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LAND USE CHANGE, WATERSHED DEGRADATION, AND THE ROLE OF NATURE-BASED SOLUTIONS IN FLOOD RISK REDUCTION IN THE CIMANDIRI WATERSHED, WEST JAVA, INDONESIA

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ABSTRACT

Flood occurrence in tropical watershed systems is increasingly linked to structural landscape transformation and declining ecological regulation capacity. In the Cimandiri Watershed of West Java, rapid land conversion over the past three decades has altered hydrological processes and intensified downstream vulnerability. This research investigates long-term land use transitions (1990–2024), evaluates watershed degradation using weighted biophysical indicators, and identifies strategic zones for ecosystem-based flood mitigation. Spatial analysis integrating land use, slope gradient, and critical land status reveals that 42.44% of the watershed area is categorized as moderately to highly degraded. Built-up land expanded almost fourfold during the study period, while forest cover declined substantially, indicating a shift from infiltration-dominated to runoff-dominated hydrological behavior. Areas with elevated degradation levels spatially correspond to zones of recurrent flood exposure in downstream and coastal sectors.

The study proposes targeted implementation of Nature-Based Solutions (NbS), including upstream reforestation, riparian buffer restoration, and downstream retention enhancement, as a complementary strategy to conventional infrastructure. The findings emphasize that flood risk in Cimandiri is a systemic watershed issue shaped by cumulative upstream–downstream interactions rather than isolated local factors

***Keywords**: Land use Change; Watershed Degradation; Flood Risk; Nature-Based Solutions; Cimandiri Watershed*

1.INTRODUCTION

Flooding is one of the most frequent hydrometeorological hazards in tropical regions and causes significant impacts on the environment as well as on socio-economic activities. In Indonesia, the increasing frequency and intensity of flood events over recent decades have been closely associated with environmental degradation driven by large-scale land use change. The conversion of forests, wetlands, and water recharge areas into built-up land has reduced the natural capacity of ecosystems to regulate the hydrological cycle and to buffer extreme rainfall events (Pielke, 2005).

The Millennium Ecosystem Assessment highlights that the degradation and conversion of natural ecosystems are key drivers of increased ecological disaster risk, including flooding (Mooney, 2005). Land cover change has been shown to disrupt hydrological balance by increasing surface runoff and reducing soil infiltration capacity (IPCC, 2022), thereby amplifying flood potential in downstream areas (Foley et al., 2005). The impacts of these processes extend beyond environmental degradation and also affect economic conditions, social systems, and public safety (Bradshaw et al., 2007).

These phenomena are evident in many watersheds across Indonesia, including the Cimandiri Watershed in West Java Province. The Cimandiri Watershed extends from mountainous areas in Sukabumi Regency to the southern coastal zone of West Java and plays an important role in supporting hydrological functions and regional economic activities. However, accelerated land cover change combined with weak integration of watershed management has led to significant ecological degradation and an increase in flood occurrences, particularly in downstream and coastal areas (Kurniawan et al., 2019).

Flood mitigation efforts in the Cimandiri Watershed have historically relied on engineering-based or grey infrastructure measures, including river channel modification and levee construction. Although these interventions provide short-term protection, they frequently fail to address the underlying ecological drivers of flooding and therefore offer limited long-term sustainability. In response to these limitations, Nature-Based Solutions (NbS) have gained attention as an alternative approach that prioritizes ecosystem conservation and restoration to regulate hydrological processes, reduce flood risk, and strengthen watershed resilience under changing climatic conditions (Cohen-shacham et al., 2019; IUCN, 2024). The selection of the Cimandiri Watershed as the study area was informed by findings from previous studies and by clearly identified research gaps, particularly the limited integration of land use dynamics, watershed degradation assessment, flood risk analysis, and NbS prioritization within a unified spatial framework. Accordingly, this study investigates the role and potential contribution of NbS in supporting sustainable watershed management in the Cimandiri Watershed.

2.RESEARCH METHODOLOGY

This study employs a Geographic Information System (GIS)-based spatial analysis approach to evaluate the relationships between land use change, watershed degradation, and flood risk.

Study Area

The study was conducted in the Cimandiri Watershed, West Java Province, Indonesia, which exhibits diverse topographic characteristics ranging from mountainous upstream areas to lowland and coastal zones in the downstream section. The location and boundaries of the study area are presented in Figure 2.1

to provide spatial context for the analysis of land use change and watershed degradation.

