershed and community resilience, sustainable hydropower in the Citarum Watershed can be achieved (Kondolf *et al.* 2014).

Achieving sustainable small hydropower projects in the Citarum Watershed requires a comprehensive strategy considering the interplay between water, energy, and food systems. By implementing sustainable land management practices, sediment management strategies, and holistic policies, stakeholders can work together to ensure the long-term viability of hydropower projects while preserving watershed integrity and supporting local communities.

4. CONCLUSION

The comprehensive analysis of the sustainability of potential small hydropower locations within the Citarum Watershed, focusing on future water supply, erosion, and sedimentation, offers valuable insights into the complex interplay of environmental factors and land use dynamics. Through the innovative application of the CA-Markov model alongside the SWAT, coupled with detailed data analysis and comparison with existing literature, this study provides a nuanced understanding of the challenges and opportunities associated with hydropower development in the region.

The assessment of catchment areas reveals diverse trends in water yield, soil erosion, and sedimentation, highlighting the multifaceted nature of watershed dynamics. While some areas exhibit increasing water availability, others face declining trends, posing significant challenges for sustainable hydropower generation. The analysis underscores the importance of considering localized factors, such as land use changes and climatic variations, in evaluating the suitability of hydropower sites and implementing effective mitigation measures.

The prediction of land use changes for 2030 and 2040 underscores the urgency of proactive conservation efforts to mitigate the adverse impacts of urban expansion and agricultural intensification on forested areas. The observed decline in forest lands and associated ecological degradation underscore the need for strategic planning and policy interventions to preserve critical ecosystems and maintain watershed health.

Furthermore, the assessment of soil erosion and sedimentation rates provides valuable insights into the environmental implications of land use changes. The observed correlations between soil erosion and sedimentation rates highlight the interconnected nature of these processes and emphasize the importance of holistic watershed management approaches. Proactive measures, such as reforestation, vegetative buffer zones, and sustainable land management practices, are essential for mitigating erosion and safeguarding water resources.

The findings of this study underscore the importance of integrating environmental considerations into decision-making processes for small hydropower development. By adopting a holistic approach that considers the complex interactions between land use, water resources, and ecosystem health, policymakers, and stakeholders can promote the sustainable development of hydropower infrastructure while safeguarding the ecological integrity of the Citarum Watershed for future generations.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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