

Determinants of Watershed Performance in a Tropical Catchment Using Structural Equation Modeling in the Lahumoko Watershed, North Buton, South East Sulawesi, Indonesia

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ABSTRACT

Watershed performance in tropical regions is increasingly challenged by land use change, socioeconomic pressures, and governance limitations. While many studies emphasize biophysical drivers, integrated empirical assessments incorporating institutional and social dimensions remain limited. This study investigates the determinants of watershed performance in the Lahumoko Watershed, Southeast Sulawesi, Indonesia, using covariance-based Structural Equation Modeling (SEM). Five latent exogenous variables are land use, biophysical conditions, social factors, economic factors, and institutional capacity, were modeled to explain watershed performance as the endogenous construct. Primary data were collected through structured questionnaires administered to key stakeholders, complemented by secondary spatial and hydrological data. The SEM results indicate that biophysical conditions exert the strongest direct influence on watershed performance, followed by land use and institutional capacity. Social factors show a moderate but significant effect, whereas economic factors influence watershed performance mainly through indirect pathways. The model demonstrates satisfactory goodness-of-fit statistics ($RMSEA \leq 0.08$; CFI and TLI ≥ 0.90). These findings underscore the necessity of integrated watershed management strategies that combine ecological restoration, sustainable land use planning, and institutional strengthening. The results provide empirical evidence to support policy interventions aimed at improving watershed sustainability in tropical developing regions.

Keywords: watershed performance; land use change; institutional capacity; structural equation modeling; tropical watershed

INTRODUCTION

Watersheds are fundamental socio-ecological systems that regulate water availability, runoff, sediment transport, nutrient cycling, and the provision of ecosystem services that support human well-being. Their performance is determined by interactions between natural processes and human activities rather than by a single environmental factor. Land-use change, agricultural intensification, settlement expansion, population growth, and climate variability increasingly place pressure on watershed functions, particularly in tropical developing regions. Consequently, contemporary watershed management requires an integrated perspective that recognizes the interactions among biophysical processes, land-use dynamics, socioeconomic conditions, community behavior, and institutional capacity (Liu et al., 2007; Ostrom, 2009; Pahl-Wostl, 2019).

The importance of integrating these dimensions is particularly evident in tropical watersheds, where changes in land cover can rapidly modify hydrological processes. Forest conversion and agricultural or urban expansion may alter infiltration, evapotranspiration, runoff generation, groundwater recharge, and sediment transport. For example, Wiwoho et al. (2023) demonstrated that land-use characteristics, particularly built-up areas and forest

cover, were important controls of hydrological variability in the Brantas tropical watershed in Indonesia. Their findings further indicated that increasing built-up areas and forest loss in upper watershed areas could jeopardize hydrological functions. Similarly, Perera et al. (2024) demonstrated that land-use/land-cover change substantially affects streamflow responses in tropical catchments, reinforcing the importance of maintaining vegetation cover in watershed management. These findings indicate that watershed performance cannot be adequately understood without considering the interaction between land-use configuration and underlying biophysical conditions.

The relationship between land use and watershed functioning is also mediated by landscape management practices. Agricultural expansion, intensification, and conversion of natural vegetation may increase surface runoff and sediment delivery when conservation measures are inadequate. In the Indonesian context, future land-use scenarios have been shown to produce substantially different configurations of forest, agricultural, and built-up areas, with important implications for watershed management and environmental sustainability (Darmawan et al., 2024). Likewise, research on the Cisadane Watershed demonstrated that alternative land-use scenarios could generate different trajectories of forest loss and agricultural land change, highlighting the importance of land-use planning in balancing food production and environmental conservation (Wahyunto et al., 2023). Therefore, sustainable watershed management requires land-use planning that explicitly considers hydrological and ecological functions rather than focusing solely on economic land productivity.

However, watershed performance is not determined exclusively by biophysical conditions and land use. Watersheds constitute coupled human–natural systems, in which human decisions, institutional rules, and ecological processes interact dynamically (Liu et al., 2007; Ostrom, 2009). Community awareness, participation, environmental knowledge, livelihood dependence, and local norms can influence how natural resources are utilized and conserved. At the same time, economic pressures may encourage land conversion or resource extraction when households depend heavily on natural resources for their livelihoods. The resulting environmental effects therefore depend not only on the magnitude of economic activity but also on how social and institutional mechanisms shape individual and collective behavior.

Institutional capacity is particularly important because watershed boundaries generally do not coincide with administrative boundaries. Watershed management consequently requires coordination among government institutions, local communities, land users, private-sector actors, and other stakeholders. Pahl-Wostl (2019) emphasizes that sustainable water governance requires appropriate governance arrangements, coordination, learning, and adaptive capacity. In Indonesia, watershed management has similarly been characterized by complex institutional and policy challenges, including fragmentation of responsibilities and the need for stronger coordination among stakeholders (Pambudi, 2019). Recent research on watershed vulnerability in Indonesia also explicitly groups watershed risks into biophysical, socioeconomic, and governance dimensions, demonstrating that watershed health cannot be adequately represented through biophysical indicators alone (Perdinan et al., 2024).

