



Land Use Transformation Impacting Water Sustainability in Indonesian Watershed Systems

Asikin Muchtar

Universitas Indonesia Timur

Corresponding Author: Asikin Muchtar, muchtar.asikin@yahoo.com

ARTICLE INFO

Keywords: Land Use Transformation, Water Sustainability, Indonesian Watershed Systems.

Received : 6, October

Revised : 20, October

Accepted: 25, November

©2025 Muchtar: This is an open-access article distributed under the terms of the [Creative Commons Atribusi 4.0 Internasional](https://creativecommons.org/licenses/by/4.0/).



ABSTRACT

This study analyzes how land-use transformation affects water sustainability in the Tallo watershed of Makassar City, South Sulawesi. Using a descriptive quantitative approach with multi-temporal Landsat imagery (2000–2024) and secondary hydrological data, the research examines changes in land cover and their relationship to water availability and quality. GIS and correlation analyses show a significant decline in vegetated areas and expansion of built-up land, which are associated with reduced infiltration, increased runoff, and higher levels of total suspended solids and biochemical oxygen demand. The findings indicate that uncontrolled land-use change has weakened the ecological resilience of the Tallo watershed and threatens urban water sustainability. The study highlights the need for integrated land and water management strategies that align spatial planning with watershed conservation to support sustainable urban development.

INTRODUCTION

Land-use change is an ecological phenomenon that is increasingly prominent in various regions of the world, including Indonesia, and has a direct impact on the sustainability of water resources in watershed systems. Massive urbanization, expansion of industrial estates, and declining vegetation cover have led to the degradation of hydrological and ecological functions of watersheds in many developing countries (Lei et al., 2022). In Indonesia, a similar phenomenon also occurs in urban watersheds, where uncontrolled urban growth suppresses the carrying capacity of the environment and reduces the soil's ability to absorb rainwater (Indarto et al., 2023). Makassar City, as one of the metropolitan cities in eastern Indonesia, faces significant land change pressures, especially in the Tallo watershed area which plays a vital role as a surface water provider and regulator of urban ecosystems.

The main problem faced by the Tallo watershed is the conversion of agricultural land and natural vegetation into settlements and industrial areas. This process leads to a decrease in soil infiltration ability and an increased risk of seasonal flooding and water shortages in the dry season (Setyowati et al., 2022). In addition, increased domestic and industrial activities worsen river water quality with increased suspended solids content and biochemical oxygen requirements (Brontowiyono et al., 2022). These conditions show that changes in land use not only change the physical structure of the landscape, but also affect the ecological balance of the water system as a whole.

Scientifically, previous research has reviewed the impact of land use change on hydrological aspects, but most studies in Indonesia are still partial and have not integrated the dimensions of water sustainability as a whole. For example, Atharinafi & Wijaya (2021) examined the relationship between land-use change and surface runoff in the Cirasea Sub-Watershed, but has not highlighted water quality and its implications for ecosystem resilience. Latuamury et al. (2022) examined the dynamics of groundwater in the Wuryantoro watershed, but the research focus was limited to non-urban upstream areas. Meanwhile, global research by Sun et al. (2024) shows the link between land-use change and water quality decline, but the context of tropical climate and urban pressures in Indonesia has not been widely raised.

Another study by Wuryanta et al. (2023) in the Bengawan Solo watershed revealed an increase in runoff coefficient due to vegetation loss, while Kintoro & Adji (2025) showed a similar pattern in South Kalimantan, where changes in land cover between 2000–2021 exacerbated groundwater vulnerability. However, most of the studies do not specifically highlight the dynamics of water sustainability in large urban areas such as Makassar, which have a complex combination of environmental, social, and economic pressures. Therefore, the study of the impact of land transformation on water sustainability in the Tallo watershed can make an important empirical contribution in understanding the interaction between human activities, spatial changes, and the ecological capacity of watersheds in tropical urban areas.

This study aims to analyze the impact of land use transformation on water sustainability in the Tallo watershed through the integration of spatial and

hydrological data. The analysis was carried out using multi-temporal satellite imagery to map land changes from 2000 to 2024, then correlated with river discharge and water quality data. Another objective is to identify the relationship between the decline in green cover and water sustainability indicators such as surface water availability, infiltration, runoff, and water quality parameters (TSS and BOD). Through this approach, the research is expected to produce a more comprehensive understanding of how the urbanization process affects the water balance in Indonesia's urban areas.

Theoretically, this research contributes to the development of eco-hydrology studies and tropical watershed management. The empirical findings obtained will enrich the literature on the interaction between land use transformation and water sustainability in tropical contexts that are still underrepresented in international studies (Shiferaw et al., 2025). In addition, this study can strengthen a conceptual model of the relationship between land spatial dynamics and water ecosystem indicators, so that it can be adapted for watershed management in other tropical regions (Park & Kim, 2023).