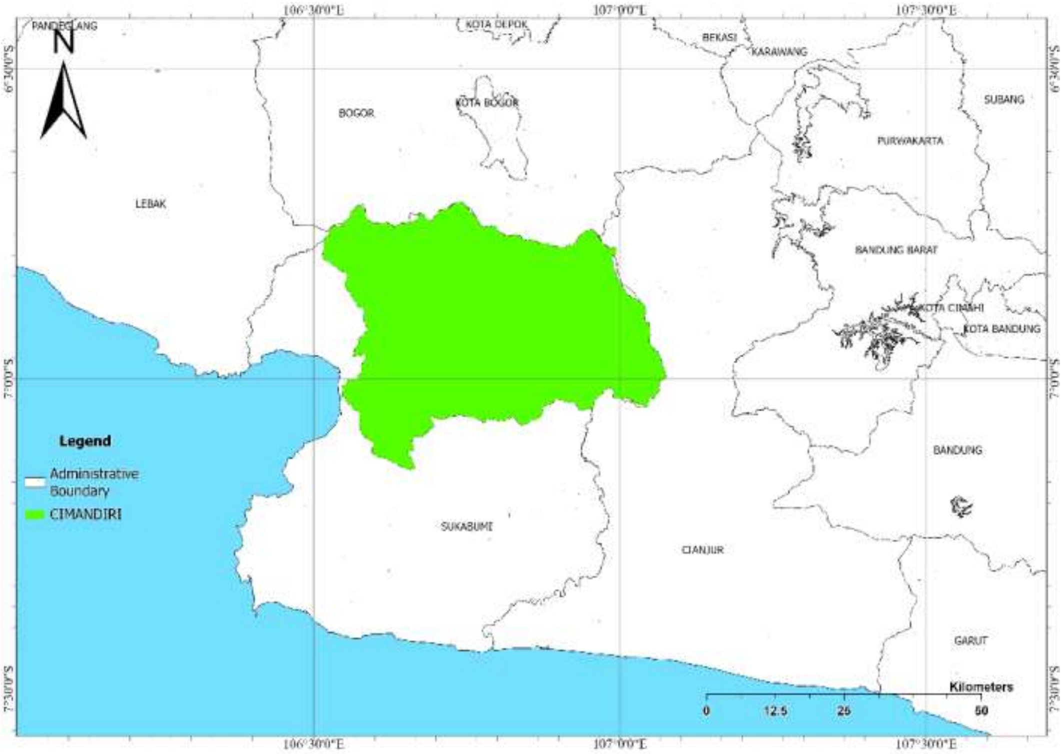

Figure 2.1 Location and boundary of the Cimandiri Watershed in West Java Province, Indonesia.

Source: Watershed boundary from the Ministry of Environment and Forestry of Indonesia (KLHK, 2023); elevation data from (DEM SRTM, 2000); processed by the authors (2025).

This location map provides the spatial framework for all subsequent analyses performed in this study.

Land use and land cover change analysis (LULC)

Land use analysis was conducted using multitemporal datasets from 1990, 1996, 2002, 2012, and the period 2017-2024 (Foley et al., 2005). These datasets were selected to capture long-term trends as well as key transition periods in land use dynamics within the Cimandiri Watershed (Lambin et al., 2003). For visualization purposes, three representative years were chosen, namely 1990 as the baseline condition prior to major anthropogenic transformation, 2012 as the primary transition phase characterized by accelerated land conversion, and 2024 representing the most recent land use condition **(Figure 2.2).**

Land use change was analyzed using a phase-based approach that groups temporal data into distinct periods of change, enabling the identification of dominant land use trajectories and their relevance to watershed hydrological processes. This approach facilitates the interpretation of gradual and abrupt land use transitions that influence surface runoff, infiltration capacity, and overall watershed response to rainfall events (Bradshaw et al., 2007; Pielke, 2005).