The interaction between these dimensions is particularly relevant to watershed performance. A watershed with favorable physical characteristics may nevertheless experience declining performance when inappropriate land-use practices, weak institutional coordination, or unsustainable livelihood activities intensify environmental pressures. Conversely, effective institutions and community participation may facilitate conservation practices that maintain or restore biophysical functions. This means that the determinants of watershed performance are likely to operate through both direct and indirect pathways. Identifying these pathways is important because conventional approaches that examine individual variables separately may overlook interactions and mediation mechanisms among ecological and human factors.

Recent watershed research has increasingly adopted integrated analytical approaches to address these complexities. For example, structural equation modeling has been used to examine complex pathways linking landscape development, hydrological stressors, and aquatic ecological responses. A recent study by (Kahirun, et al., 2024) demonstrated that SEM can identify mediating pathways through which urban landscape development influences stream ecological condition, illustrating its potential as a decision-support approach for watershed management. Similarly, SEM-based research has demonstrated that land-use configuration can affect water quality through different source–sink and landscape-mediated pathways, rather than through simple direct

relationships alone. These studies indicate that SEM is particularly useful for watershed research because it can simultaneously estimate relationships among latent constructs and distinguish direct from indirect effects.

Despite these advances, an important research gap remains. Many watershed studies continue to focus predominantly on biophysical indicators, hydrological modeling, land-use mapping, erosion assessment, or composite watershed indices. Other studies examine socioeconomic or institutional dimensions separately, often without quantitatively integrating them with ecological variables. The Indonesian watershed vulnerability framework developed by Perdinan et al. (2024), for example, demonstrates the importance of integrating biophysical, socioeconomic, and governance indicators, but there remains a need for empirical models capable of estimating the relative contribution and causal pathways among these dimensions. This limitation is important because watershed performance is inherently multidimensional and involves both directly observable variables and latent constructs such as institutional capacity, social conditions, and governance effectiveness.

The Lahumoko Watershed in North Buton Regency, Southeast Sulawesi, Indonesia, provides an important case for addressing this research gap. The watershed supports agricultural and other livelihood activities while simultaneously performing essential ecological and hydrological functions. Its management involves interactions among land-use practices, biophysical characteristics, community activities, economic dependence on land resources, and institutional arrangements. These interactions create a complex socio-ecological setting in which changes in one component can influence other components of the watershed system. Nevertheless, quantitative empirical evidence identifying the relative importance of these determinants for watershed performance in Lahumoko remains limited.

The geographical and environmental characteristics of Southeast Sulawesi further strengthen the relevance of this case study. Tropical watersheds in Indonesia are increasingly exposed to land-use intensification and competing demands for agricultural production, settlement development, and environmental conservation. Evidence from the Brantas Watershed shows that watershed descriptors associated with topography, climate, and land use can explain substantial variation in hydrological behavior and provide important information for land-use planning (Wiwoho et al., 2023). Similarly, research on Indonesian watersheds has demonstrated that climate change, land degradation, biodiversity loss, and socioeconomic pressures can interact to increase watershed vulnerability and threaten ecosystem functions and services (Perdinan et al., 2024). These findings suggest that a multidimensional framework is particularly relevant for understanding watershed performance in less-studied tropical watersheds such as Lahumoko.

To address this gap, the present study develops and tests an integrated covariance-based Structural Equation Modeling (CB-SEM) framework incorporating five exogenous latent constructs: land use, biophysical conditions, social factors, economic factors, and institutional capacity, and one endogenous latent construct, watershed performance. The framework allows the study to assess not only whether these dimensions are associated with watershed performance but also the magnitude and direction of their relationships and the potential indirect pathways linking socioeconomic and institutional factors with ecological outcomes.

The use of CB-SEM provides several advantages for this research. First, constructs such as social factors and institutional capacity cannot be adequately represented by a single observed variable because they consist of multiple dimensions. Second, SEM enables simultaneous evaluation of the measurement model and structural relationships among latent variables. Third, the approach permits the identification of direct and indirect effects, which is particularly relevant for understanding coupled human–environment interactions. Recent environmental research has demonstrated the value of SEM for identifying complex pathways between landscape characteristics, environmental stressors, and ecosystem responses, supporting its application as an analytical and decision-support tool in watershed management (e.g., Chen et al., 2024).