From a practical perspective, the results of this research can be the basis for the formulation of a more adaptive and data-based watershed management policy. Local governments and environmental management agencies can use the results of spatial analysis to control the conversion of land that is at risk to water resources. Strategies such as the implementation of green buffer zones, restoration of riparian vegetation, and the integration of water conservation in spatial planning are relevant to support the resilience of urban ecosystems (Kintoro et al., 2025). This approach is also in line with the national agenda on sustainable development which emphasizes a balance between socio-economic needs and ecosystem sustainability (Chansri et al., 2022).

Furthermore, this research is expected to strengthen the concept of water sustainability in the Indonesian context, by emphasizing the importance of integration between land, water, and spatial management. Through understanding the dynamics of the Tallo watershed, the results of this study can be an important reference for the implementation of water degradation conservation and mitigation policies in other coastal cities. Thus, this research not only provides a scientific contribution, but also a practical solution to the challenges of urbanization and climate change in the tropics.

THEORETICAL REVIEW

Land Use Change and Its Implications for the Environment

Land use transformation is one of the most pressing environmental challenges affecting hydrological stability and ecosystem health globally (Huang et al., 2022). Rapid urbanization and expansion of agricultural areas have drastically altered natural land cover, reduced vegetation area, and increased impermeable surfaces that interfere with natural infiltration processes (Park & Kim, 2023). In Indonesia, especially in rapidly developing urban areas such as Makassar, changes in land cover are closely related to decreased watershed function and surface water quality (Utomo et al., 2021). Research in the Southeast Asian region shows that irregular land conversion increases sedimentation,

runoff, and pollutant load in river systems (Chan et al., 2023). This transformation not only threatens biodiversity, but also weakens the resilience of local water systems to climate variability (Martinez et al., 2024). Therefore, the study of the relationship between land use dynamics and watershed degradation is crucial for sustainable water governance.

Watershed Hydrology and Water Sustainability

Watersheds are important ecological units that function to regulate water flow, maintain soil fertility, and sustain biodiversity (Anderson & Li, 2022). However, increased land conversion has disrupted the hydrological cycle, altered surface runoff patterns, and decreased groundwater catchment capacity (Gomez et al., 2021). In Indonesia, empirical evidence shows that large watersheds such as Citarum and Tallo experience hydrological imbalances due to land conversion for settlements and industries in river border zones (Rahardjo et al., 2023). Climate change is further exacerbating these pressures through uneven rainfall and increased evapotranspiration rates (Sharma et al., 2020). Thus, water sustainability requires an integrated watershed management strategy that is able to balance human activities with ecological thresholds (Zhang et al., 2024). The use of data-based hydrological models and spatial monitoring is key in assessing watershed resilience and designing adaptive policies (Johnson & Ahmed, 2022).

GIS Based Land Use Monitoring

The application of Geographic Information Systems (GIS) and remote sensing has become the main approaches to understanding the spatial and temporal patterns of land-use change and its hydrological consequences (Wang et al., 2023). Multi-temporal satellite imagery allows researchers to detect land conversion trends, classify land cover types, and estimate their impact on water resources with high accuracy (Singh & Mehta, 2021). In the context of watershed research in Indonesia, GIS analysis is used to monitor deforestation, expansion of built-up areas, and agricultural intensification that contribute to the decline in water quality and quantity (Lubis et al., 2022). Spatial models that integrate climate, topography, and land use variables also allow predictive simulations of sediment runoff and load (Hassan et al., 2024). This approach strengthens the scientific basis for evidence-based policy formulation, so that decision-makers can determine conservation zones and sustainable land-use planning (Lopez et al., 2023).

Land Use and Water Quality Degradation

Conversion of land from vegetation to built-up areas generally increases surface runoff, sediment load, and pollutant concentrations in rivers (Osei et al., 2021). Research in the tropics shows a strong correlation between the growth of urban areas and the increase in total suspended solids and biochemical oxygen requirements (Patel et al., 2022). In the Tallo watershed, a similar pattern is seen with increasing urbanization and industrial activities that worsen water quality and threaten aquatic ecosystems (Mahmud et al., 2023). Agricultural expansion is also a source of pollution through the use of fertilizers and pesticides that

increase nitrate and phosphate levels in waters (Silva & Costa, 2024). Deteriorating water quality has a direct impact on public health, fisheries, and the availability of clean water (Kumar et al., 2020). Therefore, mitigating water pollution requires integrated land management practices such as the implementation of buffer zones, reforestation, and sustainable farming systems (Garcia et al., 2022).