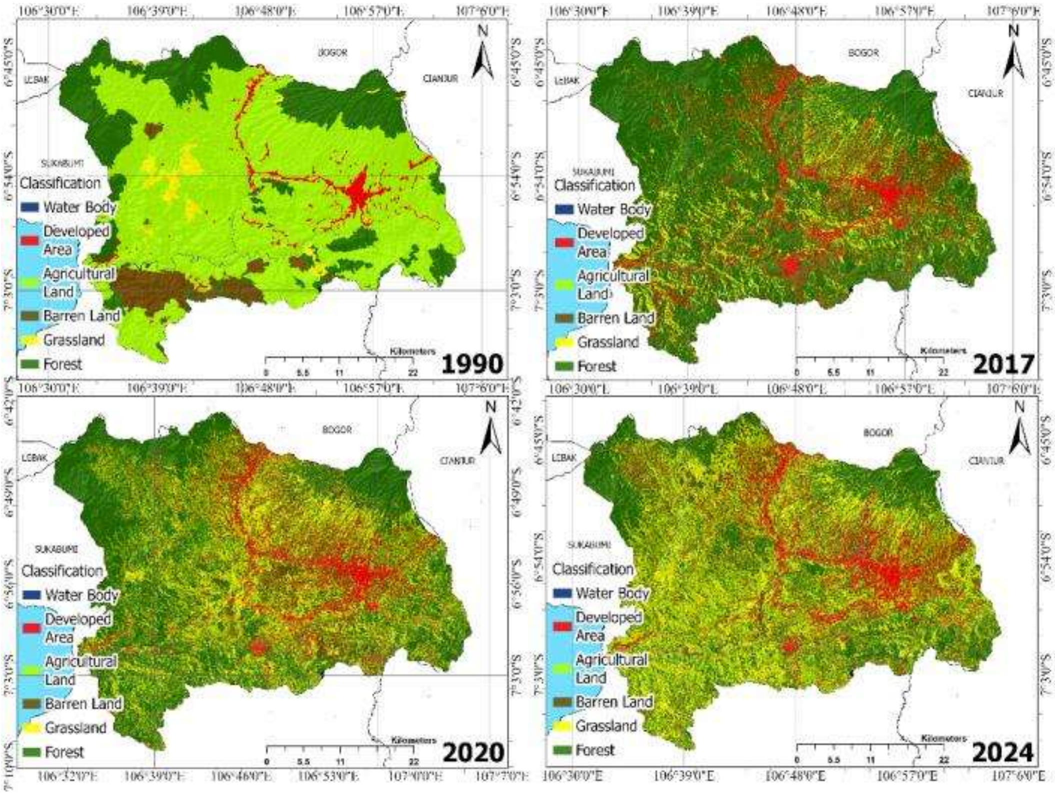

Figure 2.2 Land use maps of the Cimandiri Watershed for the years 1990, 2012, and 2024.

Source: United States Geological Survey (USGS, 2024); processed by the authors (2025).

The land use change patterns illustrated in Figure 2.2 were used to identify transition phases that potentially influence watershed hydrological responses. Temporal changes in the area of each land use class are presented in Figure 2.3 to complement the spatial analysis.

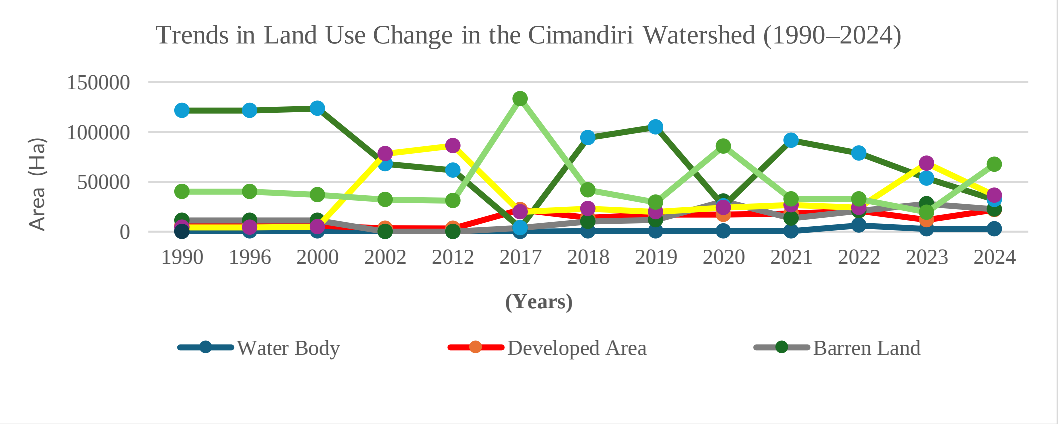

Figure 2.3. Trends in land use area changes in the Cimandiri Watershed during the period 1990–2024.