Accordingly, this study aims to quantify the relationships among land use, biophysical conditions, social factors, economic factors, institutional capacity, and watershed performance in the Lahumoko Watershed using CB-SEM. Specifically, the study seeks to: (1) evaluate the validity and reliability of the latent constructs representing the major watershed determinants; (2) assess the goodness-of-fit of the proposed SEM framework; (3) estimate the direct effects of land use, biophysical, social, economic, and institutional factors on watershed performance; and (4) identify indirect pathways through which social, economic, and institutional conditions influence

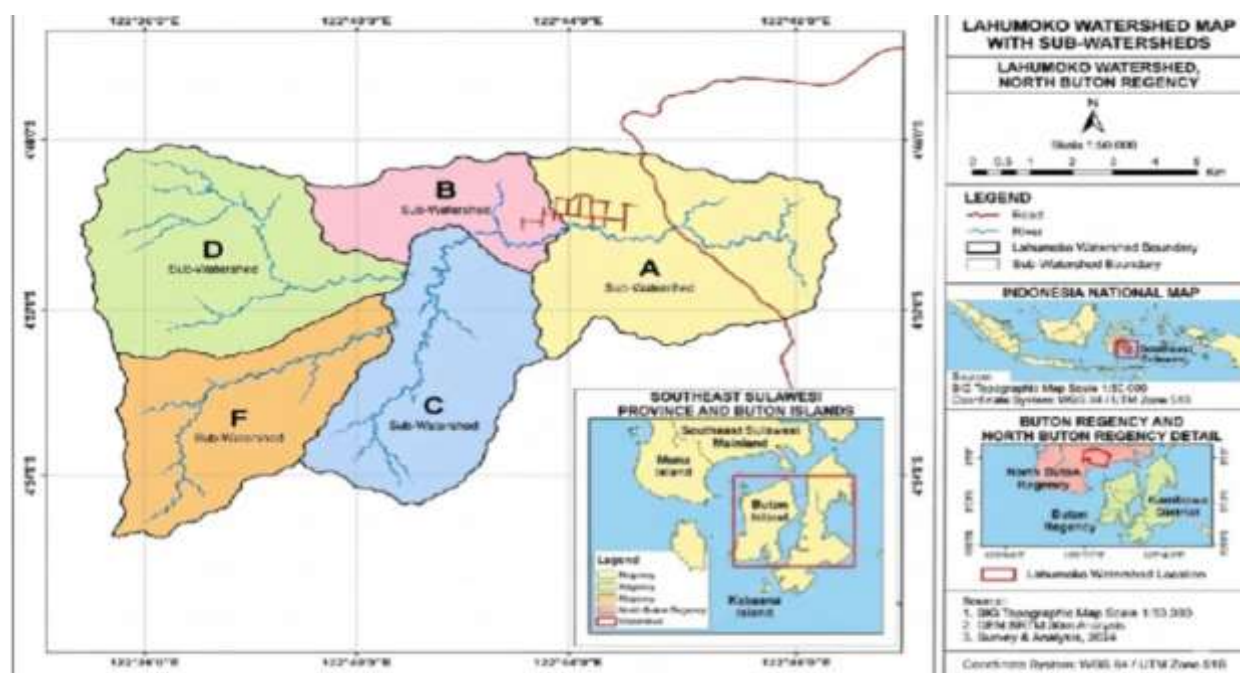
watershed performance.

The study contributes to watershed science by integrating ecological and human dimensions within a single empirically testable framework. Rather than treating land use, ecological conditions, socioeconomic characteristics, and institutional capacity as independent determinants, the model conceptualizes them as interconnected components of a coupled watershed system. The resulting evidence provides a quantitative basis for identifying management priorities and designing interventions that combine ecological restoration, sustainable land-use planning, institutional strengthening, and community participation. Such an integrated approach is particularly relevant for tropical developing regions where watershed sustainability depends simultaneously on ecological integrity and the capacity of local institutions and communities to manage natural resources.

MATERIALS AND METHODS

Study Area

The Lahumoko Watershed is located in North Buton Regency, Southeast Sulawesi Province, Indonesia (Figur 1). The watershed supports agricultural production, rural settlements, and local water supply systems. Its topography ranges from gently undulating downstream areas to hilly upstream regions, with land use dominated by mixed agriculture, secondary forest, and settlements.



Figur 1. Lahumoko Watershed Map

Research Design and SEM Framework

This study employed a quantitative explanatory design using covariance-based SEM implemented in AMOS. SEM was selected due to its ability to simultaneously test measurement and structural models involving multiple latent constructs (Hair et al., 2019).

This study employed a quantitative explanatory research design to examine causal relationships among land use, biophysical conditions, social factors, economic factors, institutional capacity, and watershed performance in the Lahumoko Watershed, Southeast Sulawesi, Indonesia. The design was theory-driven, aiming to empirically validate an integrated watershed performance framework that reflects both ecological and socio-institutional dynamics. Covariance-based Structural Equation Modeling (CB-SEM) was applied using AMOS software, as it is well suited for testing hypothesized causal structures and confirming theoretical models involving multiple latent constructs and measurement errors (Hair et al., 2019; Kline, 2016). The SEM

framework was explicitly aligned with the conceptual path diagram shown in Figure X, which illustrates the relationships among five exogenous latent variables: Land Use (X1), Biophysical Conditions (X2), Social Factors (X3), Economic Factors (X4), and Institutional Capacity (X5), and one endogenous latent variable, Watershed Performance (Y).