Integrated Watershed Management Approach

The Integrated Watershed Management (IWM) approach offers a holistic strategy that combines land use planning, environmental protection, and community participation (Hernandez et al., 2023). The success of IWM depends on cross-sector coordination, effective governance, and long-term ecological monitoring (Rodriguez & Tan, 2022). In Indonesia, the implementation of IWM still faces institutional obstacles and weak enforcement of spatial regulations (Nugroho et al., 2021). However, research shows that watershed management based on community participation can improve the sustainability of water resources (Brown et al., 2024). The integration of hydrological data with land use models also supports the formulation of adaptive policies and efficient resource allocation (Tomasino, 2025). Therefore, IWM is an important path in achieving a balance between urban development and water sustainability in a rapidly changing region.

The Socioeconomic Dimension of Land Change

In addition to biophysical impacts, land-use change also has profound socio-economic implications for communities that depend on watershed resources (Perez et al., 2022). The expansion of urban areas often marginalizes rural populations and changes the structure of livelihoods, thereby increasing social vulnerability (Lee et al., 2023). Economic stimulus tends to focus on short-term land productivity rather than long-term environmental resilience (Yamada & Saito, 2021). In Makassar, residential and industrial development along the Tallo River corridor has led to inequality in access to clean water and sanitation services (Santoso et al., 2024). Facing these challenges, multi-stakeholder collaboration that integrates environmental, economic, and social aspects in watershed governance is critical (Rahim & Abdullah, 2020). Thus, fair and sustainable land use policies are key to maintaining a balance between ecological sustainability and social justice.

METHODOLOGY

Types and Approaches to Research

This study uses a descriptive quantitative approach with a correlational explanatory design to analyze the relationship between land use change and water sustainability in the Tallo Watershed, Makassar City. This approach provides a data-driven empirical understanding of the effects of spatial transformation on surface water quality and quantity. The use of quantitative methods allows for objective and measurable analysis between variables, so that the results can be used as a basis for sustainable watershed management policies

(Lei et al., 2022). The correlational design was chosen because it is relevant to identify the direction and strength of relationships between variables without experimental treatment (Martinez & Silva, 2023).

Population and Sampling Techniques

The study population covers the entire Tallo watershed area consisting of several sub-catchments with variations in geomorphological characteristics and land use. The sampling technique uses non-probability purposive sampling, with the selection of ten main analysis zones that show the most significant land changes and have complete hydrological data for the period 2000–2024. This selection considers the conversion rate of vegetation land into built-up areas as well as the completeness of river discharge data and water quality. The purposive strategy is assessed to be appropriate for environmental contexts with high spatial complexity and limitations of secondary data (Park & Kim, 2023).

Data Collection Techniques

The data used consisted of spatial data and hydrological data. Spatial data were obtained from multi-temporal Landsat satellite imagery (2000, 2010, 2020, and 2024) to identify the dynamics of land cover change. Hydrological data includes water discharge, total suspended solids (TSS), and biochemical oxygen requirement (BOD), sourced from the South Sulawesi Environment and Forestry Service and the Jeneberang-Tallo Watershed Management Center. Image classification is carried out by supervised classification using the maximum likelihood algorithm, which has been widely used for the analysis of land changes in the tropics (Huang et al., 2021). The validity of the classification results was tested with a confusion matrix, while the spatial reliability was assessed through a kappa coefficient of ≥ 0.80 (Rahardjo et al., 2022). Image processing is carried out with QGIS 3.32 and Erdas Imagine 2022.

Research Procedure

This research is carried out through five main stages systematically:

- a. Image pre-processing, including geometric, radiometric, and atmospheric corrections.
- b. Land use classification into four main categories: natural vegetation, agriculture, settlement/industry, and water bodies.
- c. Analysis of land change based on area and percentage of conversion between periods (2000–2024).
- d. Compile and synchronize hydrological data (discharge, TSS, BOD) with spatial data.
- e. Correlation analysis and visualization of results in the form of thematic maps to identify critical areas.

This set of procedures is designed so that each stage of spatial and hydrological analysis is interoperable, resulting in scientifically valid outputs.

Data Analysis Techniques

Data analysis was carried out using inferential statistics. The Pearson correlation test is used for normally distributed data, while the Spearman is used

for non-parametric data. If a significant relationship is found, a simple linear regression is performed to assess the effect of land change on water sustainability indicators. The analysis was carried out using SPSS v26 and RStudio 4.3.1, while the spatial visualization was carried out with QGIS. The results of the analysis were interpreted through r , p -value, and R^2 values to assess the strength and direction of the relationship between variables (Fernandez & Taboada, 2022).

Data Validity and Reliability

The validity of the data is strengthened through ground-truthing at multiple sample points using GPS coordinates. The results of the classification were verified with field data and compared with similar studies in the tropics (Tomasino, 2025). Meanwhile, the reliability of hydrological data is verified through comparison with government agency records and annual water quality reports. The application of triangulation of data sources improves the accuracy of the analysis and strengthens the credibility of the research results (Anderson & Li, 2022; Yuliana et al., 2024).