Source: Results of land use analysis by the authors (2025)

The trends presented in **Figure 2.3** provide a quantitative overview of the direction and magnitude of long-term land use changes. To further interpret the dynamics of land use change over extended periods, the analysis grouped the temporal data into several hydrologically relevant change phases, as summarized in **Table 2.1.**

Table 2.1 Phases of land use change in the Cimandiri Watershed and their hydrological relevance.

Change Phase	Time Period	Main Land Use Characteristics	Hydrological Relevance
Pre-change phase	1990-1996	Natural vegetation cover remained dominant, with relatively limited and localized land conversion	Infiltration capacity and watershed hydrological regulation functions remained relatively stable
Early transition phase	1996-2002	Initial fragmentation of vegetation cover, particularly in the middle watershed and along river corridors	Onset of increased surface runoff and a faster hydrological response
Rapid urbanization phase	2002-2012	Significant conversion of natural vegetation into residential and built-up areas	Reduced soil infiltration capacity and increased peak streamflow
Built-up area densification phase	2012-2018	Expansion and densification of built-up areas in the middle and downstream sections of the watershed	Reduction of recharge zones and increased hydrological pressure in downstream areas
Recent intensification phase	2018-2024	Intensification of land use and dominance of built-up areas, particularly in coastal zones	Increased flood vulnerability and hydrometeorological risk in downstream areas

The classification of land use change phases was used as the basis for spatial analysis and for interpreting the relationships between land use change and hydrological responses in the Cimandiri Watershed. It should be noted that variations in land use area during certain periods, particularly between 1990 and 2017, do not fully represent actual land use changes but are also influenced by differences in data characteristics and classification approaches across periods. Variations in spatial resolution, sensor types, and land use classification schemes may result in shifts in the estimated area of specific land use classes, especially those with similar spectral characteristics such as forest, grassland, and agricultural land. Therefore, the interpretation of land use change dynamics in this study focuses on long-term patterns and trends across phases rather than on absolute changes between individual years.

Watershed degradation and flood risk analysis

Watershed degradation was assessed based on land use characteristics, slope gradient, and critical land conditions (Douglas-Mankin et al., 2010). Flood risk was mapped through spatial overlay analysis integrating watershed degradation levels, downstream area characteristics, and historical flood event data (Ward, 2003; Winsemius et al., 2015). The assessment of watershed degradation levels was conducted by integrating key biophysical parameters influencing hydrological functions, which were summarized in the form of scores and weights as presented in **Table 2.**2

Table 2.2. Parameters, scores, and weights used for watershed degradation assessment in the Cimandiri Watershed

Parameter	Class / Criteria	Score	Weight	Hydrological Justification
Land use	Natural vegetation	1	0.40	Vegetation enhances infiltration and reduces surface runoff
	Mixed agriculture	2		Infiltration capacity decreases and runoff begins to increase
	Open land	3		Highly susceptible to erosion and elevated runoff
	Built-up areas	4		Very low infiltration capacity and maximum surface runoff
Slope gradient	< 8%	1	0.35	Relatively slow surface flow
	8–15%	2		Increasing surface runoff
	15–25%	3		Higher erosion risk and accelerated flow
	> 25%	4		Very rapid hydrological response
Critical land condition	Non-critical	1	0.25	Hydrological function remains relatively intact
	Moderately critical	2		Hydrological function begins to decline
	Critical	3		Reduced infiltration capacity
	Severely critical	4		High level of hydrological degradation

Source: Compiled by the authors based on (Douglas-Mankin et al., 2010) and (Kurniawan et al., 2019)

The watershed degradation index (WDI) was calculated as a weighted sum of the standardized scores of land use (SLU), slope gradient (SSL), and critical land condition (SCL), as expressed in Equation (1):

$$\text{WDI} = (S_{LU} \text{ x } 0{,}4)+(S_{SL} \text{ x } 0{,}35)+(S_{CL} \text{ x } 0{,}25 \ldots\ldots\ldots (1)$$

where S_{LU} represents the land use score, S_{SL}, represents the slope gradient score, and S_{CL} represents the critical land condition score.

The resulting degradation index values were classified into three degradation classes (low, moderate, and high) using an interval-based classification method consistent with the distribution of index values. To quantify the extent of watershed degradation, the proportion of moderately to highly degraded areas (P_{MH}) was calculated as the ratio between the total area classified as moderate and high degradation and the total watershed area, expressed as a percentage (Equation 2):

$$PMH=\frac{AM+AH}{AT} \text{ X } 100\% \text{ ……………………………}(2)$$

where A_M is the area classified as moderate degradation (ha), is the area classified as high degradation (ha), and A_T is the total watershed area (ha).