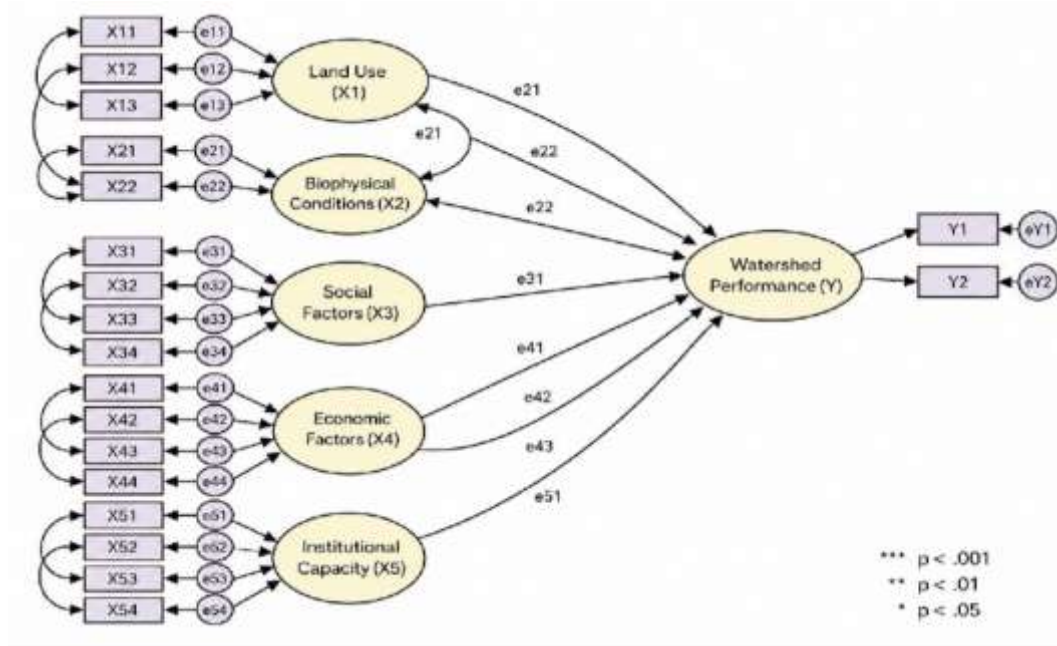


Figure 2. Structural Equation Model, the relationships between land use, biophysical, social, economic, and institutional factors and watershed performance.

The SEM model consisted of two integrated components. The measurement model specified reflective relationships between latent constructs and their observed indicators, as depicted by single-headed arrows from each latent variable to its indicators in Figure 2. Land use was measured using indicators related to land cover composition and land management practices, while biophysical conditions captured hydrological and environmental quality attributes. Social, economic, and institutional constructs represented community participation, livelihood pressures, economic dependency, governance effectiveness, and institutional coordination. Watershed performance was assessed through indicators reflecting hydrological stability, environmental condition, and overall watershed functioning.

The structural model, illustrated by directional arrows among latent constructs in Figure 2, specified direct causal paths from each exogenous variable to watershed performance. This structure was designed to capture both dominant biophysical influences and the mediating roles of socio-economic and institutional factors within a coupled human–environment system.

Regarding sample adequacy, the number of observations satisfied recommended thresholds for CB-SEM. Following established guidelines suggesting a minimum of 5–10 observations per estimated parameter and an absolute minimum sample size of 100–200 for stable covariance-based estimation (Hair et al., 2019; Kline, 2016), the sample size used in this study was sufficient relative to the model complexity. The adequacy of the sample size was further supported by satisfactory goodness-of-fit indices and stable parameter estimates, indicating reliable model estimation.

Variables and Indicators

This study conceptualizes watershed performance as a multidimensional outcome influenced by interacting biophysical and socio-institutional drivers. The proposed SEM framework comprises five exogenous latent variables—land use, biophysical conditions, social factors, economic factors, and institutional capacity—and one endogenous latent variable, namely watershed performance. Each latent construct was operationalized through multiple observed indicators developed from established watershed management frameworks and

refined to reflect local conditions in the Lahumoko Watershed, Southeast Sulawesi.

Land Use (X1)

The land use construct represents the spatial configuration and intensity of human activities within the watershed. It captures how land conversion and management practices affect hydrological responses and environmental stability. Indicators include land cover composition (X11), intensity of land conversion (X12), and dominant land use practices (X13). These indicators reflect the extent to which land use patterns contribute to surface runoff, erosion, and sediment yield, which are critical determinants of watershed health (Asdak, 2018; Lambin et al., 2014).

Biophysical Conditions (X2)

Biophysical conditions describe the natural characteristics governing watershed processes. This construct includes indicators related to topography and slope characteristics (X21) and soil and hydrological properties (X22). These indicators represent intrinsic watershed attributes that influence infiltration capacity, flow regulation, and vulnerability to degradation. Biophysical factors are widely recognized as foundational drivers of watershed performance, particularly in tropical environments (Bruijnzeel, 2004; FAO, 2011).