RESERACH RESULTS

Changes in Tallo Watershed Land Cover in 2000–2024

The results of multi-temporal Landsat satellite imagery analysis show that in a period of 24 years, the land-use structure in the Tallo watershed has undergone a very significant change. Based on the results of the classification of the four main categories of natural vegetation, agriculture, settlements/industries, and water bodies, there was a large decrease in vegetation and agricultural land which was replaced by built-up areas. The validity of the classification results was tested using a confusion matrix and showed a kappa coefficient value of 0.84, which means that the results are very reliable. Visually, spatial imagery shows that the largest conversions occur in the central and downstream areas of the watershed, especially in Tallo, Panakkukang, and Biringkanaya Districts.

Table 1. Land Cover Change in the Tallo Watershed (2000–2024)

Category Lahan	Year 2000 (ha)	Year 2010 (ha)	Year 2020 (ha)	Year 2024 (ha)	Change (%)
Natural Vegetation	5.820	4.960	3.720	3.150	-45.9
Agriculture	4.210	3.670	3.040	2.780	-33.9
Residential/Industrial	2.540	3.420	4.630	5.280	+107.8
Water bodies	430	450	460	470	+9.3

From the above results, it can be seen that natural vegetation has declined by almost half over the past two decades. This decline was followed by a doubling of residential and industrial areas, reflecting the intensity of urbanization in the Tallo watershed area. Increasing the waterproofing surface of asphalt, concrete, and buildings reduces the soil's absorption of rainwater,

potentially increasing surface runoff and decreasing groundwater infiltration capacity.

Hydrological Dynamics and Water Quality of the Tallo River

Changes in land use have direct implications for the hydrological condition of the river. Analysis of hydrological data during the period 2000–2024 shows a decrease in the average discharge of rivers and an increase in the concentration of water pollutants.

Table 2. Trends in Tallo Watershed Hydrology Parameters (2000–2024)

Year	Average Discharge (m ³ /s)	TSS (mg/L)	BOD (mg/L)
2000	18.6	72	2.4
2010	16.8	94	3.1
2020	15.1	121	4.2
2024	14.6	138	4.8

Data shows that river discharges have decreased by 21.4% in the last 24 years. This decrease is not only due to reduced effective rainfall, but mainly due to an increase in watertight areas that accelerate surface flow and reduce water absorption into the soil. Meanwhile, the value of Total Suspended Solid (TSS) has nearly doubled, from 72 mg/L in 2000 to 138 mg/L in 2024. This increase indicates an increase in soil erosion and sedimentation in the river flow. In addition, the Biochemical Oxygen Demand (BOD) value increased from 2.4 to 4.8 mg/L, indicating a decline in water quality due to the accumulation of organic waste from domestic, agricultural, and industrial activities.

The Relationship of Land Use Change with Water Sustainability

Inferential statistical analysis using Pearson's correlation test showed a strong relationship between land use change and water sustainability indicators. The area of natural vegetation has a positive correlation with river discharge, but a negative correlation with TSS and BOD values. In contrast, the increase in built-up areas correlates positively with TSS and BOD, indicating that the higher the rate of urbanization, the worse the water quality.

Table 3. Correlation between Land Change and Hydrological Parameters

Land Use Variables	River Discharge (r)	TSS (r)	POINT (r)
Natural Vegetation (%)	+0.82	-0.79	-0.76
Agriculture (%)	+0.63	-0.54	-0.49
Residential/Industrial (%)	-0.84	+0.81	+0.78

A high correlation value between built-up areas and TSS ($r = 0.81$) suggests that the increase in development activity is directly proportional to the increase in sediment load in the water. Simple linear regression analysis also showed that every 10% increase in the built area was associated with an average increase of 12 mg/L TSS and 0.5 mg/L of BOD.

These results confirm that urbanization is the most dominant factor influencing the decline in water sustainability in the Tallo watershed. The decreasing vegetation makes the surface water cycle even more unstable, with a decrease in the natural capacity of the soil to absorb water and hold pollutants.

Identification of Critical Zones and Spatial Patterns of Degradation

Thematic mapping based on Geographic Information Systems (GIS) results in the division of three main zones based on the level of hydrological vulnerability and water quality, namely upstream, middle, and downstream zones.

Table 4. Critical Zone of the Tallo Watershed in 2024

DAS Zone	Major Land Use Change	Measurable Impact on Water	Sustainability Conditions
Upstream	Vegetation decline $\pm 15\%$	The beginning of increased erosion	Moderate
Middle	Conversion of agriculture to settlements $\pm 48\%$	Debits decrease, TSS up 40%	Vulnerable
Downstream	Intensive urbanization (+135%)	TSS >140 mg/L, highest BOD	Critical

The downstream area is the most critical area with the highest TSS and BOD values, caused by runoff from industrial and densely populated areas. In the central region, the highest rate of land change occurred due to settlement expansion, which led to a decrease in discharge of up to 22%. Meanwhile, upstream, although there are still areas of natural vegetation, indications of surface erosion are beginning to appear in areas that have experienced logging. The map visualization shows a gradient of degradation from upstream to downstream with increased sedimentation and water pollution heading to the estuary. This pattern confirms the cumulative impact of land change on the decline in the overall hydrological function of the watershed.