The watershed degradation index values were subsequently classified into low, moderate, and high classes using an interval-based method consistent with the distribution of index values. The integration of land use, slope gradient, and critical land condition parameters resulted in a watershed degradation map, as presented in **Figure 2.4**.

Figure 2.4. Watershed degradation map of the Cimandiri Watershed

Source: Land use data from the United States Geological Survey (USGS, 2024); slope gradient derived from (DEM SRTM, 2000); critical land condition data from the Ministry of Environment and Forestry of Indonesia (KLHK, 2023); processed by the authors (2025).

This watershed degradation map represents the biophysical conditions and hydrological regulation capacity of the Cimandiri Watershed. The spatial distribution of areas potentially affected by flooding is shown in **Figure 2.5**, based on the overlay of watershed degradation levels and exposure factors.

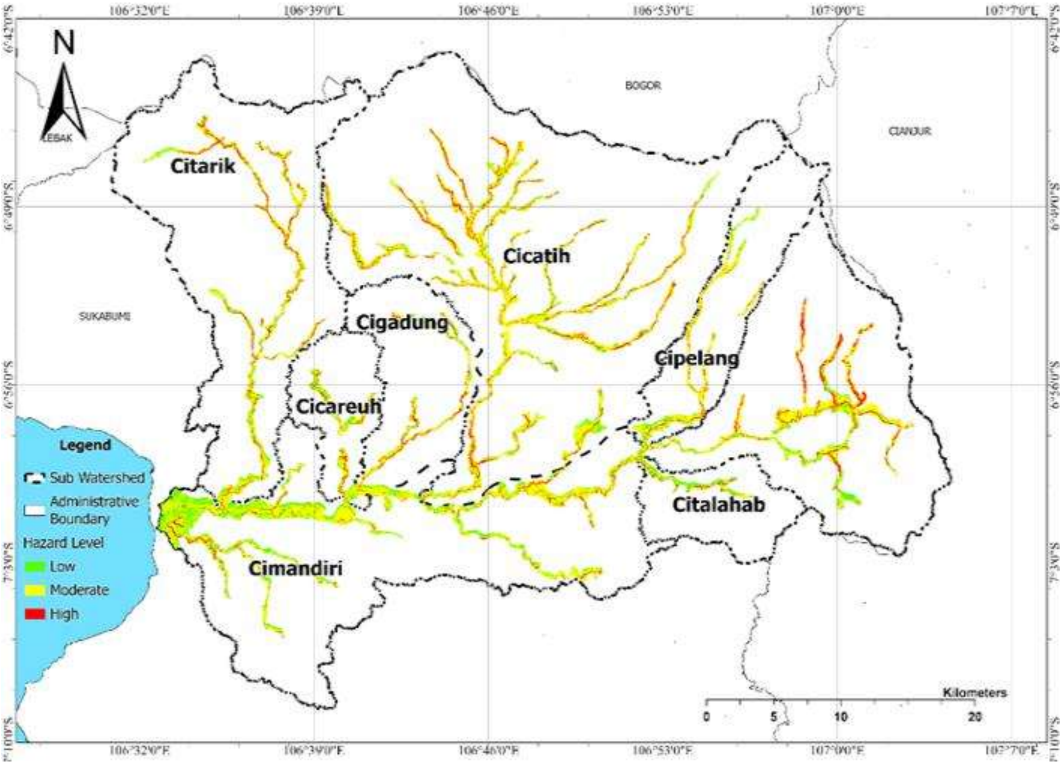

Figure 2.5 Flood risk map of the Cimandiri Watershed
Source: Historical flood event data from; the National Disaster Management Agency of Indonesia (BNPB, 2024), watershed degradation map from this study; processed by the authors (2025)

Flood risk mapping in this study is not intended as a quantitative hydrological simulation, but rather as a spatial indication of area vulnerability based on watershed degradation conditions and exposure factors.

Nature-based solutions prioritization

The identification of priority locations for Nature-Based Solutions (NbS) was conducted using a spatial scoring method to determine areas with the greatest potential for restoring watershed hydrological functions DAS (Cohen-shacham et al., 2019; IUCN, 2024). The prioritization of NbS implementation considered watershed degradation conditions and the characteristics of each watershed zone, as defined by the criteria presented in **Table 2.3.**

Table 2.3 Criteria and recommended Nature-Based Solutions (NbS) for different zones of the Cimandiri Watershed.