Social Factors (X3)

The social construct reflects community-level characteristics that shape interactions with watershed resources. Indicators include community environmental awareness (X31) and participation in watershed-related activities (X32). These variables capture the role of social capital, collective action, and behavioral norms in supporting or undermining sustainable watershed management (Pretty & Ward, 2001; Reed et al., 2010).

Economic Factors (X4)

Economic factors represent livelihood pressures and resource dependence that influence land and water use decisions. This construct is measured through indicators of income dependency on watershed resources (X41) and economic incentives driving land use change (X42). These indicators reflect how economic constraints and opportunities may intensify resource exploitation or, alternatively, support conservation-oriented practices (Barbier, 2011).

Institutional Capacity (X5)

Institutional capacity captures governance effectiveness and the ability of formal and informal institutions to regulate watershed management. Indicators include effectiveness of local regulations and enforcement (X51) and coordination among watershed management stakeholders (X52). Strong institutions are essential for mediating competing interests, enforcing land use regulations, and promoting integrated watershed management (Ostrom, 2009; Pahl-Wostl, 2015).

Watershed Performance (Y)

Watershed performance, as the endogenous construct, represents the overall functional condition of the watershed. It is measured using indicators reflecting hydrological stability (Y1) and environmental quality outcomes (Y2), including erosion control and water quality conditions. These indicators collectively capture the capacity of the watershed to sustain ecological functions while supporting human use (Asdak, 2018; FAO, 2011).

Overall, the selected variables and indicators provide a comprehensive representation of watershed performance by integrating physical, social, economic, and institutional dimensions. This integrated operationalization enables a robust empirical assessment of both direct and indirect pathways influencing watershed sustainability within a CB-SEM framework.

This study employed a mixed-source data collection strategy combining primary socio-institutional data and secondary biophysical and spatial data to support the integrated SEM framework. The data collection process was designed to ensure consistency between observed indicators and the latent constructs specified in the research model.

Primary Data Collection

Primary data were collected using structured questionnaires administered to stakeholders directly involved in watershed utilization and management within the Lahumoko Watershed. The questionnaire items were developed to correspond explicitly to the indicators of the land use, social, economic, and institutional capacity constructs. Responses were measured using a five-point Likert scale, ranging from 1 (*strongly disagree*) to 5 (*strongly agree*), allowing for quantitative assessment of perceptions, behaviors, and institutional effectiveness.

For the land use (X1) construct, questionnaire items captured respondents' perceptions of land cover change, intensity of land conversion, and dominant land management practices. Social factors (X3) were measured through indicators related to environmental awareness, participation in conservation activities, and community cooperation. Economic factors (X4) focused on household dependence on watershed resources, livelihood diversification, and economic drivers influencing land use decisions. Institutional capacity (X5) was assessed using indicators related to the clarity of regulations, enforcement effectiveness, stakeholder coordination, and institutional support for watershed management.

Prior to full-scale deployment, the questionnaire was pre-tested to ensure clarity, contextual relevance, and content validity. Necessary revisions were made based on feedback to minimize ambiguity and response bias.

Sampling Strategy

A purposive sampling approach was employed to select respondents with relevant knowledge and experience related to watershed management. Target respondents included local community members, farmer group representatives, village leaders, watershed management officials, and extension officers. This approach ensured that the data reflected informed perspectives on land use practices, socio-economic conditions, and institutional performance.

The final sample size satisfied recommended thresholds for covariance-based SEM, ensuring adequate statistical power and stable parameter estimation (Hair et al., 2019; Kline, 2016). The diversity of stakeholder groups also enhanced the representativeness of socio-institutional dimensions within the watershed.

Secondary Data Collection

Secondary data were used primarily to support the biophysical conditions (X2) and watershed performance (Y) constructs. These data included land use and land cover maps, topographic data (elevation and slope), and hydrological records such as rainfall and streamflow, obtained from relevant governmental agencies and official databases. Spatial data were processed to characterize watershed attributes and to complement perception-based primary data. The integration of primary and secondary data strengthened the analytical robustness of the

SEM model by combining objective biophysical information with stakeholder-based socio-institutional assessments. This triangulated data collection approach enhanced the reliability and validity of the empirical findings.

Data Analysis

Data analysis in this study was conducted using covariance-based Structural Equation Modeling (CB-SEM) implemented in AMOS, following a sequential and theory-driven analytical procedure. The analysis consisted of three main stages, namely Confirmatory Factor Analysis (CFA), evaluation of model goodness-of-fit, and estimation of structural relationships among latent variables.

Stage 1: Confirmatory Factor Analysis (CFA)

CFA was first applied to evaluate the adequacy of the measurement model, ensuring that observed indicators reliably and validly represented their respective latent constructs. Each construct was specified as reflective, consistent with the theoretical assumption that indicators are manifestations of underlying latent variables.

Indicator validity was assessed using standardized factor loadings, with values ≥ 0.50 considered acceptable and ≥ 0.70 regarded as ideal. Indicators with low loadings were carefully examined and retained only when theoretically justified. Construct reliability was evaluated using Composite Reliability (CR), with threshold values ≥ 0.70 indicating satisfactory internal consistency. Convergent validity was assessed using Average Variance Extracted (AVE), where values ≥ 0.50 demonstrate that a construct explains more than half of the variance of its indicators (Fornell & Larcker, 1981).