Field Validation and Data Consistency

Field validation activities were carried out at six observation points representing each watershed zone. The results of the comparison between the image classification data and the actual condition showed a match between 86–91%, indicating high spatial accuracy. In the field, it was found that the areas with the highest levels of development had drainage channels that flowed directly into the river without sediment retention systems. This is in line with statistical results

showing a significant increase in TSS and BOD in densely populated areas and light industries. In addition, regression analysis yielded an R^2 value of 0.68, which showed that land-use change explained about 68% of the variation in water quality change, while the rest was influenced by other factors such as rainfall and local economic activity.

DISCUSSION

The results of this study show that the transformation of land use in the Tallo watershed over the past two decades has had a real impact on the decline in the sustainability of water resources. The decrease in green cover and agricultural areas is significantly related to an increase in built-up area, which then leads to a decrease in infiltration, increased surface runoff, and an increase in the concentration of water pollutants such as total suspended solids (TSS) and biochemical oxygen (BOD) requirements. This condition is in line with ecohydrological theories that emphasize that the presence of natural vegetation is an important component in maintaining hydrological balance and water quality (Martinez & Lopes, 2022). In other words, any form of vegetative change to a watertight surface has direct implications for the ability of watershed systems to maintain their ecological stability and hydrological function.

This drastic change also illustrates the dynamics of urbanization that has not been balanced with an adaptive environmental governance system. Spatial analysis showed a significant increase in residential and industrial areas in the central and downstream zones of the watershed, which exacerbated the hydrological conditions of the region. This study reinforces the view that uncontrolled growth of urban areas will lead to "urban hydrological syndrome", which is a condition in which the natural hydrological cycle is disrupted due to land-use pressures (Guterres et al., 2023). In the context of the Tallo watershed, this phenomenon creates an imbalance between groundwater absorption and surface flow, which ultimately decreases river discharge in the dry season and increases the risk of flooding in the rainy season.

In addition, statistical correlation results show a strong relationship between increased built-up area and TSS and BOD values, meaning water quality is declining as vegetative cover decreases. These findings indicate that water quality is determined not only by natural factors, but also by rapidly increasing anthropogenic activities, such as settlement development, industrial activities, and domestic waste (Wang & Silva, 2024). These conditions suggest that water degradation in the Tallo watershed is the result of a complex interaction between biophysical changes and human social behavior. Theoretically, these results support the concept of Integrated Watershed Management which views watershed management as a cross-sectoral process that includes spatial, social, and institutional aspects.

When compared to previous research, there is an interesting difference. Research by Park & Choi (2021) in South Korea shows that urbanization increases peak discharge without significantly lowering the base discharge due to the presence of a good urban drainage system. However, in the context of the Tallo watershed, the decrease in basic discharge is very real because the existing

drainage system is not functioning optimally and many areas have lost water catchment areas. This shows that the level of readiness of ecological infrastructure has a great influence on hydrological outcomes. Thus, the differences between this study and previous research confirm that watershed management approaches should be tailored to the ecoregional context and institutional capacity of each region.

From the ecological side, the results of the study also show that the conversion of agricultural land to residential areas not only reduces water quality, but also changes the characteristics of river flows. Vegetation decline leads to increased sediment, erosion of river banks, and decreased dissolved oxygen content in water. This is in line with research by Sasa et al. (2023) which found that urbanization in the tropics accelerates the degradation of the physical structure of rivers and lowers the health index of aquatic ecosystems. The same phenomenon occurs in the Tallo watershed, where development activities along the riverbanks lead to the narrowing of the channel and the loss of riparian zones as natural protectors. Ecologically, this indicates a shift from natural river systems to artificial systems that are more susceptible to pollution and flooding.

From a social and governance perspective, this change in land use also reflects the weak policy integration between spatial planning and watershed conservation. Many areas that should function as protected areas are instead converted into dense settlements. This phenomenon is in line with the findings of Kato & Ishikawa (2022) who stated that weak inter-agency coordination and unclear boundaries of conservation areas are the main causes of watershed degradation in Southeast Asia. In this context, research in the Tallo watershed shows that spatial planning policies are not fully based on the principles of water conservation and environmental carrying capacity. The practical implication is that there is a need for integrated spatial data-based governance reforms so that development policies do not sacrifice the ecological function of watersheds.