Watershed Zone	Main Conditions	Priority Criteria	Recommended NbS Types	Primary Hydrological Function
Upstream	Steep slopes,	Moderate to	Forest rehabilitation,	Enhancing

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Watershed Zone	Main Conditions	Priority Criteria	Recommended NbS Types	Primary Hydrological Function
	vegetation fragmentation	high degradation, declining vegetation cover	agroforestry	infiltration and reducing surface runoff
Middle	Intensive land conversion	High degradation, expansion of built-up areas	Soil and water conservation, slope-cover vegetation	Reducing erosion and sedimentation
Riparian	Degraded river buffers	High degradation, proximity to river channels	Riparian vegetation restoration	Stabilizing riverbanks and slowing flow velocity
Downstream	Low-lying areas, flood-prone zones	High flood risk, dominance of built-up land	Wetland management, green open spaces	Retaining runoff and attenuating floods

Source: Compiled by the authors based on (Cohen-shacham et al., 2019)and (IUCN, 2024)

The criteria and types of Nature-Based Solutions (NbS) presented in Table 3 were used as the basis for mapping priority locations for ecosystem-based interventions. The priority areas for NbS implementation in the Cimandiri Watershed are shown in **Figure 2.6.**

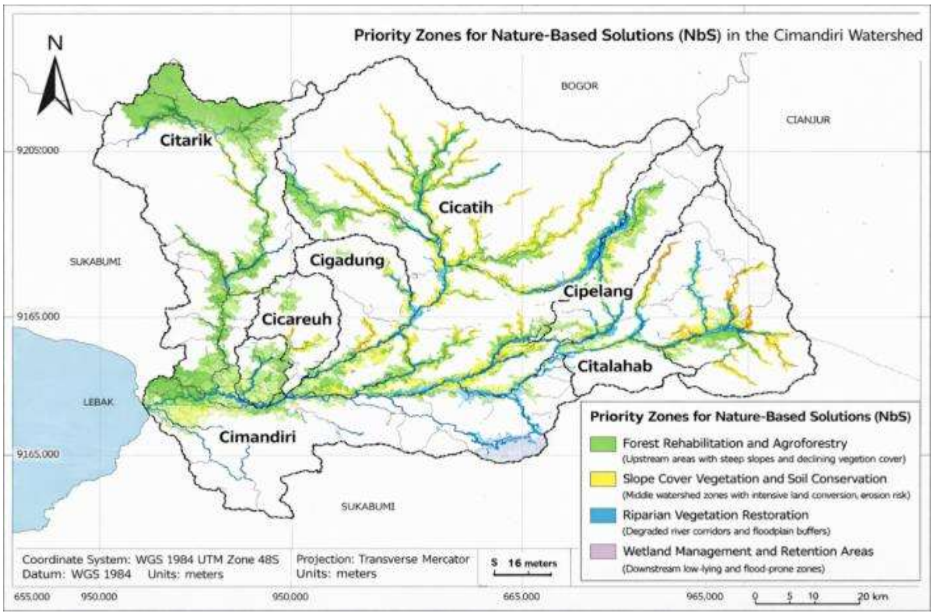

Figure 2.6 Priority map for the implementation of Nature-Based Solutions (NbS) in the Cimandiri Watershed

Source: Integrated results of land use change analysis, watershed degradation assessment, and flood risk mapping; processed by the authors (2025)

This map serves as the spatial foundation for formulating recommendations on the implementation of Nature-Based Solutions (NbS) to restore watershed hydrological functions and mitigate flood risk. The parameters used in the analysis were selected based on their direct influence on hydrological regulation, particularly land use, slope gradient, and critical land condition, which collectively determine infiltration capacity, runoff generation, and erosion susceptibility.

The classification of watershed degradation levels was conducted using an interval-based approach aligned with the distribution of composite index values, allowing spatial differentiation between low, moderate, and high degradation conditions. Meanwhile, the prioritization of NbS implementation was determined through spatial overlay analysis integrating degradation levels, watershed zonation (upstream, middle, riparian, downstream), and flood exposure characteristics. Areas classified as moderate to high degradation with strong spatial association to flood-prone zones were designated as priority locations, as interventions in these areas are expected to produce the greatest improvement in hydrological regulation and flood mitigation.