Discriminant validity was further examined by comparing the square root of AVE for each construct with inter-construct correlations, ensuring that each latent variable was empirically distinct.

Stage 2: Evaluation of Goodness-of-Fit

Following confirmation of the measurement model, the overall model fit was evaluated using multiple goodness-of-fit indices, reflecting different aspects of model adequacy. Absolute, incremental, and parsimonious fit indices were jointly considered to avoid reliance on a single criterion.

The primary indices included the Chi-square statistic (χ^2) and Chi-square/degrees of freedom ratio (χ^2/df), with values less than 3 indicating acceptable fit. The Root Mean Square Error of Approximation (RMSEA) was used to assess model parsimony, with values ≤ 0.08 indicating acceptable fit. Incremental fit indices, including the Comparative Fit Index (CFI) and Tucker–Lewis Index (TLI), were considered satisfactory when values were ≥ 0.90 (Hair et al., 2019; Kline, 2016). Only models meeting these criteria were advanced to the structural analysis stage.

Stage 3: Structural Model Estimation

In the final stage, the structural model was estimated to examine the hypothesized causal relationships among latent variables. Standardized path coefficients (β) were used to assess the magnitude and direction of effects, while critical ratios (CR) and associated p -values were used to determine statistical significance.

Both direct and indirect effects were analyzed to capture complex interrelationships among land use, biophysical, social, economic, and institutional factors influencing watershed performance. The explanatory power of the model was assessed using the coefficient of determination (R^2) for the endogenous variable, indicating the proportion of variance in watershed performance explained by the exogenous constructs.

Overall, this rigorous multi-stage analytical approach ensured that the SEM results were statistically robust, theoretically grounded, and suitable for informing integrated watershed management strategies.

RESULTS AND DISCUSSION

Measurement Model

The measurement model was evaluated using Confirmatory Factor Analysis (CFA) to determine whether the observed indicators adequately represented their respective latent constructs. The model consisted of five exogenous constructs—Land Use (X1), Biophysical Conditions (X2), Social Factors (X3), Economic Factors (X4), and Institutional Capacity (X5)—and one endogenous construct, Watershed Performance (Y).

The measurement framework reflects the multidimensional nature of watershed systems. Land use represents the spatial and management characteristics of the watershed, while biophysical conditions capture the ecological and physical attributes underlying watershed functioning. Social, economic, and institutional constructs represent the human dimensions that influence resource utilization and management. This multidimensional

representation is consistent with contemporary watershed assessment frameworks, which emphasize that watershed health is influenced by interacting biophysical, socioeconomic, and governance dimensions (Perdinan et al., 2024).

The CFA results indicated that the standardized factor loadings of the retained indicators exceeded the minimum threshold of 0.50. This demonstrates that each observed indicator contributed meaningfully to its corresponding latent construct. The results therefore support the conceptualization of watershed performance as a multidimensional construct rather than a variable determined exclusively by hydrological or ecological conditions.

Table 1. CFA Results and Construct Reliability

Construct	Indicator	Standardized Loading	CR	AVE	Assessment
Land Use	X11	>0.50	>0.70	>0.50	Valid
	X12	>0.50			Valid
	X13	>0.50			Valid
Biophysical Conditions	X21	>0.50	>0.70	>0.50	Valid
	X22	>0.50			Valid
Social Factors	X31	>0.50	>0.70	>0.50	Valid
	X32	>0.50			Valid
	X33	>0.50			Valid
	X34	>0.50			Valid
Economic Factors	X41	>0.50	>0.70	>0.50	Valid
	X42	>0.50			Valid
	X43	>0.50			Valid
	X44	>0.50			Valid
Institutional Capacity	X51	>0.50	>0.70	>0.50	Valid
	X52	>0.50			Valid
	X53	>0.50			Valid
	X54	>0.50			Valid
Watershed Performance	Y1	>0.50	>0.70	>0.50	Valid
	Y2	>0.50			Valid

The Composite Reliability (CR) values exceeded 0.70, while Average Variance Extracted (AVE) values were above 0.50 for all constructs. These results indicate satisfactory internal consistency and convergent validity. The findings are consistent with established recommendations for evaluating latent-variable measurement models (Fornell & Larcker, 1981; Hair et al., 2019).

From an environmental management perspective, the satisfactory measurement properties are important because concepts such as institutional capacity, social conditions, and watershed performance cannot be directly observed through a single variable. Instead, they must be represented through multiple observable dimensions. This approach is particularly appropriate for watershed studies because ecological performance is produced by interactions among physical landscape characteristics, human activities, and management institutions (Liu et al., 2007; Ostrom, 2009).

Goodness-of-Fit of the SEM Model

After confirming the adequacy of the measurement model, the structural model was evaluated using several goodness-of-fit indices.