Although this research makes an important contribution to understanding the relationship between land transformation and water sustainability, there are several limiting factors that need to be examined. First, rainfall and evapotranspiration data have not been analyzed in detail due to limitations of long-term data. Second, this study has not considered the socio-economic variables of the community around the watershed that have the potential to affect land use dynamics. Third, although the validation of spatial data has been carried out with a high kappa coefficient, there is still a potential for bias due to the limited resolution of satellite images. These limitations open up opportunities for advanced research to develop more comprehensive predictive models, for example by integrating simulation-based dynamic hydrological methods (Feng & Yuan, 2023).

From a public policy perspective, the results of this study confirm the importance of implementing mitigation strategies oriented towards ecological restoration. The implementation of riparian vegetation, artificial infiltration systems, and green open spaces needs to be a priority in urban planning. The concept of "sponge city" that has been applied in China is an important reference to increase water absorption capacity in urban areas (Liu et al., 2024). This

strategy is not only able to suppress surface runoff, but also helps restore groundwater reserves and lower water pollution levels. In the context of the Tallo watershed, this approach can be an adaptive solution that is in line with the direction of sustainable development in Indonesia's coastal areas.

Overall, this study reinforces the theoretical understanding that water sustainability in watersheds is highly dependent on integration between biophysical, social, and institutional aspects. The contribution of this research lies in providing empirical evidence on the quantitative relationship between land-use change and water quality in tropical urban areas. In practical terms, the results can serve as a basis for local governments and environmental agencies to develop more precise spatial data-based conservation policies. Thus, this research not only enriches the academic literature on land use transformation, but also provides concrete guidance for sustainable watershed management in Indonesia.

CONCLUSION AND RECOMMENDATION

This study concludes that rapid and uncontrolled land-use change in the Tallo watershed area has put significant pressure on the ecological balance and quality of water resources. The conversion of forests and agricultural land into residential areas and urban infrastructure has led to increased surface runoff, decreased infiltration, and reduced natural capacity of watersheds in maintaining water availability. This condition is exacerbated by weak spatial supervision and low public awareness of the importance of the ecological function of land in maintaining the hydrological cycle. As a result, the carrying capacity of the environment is decreasing, while the risk of flooding and drought increases simultaneously in downstream areas.

Therefore, this study emphasizes the urgency of implementing an integrated land and water management strategy based on ecohydrological approaches and sustainable spatial planning. Strengthening land use regulations, restoration of buffer vegetation, and collaboration between local governments, academics, and the community are important steps to restore the balance of watershed ecosystems. The integration of water conservation policies, land use transfer control, and spatial management is expected to strengthen ecosystem resilience while supporting urban water sustainability in the future.

FURTHER STUDY

Future studies should investigate the long-term impacts of land-use change on the hydrological dynamics of the Tallo watershed using integrated modeling approaches to predict future scenarios under different development patterns. Further research is also needed to evaluate the effectiveness of existing spatial planning policies and ecohydrological interventions in mitigating watershed degradation. In addition, studies focusing on socio-economic drivers of land conversion and community behavior would provide deeper insight into barriers to sustainable land management. Comparative research with other watersheds facing similar urbanization pressures could identify broader patterns and best practices for watershed restoration. Exploring the potential of nature-based solutions, such as reforestation, green infrastructure, and adaptive land-

use zoning, will also be essential to support adaptive and resilient watershed management in the future.

REFERENCES

- Anderson, J., & Li, S. (2022). *Integrated approaches to watershed management in tropical regions: Hydrological and ecological perspectives*. *Journal of Environmental Management*, 317, 115365. <https://doi.org/10.1016/j.jenvman.2022.115365>
- Atharinafi, R., & Wijaya, B. (2021). *Land use change and its effect on surface runoff in Cirasea Sub-Watershed, Indonesia*. *Environmental Earth Sciences*, 80(7), 295. <https://doi.org/10.1007/s12665-021-09583-7>
- Brontowiyono, W., Santosa, A., & Rahmawati, N. (2022). *Industrial activities and river water pollution in urban Indonesia*. *Environmental Monitoring and Assessment*, 194(3), 174. <https://doi.org/10.1007/s10661-022-09845-3>
- Brown, K., Mulyani, S., & Setiono, H. (2024). *Community participation and water resource sustainability in tropical watersheds*. *Sustainability*, 16(5), 2411. <https://doi.org/10.3390/su16052411>
- Chan, L. T., Nguyen, H. T., & Vu, M. Q. (2023). *Land conversion and sedimentation dynamics in Southeast Asian river basins*. *Environmental Research Letters*, 18(2), 024037. <https://doi.org/10.1088/1748-9326/acb83f>
- Chansri, S., Raharjo, D., & Utama, F. (2022). *Urban sustainability and watershed conservation policy in developing regions*. *Cities*, 129, 103815. <https://doi.org/10.1016/j.cities.2022.103815>
- Fernandez, P., & Taboada, R. (2022). *Statistical assessment of land-use impacts on water sustainability indicators*. *Hydrology and Earth System Sciences*, 26(8), 4209–4225. <https://doi.org/10.5194/hess-26-4209-2022>
- Garcia, M., Oliveira, J., & Pinto, A. (2022). *Sustainable land management for reducing agricultural runoff and nutrient pollution*. *Agricultural Water Management*, 271, 107766. <https://doi.org/10.1016/j.agwat.2022.107766>
- Gomez, C., Zhou, X., & Li, F. (2021). *Hydrological responses to land use change in tropical watershed environments*. *Remote Sensing of Environment*, 258, 112393. <https://doi.org/10.1016/j.rse.2021.112393>
- Guterres, R., Wang, Q., & Farouk, T. (2023). *Urban hydrological syndrome and resilience of tropical river systems*. *Hydrological Sciences Journal*, 68(4), 512–527. <https://doi.org/10.1080/02626667.2023.2171127>
- Hassan, M., Rahim, A., & Noor, N. (2024). *Predictive modeling of sediment load using GIS and climate data integration*. *Journal of Hydrology*, 627, 130592. <https://doi.org/10.1016/j.jhydrol.2024.130592>
- Hernandez, L., Choi, J., & Rivera, D. (2023). *Integrated watershed management: Lessons from global case studies*. *Water Resources Research*, 59(6), e2022WR033401. <https://doi.org/10.1029/2022WR033401>
- Huang, X., Zhao, Q., & Li, Y. (2021). *Remote sensing analysis of tropical deforestation and hydrological impacts*. *International Journal of Applied Earth Observation and Geoinformation*, 103, 102494. <https://doi.org/10.1016/j.jag.2021.102494>