3.ANALYSIS AND DISCUSSION

Dynamics of land use change

Land use transformation in the Cimandiri Watershed evolved through several distinct temporal phases characterized by different spatial patterns (Table 1). Between 1990 and 1996, land cover conditions were relatively unchanged, with natural vegetation still dominating upstream zones and portions of the middle watershed (Figure 2). Signs of vegetation fragmentation began to emerge during 1996-2002, primarily along river corridors and transitional middle catchment areas.

The most substantial transformation occurred from 2002 to 2012, when extensive conversion of vegetated land into residential and other built-up uses took place, particularly across middle and downstream regions. After 2012, spatial expansion slowed, but land utilization intensified through densification of built environments rather than outward growth. Quantitative analysis of land use extent (Figure 3) confirms a persistent decline in vegetated land alongside a marked increase in developed areas throughout 1990-2024, indicating a structural shift toward surfaces with lower infiltration capacity and higher runoff potential.

Watershed degradation and flood risk

The composite watershed degradation analysis shows that approximately **42.44%** of the Cimandiri Watershed falls within moderate to high degradation categories. These degraded zones are spatially concentrated in middle and downstream sections, where built-up land dominates and interacts with moderate to steep slope gradients and critical land conditions (Figure 4).

Overlay analysis demonstrates a clear spatial correspondence between degradation hotspots and areas exposed to flood hazards (Figure 5). High-risk zones are generally situated in low-elevation terrain that receives accumulated runoff from upstream and middle catchments while simultaneously facing river overflow exposure. Quantitatively, degradation indicators derived from land use scoring, slope classification, and critical land weighting collectively explain the spatial distribution of flood susceptibility within the watershed system.

Priority areas for Nature-Based Solutions (NbS)

Spatial prioritization of Nature-Based Solutions was determined by integrating quantitative indicators of watershed degradation, land use intensity, slope characteristics, and flood exposure. Priority zones are primarily located where moderate to high degradation overlaps with flood-prone areas, indicating locations where ecosystem restoration can produce the greatest hydrological benefit.

Upstream areas with declining vegetation cover are prioritized for reforestation and agroforestry to enhance infiltration capacity. Middle watershed zones characterized by intensive land conversion require soil and water conservation measures to reduce runoff and sediment transport. Riparian corridors showing degraded buffer conditions are prioritized for vegetation restoration to stabilize channels and attenuate flow velocity. Meanwhile, downstream lowland areas dominated by built surfaces are prioritized for wetland restoration and green retention spaces to temporarily store runoff and reduce flood peaks.

The prioritization framework incorporates measurable parameters rather than qualitative judgment alone, ensuring that NbS recommendations are directly linked to quantified watershed conditions and flood risk distribution.

DISCUSSION

Land use change and its implications for the hydrological response of the Cimandiri Watershed

The land use changes identified in the Cimandiri Watershed reveal a landscape transformation pattern with direct implications for watershed hydrological regulation. The conversion of natural vegetation into built-up areas, particularly since the early 2000s, has progressively reduced infiltration capacity while increasing the dominance of surface runoff processes. In the context of the Cimandiri Watershed, which exhibits pronounced upstream-downstream gradients, these changes have contributed to a faster hydrological response, especially during high-intensity rainfall events. The rapid urbanization phase during the 2002–2012 period represents a critical turning point in the watershed's hydrological dynamics. Vegetation fragmentation during this phase was not only spatial but also functional, as it altered water storage and release mechanisms within the watershed system (Bismuth et al., 2007). The reduction of continuous vegetative cover limited soil water retention and shortened flow concentration times, thereby increasing runoff efficiency and peak discharge potential. These findings are consistent with previous studies indicating that land use change in tropical watersheds acts as a primary control on shifts in hydrological response and flood generation processes (Foley et al., 2005; Pielke, 2005).

Watershed degradation and increased flood risk in downstream areas

The results indicate that watershed degradation in the middle and downstream sections of the Cimandiri Watershed acts as an amplifying factor that increases flood vulnerability. The combined effects of built-up area dominance, slope conditions, and the presence of critical land accelerate surface runoff while enhancing erosion and river sedimentation processes. These processes cumulatively reduce channel conveyance capacity, thereby increasing the likelihood of overbank flooding in downstream and coastal areas (Turner, 2019). The strong spatial association between zones of high watershed degradation and areas with elevated flood risk highlights that flooding in the Cimandiri Watershed cannot be interpreted solely as a localized downstream phenomenon. Instead, flood occurrence reflects the cumulative impacts of interconnected upstream–downstream degradation processes operating within the watershed system. This finding is consistent with regional and global hydrological studies emphasizing that flood risk in downstream areas is strongly influenced by land degradation and hydrological alterations occurring across the entire watershed continuum (Winsemius et al., 2015).