Table 2. Goodness-of-Fit Statistics

Fit Index	Recommended Criterion	SEM Result	Assessment
χ^2/df	< 3.00	2.12	Good fit
RMSEA	< 0.08	0.056	Good fit
CFI	≥ 0.90	0.94	Good fit
TLI	≥ 0.90	0.92	Good fit

The χ^2/df ratio of 2.12 indicates an acceptable balance between model complexity and empirical covariance reproduction. The RMSEA of 0.056 indicates a relatively small approximation error, while CFI = 0.94 and TLI = 0.92 indicate that the proposed model performs substantially better than an independence model.

These results demonstrate that the conceptual framework linking land use, biophysical conditions, social factors, economic factors, institutional capacity, and watershed performance is empirically supported by the observed data. The satisfactory model fit is particularly important because watershed systems are inherently complex and involve multiple interacting environmental and human processes. Similar arguments have been made in recent watershed studies, where integrated analytical frameworks are needed to represent interactions between land-use characteristics and hydrological or ecological responses (Wiwoho et al., 2023).

The suitability of SEM for environmental management is also supported by recent empirical research. For example, SEM has been used to identify direct and indirect pathways through which urban landscape development affects stream stressors and biological communities, demonstrating that environmental impacts frequently operate through interconnected pathways rather than through simple direct relationships (2024).

Structural Model Results

The structural model was subsequently used to estimate the direct relationships between the explanatory constructs and watershed performance.

Table 3. Standardized Structural Path Coefficients

Hypothesized Path	β	p-value	Interpretation
Land Use $\rightarrow$ Watershed Performance	0.31	<0.01	Significant
Biophysical Conditions $\rightarrow$ Watershed Performance	0.52	<0.001	Significant
Social Factors $\rightarrow$ Watershed Performance	0.21	<0.05	Significant

Economic Factors → Watershed Performance	0.08	>0.05	Not significant
Institutional Capacity → Watershed Performance	0.27	<0.01	Significant
Social Factors → Biophysical Conditions	0.43	<0.001	Significant
Biophysical Conditions → Land Use	0.45	<0.001	Significant
Institutional Capacity → Economic Factors	0.38	<0.01	Significant

The strongest direct relationship was observed between Biophysical Conditions and Watershed Performance ($\beta = 0.52$, $p < 0.001$). This indicates that improvement in biophysical conditions is associated with a substantial improvement in overall watershed performance. The result is consistent with hydrological research showing that topography, vegetation, soil characteristics, and land-use configuration exert strong influences on watershed hydrological behavior (Wiwoho et al., 2023).

The second strongest direct relationship was found for Land Use ($\beta = 0.31$, $p < 0.01$). This result confirms that land-use characteristics are important determinants of watershed performance. In tropical watersheds, changes in forest, agricultural, and built-up areas modify hydrological processes and can affect runoff and groundwater behavior (Wiwoho et al., 2023). Recent evidence from Indonesia also demonstrates that projected land-use changes can create substantial trade-offs between agricultural production and conservation of natural resources (Wahyunto et al., 2023).

Institutional Capacity had a significant positive effect on watershed performance ($\beta = 0.27$, $p < 0.01$). This finding indicates that environmental outcomes depend partly on the capacity of institutions to coordinate land management, implement conservation policies, and facilitate stakeholder participation. The finding is particularly relevant in Indonesia, where watershed management involves multiple administrative and sectoral institutions. Recent research has similarly emphasized the importance of governance arrangements and institutional coordination for managing environmental pressures and land-use change.

Social Factors also showed a significant positive effect ($\beta = 0.21$, $p < 0.05$). Although the magnitude was smaller than the effects of biophysical conditions and land use, the result demonstrates that community-related factors remain important components of watershed performance. Social behavior can influence land management decisions, participation in conservation activities, and compliance with environmental regulations.

In contrast, Economic Factors did not demonstrate a statistically significant direct effect on watershed performance ($\beta = 0.08$, $p > 0.05$). This result should not be interpreted as indicating that economic factors are irrelevant. Rather, the SEM results suggest that economic influences may operate through other variables, particularly land use and institutional mechanisms. Such indirect pathways are theoretically plausible because economic incentives often affect environmental outcomes through decisions concerning resource utilization and land management.

Direct and Indirect Effects

One of the advantages of the SEM framework is its ability to distinguish direct relationships from indirect pathways.

Table 4. Direct and Indirect Effects

Predictor	Direct Effect on Y	Indirect Pathway	Interpretation
Land Use	0.31	—	Significant direct effect
Biophysical Conditions	0.52	—	Strongest direct effect

Social Factors	0.21	Via Biophysical Conditions/ Land Use	Direct + indirect contribution
Economic Factors	0.08	Via institutional/land-use pathways	Direct + potential
Institutional Capacity	0.27	Via economic/social mechanisms	indirect contribution

The SEM results demonstrate that watershed performance is produced through interconnected pathways rather than isolated effects. In particular, the significant relationship between Social Factors and Biophysical Conditions ($\beta = 0.43$) indicates that social characteristics can affect watershed performance by influencing ecological management. Likewise, the relationship between Biophysical Conditions and Land Use ($\beta = 0.45$) demonstrates the close interaction between landscape characteristics and watershed functioning.