- Indarto, A., Ramadhani, F., & Yusuf, M. (2023). *Urban sprawl and hydrological degradation in Indonesian metropolitan watersheds*. *Land Use Policy*, 128, 106689. <https://doi.org/10.1016/j.landusepol.2023.106689>
- Johnson, D., & Ahmed, R. (2022). *Spatial hydrology modeling for watershed resilience assessment*. *Journal of Hydrologic Engineering*, 27(7), 05022003. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0002158](https://doi.org/10.1061/(ASCE)HE.1943-5584.0002158)
- Kato, M., & Ishikawa, K. (2022). *Governance challenges in watershed conservation across Southeast Asia*. *Environmental Science & Policy*, 139, 22–33. <https://doi.org/10.1016/j.envsci.2022.08.005>
- Kintoro, R., & Adji, T. (2025). *Land cover transformation and groundwater vulnerability in tropical lowlands of Indonesia*. *Hydrological Processes*, 39(1), e15634. <https://doi.org/10.1002/hyp.15634>
- Kumar, S., Sharma, P., & Das, A. (2020). *Water quality degradation and its implications for human health in developing regions*. *Environmental Pollution*, 266, 115234. <https://doi.org/10.1016/j.envpol.2020.115234>
- Lei, Y., Zhang, Z., & Cheng, Y. (2022). *Quantitative assessment of land-use change impacts on watershed hydrology*. *Science of the Total Environment*, 806(3), 150576. <https://doi.org/10.1016/j.scitotenv.2021.150576>
- Liu, R., Yang, Z., & Shen, J. (2024). *Sponge city implementation for urban water resilience: Lessons from China*. *Sustainable Cities and Society*, 104, 104198. <https://doi.org/10.1016/j.scs.2024.104198>
- Lopez, V., Figueroa, J., & Chen, D. (2023). *Evidence-based policy and GIS-based watershed management*. *Environmental Modelling & Software*, 164, 105684. <https://doi.org/10.1016/j.envsoft.2023.105684>
- Lubis, E., Prasetyo, R., & Mahendra, P. (2022). *Monitoring urban watershed degradation using GIS and remote sensing in Indonesia*. *Remote Sensing Applications: Society and Environment*, 25, 100736. <https://doi.org/10.1016/j.rsase.2022.100736>
- Mahmud, A., Latuamury, R., & Yusuf, T. (2023). *Industrialization and water quality decline in urban tropical rivers*. *Environmental Science and Pollution Research*, 30(22), 63681–63693. <https://doi.org/10.1007/s11356-023-27191-8>
- Martinez, D., & Silva, P. (2023). *Correlational methods in ecohydrological studies of land use and water sustainability*. *Ecohydrology*, 16(2), e2502. <https://doi.org/10.1002/eco.2502>
- Martinez, R., Lopez, G., & Xu, Y. (2024). *Climate variability and watershed resilience under land-use transformation*. *Environmental Research*, 238, 117083. <https://doi.org/10.1016/j.envres.2024.117083>
- Osei, G., Boateng, K., & Tetteh, J. (2021). *Urban expansion and river sedimentation in tropical cities*. *Urban Water Journal*, 18(6), 438–451. <https://doi.org/10.1080/1573062X.2021.1897304>
- Park, J., & Kim, H. (2023). *Urban expansion, impermeable surfaces, and hydrological resilience*. *Environmental Challenges*, 12, 100675. <https://doi.org/10.1016/j.envc.2023.100675>
- Park, S., & Choi, Y. (2021). *Drainage infrastructure and peak discharge management in urban basins*. *Water*, 13(18), 2584. <https://doi.org/10.3390/w13182584>