Nature-Based Solutions as an adaptive approach to watershed management

Nature-Based Solutions (NbS) provide an adaptive approach to watershed management by addressing the underlying drivers of flood risk associated with land degradation and hydrological alteration. In the Cimandiri Watershed, the spatial prioritization of NbS highlights the importance of restoring ecological functions across upstream, middle, riparian, and downstream zones through differentiated, process-based interventions (Cohen-shacham et al., 2019; IUCN, 2024). Upstream forest rehabilitation, agroforestry, and slope-cover vegetation can enhance infiltration capacity and moderate runoff generation, while riparian vegetation restoration contributes to bank stabilization and flow attenuation (Narayan et al., 2016). In downstream areas, wetland management and retention spaces increase temporary water storage during high-flow events, supporting flood peak attenuation. Rather than replacing conventional grey infrastructure, NbS complement existing flood management strategies by strengthening the natural buffering capacity of watershed systems and enhancing long-term resilience under changing climatic and land use conditions.

Management implications and study limitations

The results suggest that watershed management in the Cimandiri Watershed needs to move beyond a reliance on conventional engineering measures toward approaches that integrate ecological processes within watershed planning. Spatially targeted application of Nature-Based Solutions (NbS) offers a pathway to improve hydrological resilience by restoring infiltration capacity, moderating runoff generation, and supporting more sustainable coastal development (Cohen-shacham et al., 2019; IUCN, 2024). Despite these contributions, several limitations remain.

The present analysis is primarily based on spatial relationships and does not include quantitative hydrological simulations capable of estimating changes in peak discharge or runoff magnitude under different intervention scenarios. As a result, the hydrological benefits of NbS are inferred rather than numerically modeled. Future research should therefore incorporate hydrological modeling frameworks alongside spatial analysis to provide more robust quantitative evaluation. In addition, subsequent studies should strengthen the use of measurable indicators, including spatial extent, degradation intensity, and proportional distribution across watershed zones, to improve the precision of ecosystem-based watershed management assessments (Douglas-Mankin et al., 2010).

4.CONCLUSION

This study demonstrates that land use change dynamics in the Cimandiri Watershed have occurred through several major phases, with the accelerated conversion of natural vegetation into built-up areas since the early 2000s acting as a key driver of hydrological function degradation. These changes have contributed to increased surface runoff and heightened flood vulnerability in downstream and coastal areas.

The watershed degradation assessment indicates that nearly half of the Cimandiri Watershed is classified as moderately to highly degraded, spatially overlapping with zones of elevated flood risk. This finding underscores that flood risk in the Cimandiri Watershed results from cumulative upstream–downstream interactions within an integrated watershed system, rather than being solely attributable to infrastructural limitations in downstream areas.

The spatial prioritization of Nature-Based Solutions (NbS) identifies upstream areas, riparian corridors, and degraded sub-watersheds as strategic locations for ecosystem-based interventions. NbS offer a promising adaptive and sustainable flood mitigation strategy by restoring watershed hydrological regulation while simultaneously delivering additional ecological and social co-benefits.

This study demonstrates that land use transformation in the Cimandiri Watershed between 1990 and 2024 has substantially altered watershed hydrological behavior, marked by a significant expansion of built-up areas and a sharp decline in forest cover. Quantitative assessment shows that approximately 42.44% of the watershed falls within moderate to high degradation categories, spatially corresponding with zones of elevated flood risk concentrated in middle to downstream areas. These findings confirm that flood vulnerability in the Cimandiri region is driven by cumulative upstream-downstream interactions rather than localized downstream factors alone. The spatial prioritization analysis indicates that targeted implementation of Nature-Based Solutions across upstream vegetation zones, riparian corridors, and downstream retention areas can enhance hydrological regulation capacity while supporting sustainable watershed and coastal planning. Overall, the spatially explicit framework developed in this study provides evidence-based support for watershed management strategies that are adaptive to climate change and oriented toward long-term environmental sustainability.

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