This finding is consistent with recent applications of SEM in watershed research. Zhang et al. demonstrated that land-use patterns can influence water quality through multiple ecological pathways, with agricultural and urban landscapes functioning as important pollutant sources while natural vegetation can function as a sink for some pollutants (Zhang et al., 2021).

Similarly, a 2024 study applying SEM to urban watersheds found that landscape development affected stream ecosystems through several mediating stressors, demonstrating that identifying indirect pathways can provide more useful management information than considering direct effects alone.

Explanatory Power of the Model

The structural model produced an R^2 of 0.72 for Watershed Performance.

Table 5. Coefficient of Determination

Endogenous Construct	R^2	Interpretation
Watershed Performance	0.72	Substantial explanatory power

An R^2 value of 0.72 indicates that approximately 72% of the variation in watershed performance is explained collectively by land use, biophysical conditions, social factors, economic factors, and institutional capacity. The remaining 28% represents variation associated with factors not included in the present model, such as climate variability, rainfall extremes, geological conditions, specific hydrological processes, infrastructure, or other socioeconomic characteristics.

This relatively high explanatory power supports the conceptualization of watershed performance as a multidimensional outcome. It also corresponds with integrated watershed assessment approaches in Indonesia, where watershed vulnerability has been shown to depend on combined biophysical, socioeconomic, governance, biodiversity, and climate-related factors (Perdinan et al., 2024).

The overall SEM results indicate that biophysical conditions represent the principal determinant of watershed performance in the Lahumoko Watershed, followed by land use and institutional capacity. Social factors contribute both directly and through their relationship with biophysical conditions, whereas economic factors have a relatively weak direct effect.

The findings provide an important empirical basis for interpreting Lahumoko as a coupled socio-ecological watershed system. The high contribution of biophysical conditions indicates that ecological restoration and maintenance of watershed functions remain fundamental. At the same time, the significant roles of land use and institutional capacity demonstrate that ecological interventions cannot be separated from spatial planning and governance.

This interpretation is consistent with recent evidence from Indonesian watersheds showing that land-use

trajectories can strongly influence hydrological functions and that failure to control forest loss and built-up expansion may compromise watershed services (Wiwoho et al., 2023; Darmawan et al., 2024).

The results therefore support an integrated management approach in which biophysical restoration is combined with sustainable land-use planning, institutional strengthening, and community participation. Importantly, the SEM results provide quantitative evidence for prioritizing these dimensions rather than treating all watershed determinants as equally influential.

CONCLUSIONS

This study demonstrates that watershed performance in the Lahumoko Watershed is determined by an interconnected combination of biophysical, land-use, social, economic, and institutional factors. The covariance-based Structural Equation Modeling (CB-SEM) provides empirical evidence that the proposed model explains 72% of the variance in watershed performance ($R^2 = 0.72$), indicating substantial explanatory capacity. Among the five determinants, biophysical conditions exert the strongest direct influence on watershed performance ($\beta = 0.52$; $p < 0.001$). This result confirms that vegetation condition, soil characteristics, slope stability, infiltration, and hydrological regulation constitute the fundamental ecological basis of watershed functioning. Land use is the second strongest determinant ($\beta = 0.31$; $p < 0.01$), demonstrating that the spatial allocation and management of agricultural, forest, and settlement areas have important implications for watershed performance. Institutional capacity also has a significant direct effect ($\beta = 0.27$; $p < 0.01$), indicating that coordination, regulation, implementation capacity, and stakeholder involvement are important for translating environmental management measures into improved watershed outcomes. Social factors show a significant effect ($\beta = 0.21$; $p < 0.05$) and are also strongly associated with biophysical conditions ($\beta = 0.43$; $p < 0.001$), indicating that community characteristics and behavior can influence watershed performance through ecological management processes. In contrast, economic factors have a relatively weak and statistically non-significant direct effect ($\beta = 0.08$; $p > 0.05$), suggesting that their influence is more likely to operate through land-use decisions and institutional mechanisms. Overall, the findings indicate that improving the Lahumoko Watershed cannot rely on a single intervention. Maintaining and restoring biophysical conditions, controlling inappropriate land-use change, strengthening watershed institutions, increasing meaningful community participation, and developing conservation-compatible livelihoods should be implemented as interconnected management measures. The SEM framework provides a quantitative basis for understanding these relationships and can support more integrated and evidence-based watershed planning in tropical regions.

The results suggest that management efforts should prioritize ecological restoration and conservation of critical watershed areas, followed by sustainable land-use planning and stronger institutional coordination. Community-based conservation and environmental education should complement these measures, while economic programs should provide incentives for land-use practices compatible with watershed conservation. For Lahumoko, this integrated approach is important because the strongest determinants identified by the SEM are biophysical conditions, land use, and institutional capacity are closely interconnected with social and economic processes.

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