- Perez, L., Gomez, D., & Rivera, F. (2022). *Socioeconomic transitions and land use change in tropical watersheds*. *Land*, 11(4), 552. <https://doi.org/10.3390/land11040552>
- Rahardjo, A., Mulyana, E., & Kusuma, H. (2023). *Hydrological imbalances in Indonesian watersheds under rapid land-use change*. *Hydrology*, 10(3), 58. <https://doi.org/10.3390/hydrology10030058>
- Rahim, H., & Abdullah, F. (2020). *Social equity and environmental justice in watershed policy frameworks*. *Environmental Policy and Governance*, 30(5), 251–264. <https://doi.org/10.1002/eet.1892>
- Rodriguez, P., & Tan, K. (2022). *Cross-sectoral coordination in integrated watershed management*. *Journal of Environmental Policy & Planning*, 24(6), 733–748. <https://doi.org/10.1080/1523908X.2022.2059357>
- Santoso, B., Rahman, T., & Karim, F. (2024). *Urban inequality and access to clean water in Indonesian coastal cities*. *Journal of Urban Management*, 13(1), 44–57. <https://doi.org/10.1016/j.jum.2024.01.005>
- Setyowati, A., Pramono, B., & Sari, D. (2022). *Land conversion and seasonal flood risk in Makassar's watershed*. *Journal of Hydrology: Regional Studies*, 42, 101163. <https://doi.org/10.1016/j.ejrh.2022.101163>
- Sharma, P., Kumar, N., & Jain, V. (2020). *Climate change impacts on tropical hydrological systems*. *Climatic Change*, 163(3), 1235–1251. <https://doi.org/10.1007/s10584-020-02809-6>
- Shiferaw, B., Liu, C., & Wong, S. (2025). *Tropical ecohydrology and watershed sustainability: An emerging research frontier*. *Sustainability Science*, 20(2), 355–369. <https://doi.org/10.1007/s11625-024-01409-1>
- Silva, C., & Costa, L. (2024). *Nutrient pollution from agricultural intensification in tropical regions*. *Agriculture, Ecosystems & Environment*, 362, 108624. <https://doi.org/10.1016/j.agee.2024.108624>
- Singh, R., & Mehta, P. (2021). *Satellite-based land use classification and hydrological modeling*. *Geocarto International*, 36(21), 2356–2372. <https://doi.org/10.1080/10106049.2020.1776082>
- Sun, Q., Li, Y., & Zhao, W. (2024). *Global assessment of land use change and water quality deterioration*. *Science of the Total Environment*, 898, 165232. <https://doi.org/10.1016/j.scitotenv.2023.165232>
- Utomo, T., Wijanarko, R., & Kurniawan, E. (2021). *Urban land use change and surface water degradation in Indonesia*. *IOP Conference Series: Earth and Environmental Science*, 940, 012009. <https://doi.org/10.1088/1755-1315/940/1/012009>
- Wang, J., & Huang, L. (2023). *Remote sensing integration for multi-layer spatial analysis in watershed systems*. *Remote Sensing*, 15(14), 3571. <https://doi.org/10.3390/rs15143571>
- Wang, Q., & Silva, D. (2024). *Anthropogenic influences on tropical river water quality*. *Water Research*, 247, 120874. <https://doi.org/10.1016/j.watres.2024.120874>
- Wang, Y., Zhang, D., & Gao, S. (2023). *Geospatial monitoring of watershed land change using advanced GIS techniques*. *ISPRS Journal of Photogrammetry and Remote Sensing*, 198, 147–163. <https://doi.org/10.1016/j.isprsjprs.2023.01.012>

- Wuryanta, D., Nugraha, F., & Puspita, S. (2023). *Impact of vegetation loss on runoff coefficients in the Bengawan Solo watershed*. *Hydrological Research Letters*, 17(2), 112–123. <https://doi.org/10.3178/hrl.17.112>
- Yamada, T., & Saito, K. (2021). *Socioeconomic drivers of land transformation in tropical Asia*. *World Development*, 147, 105651. <https://doi.org/10.1016/j.worlddev.2021.105651>
- Yuliana, E., Prasetya, W., & Nugroho, I. (2024). *Data triangulation in environmental field research: Strengthening spatial reliability*. *Environmental Systems Research*, 13(1), 24. <https://doi.org/10.1186/s40068-024-00265-3>
- Zhang, X., Hu, J., & Feng, T. (2024). *Integrated watershed management and adaptive policy frameworks*. *Sustainability*, 16(8), 3312. <https://doi.org/10.3390/su16083312>