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Flood Management Study in The Upper Kuncir River: Hydrological Analysis and Watershed Conservation

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Abstract

Flooding in the Upper Kuncir River, Nganjuk Regency, is an annual issue causing environmental degradation, infrastructure damage, and economic losses. Increased runoff, erosion, and sedimentation have worsened flood risks due to deforestation and land-use changes. This study analyzes flood factors and conservation strategies through hydrological modeling (HEC-RAS), GIS-based erosion analysis, and watershed simulations. Findings show that high soil erosion (50-80 tons/ha/year) and sediment inflow (18,500 m³ annually) have reduced river capacity by 15%. Peak discharge for a 25-year return period is 125.905 m³/s, exceeding the river's 85.4 m³/s capacity. Check dams, reforestation, and river normalization are proposed to reduce runoff and control sedimentation. Simulations indicate that structural (check dams, river widening) and non-structural (vegetative cover, soil conservation) measures can reduce peak discharge by 50%. Adaptive reservoir operations at Margopatut Dam can enhance flood control. Integrated watershed management combining engineering and ecohydrological solutions is recommended to ensure sustainable flood mitigation

Keywords: Flood; HEC-RAS; Sediment Control; Upper Kuncir River; Watershed Conservation.

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1. Introduction

Flooding is one of the most frequent hydrological disasters caused by both natural and anthropogenic factors. Changes in land use, increased rainfall intensity, and insufficient watershed management contribute to higher flood risks. The Upper Kuncir River, located in Nganjuk Regency, experiences seasonal flooding, adversely affecting agriculture, infrastructure, and community livelihoods (Santoso et al., 2021).

Hydrological disasters like floods are often intensified by climate variability, deforestation, and improper land-use practices. Studies have shown that extreme weather events, including intense rainfall due to climate change, have increased the frequency and magnitude of floods in Indonesia (Nugroho et al., 2022). Additionally, unregulated urban expansion and deforestation in upstream areas contribute to reduced soil infiltration and increased surface runoff, exacerbating flood hazards (Abidin et al., 2020; Yusifov et al., 2020).

The Kuncir watershed has diverse topographic characteristics with varying slopes. Its geological composition includes andosol, grumosol, latosol, and regosol soil types, which have different permeability levels, influencing infiltration and runoff rates (Widyaningrum et al., 2019). High rainfall intensity, coupled with an inadequate drainage system, often results in the river exceeding its capacity during the rainy season (Liu et al., 2018). Furthermore, excessive sedimentation caused by erosion in the upstream area leads to a decline in riverbed capacity, increasing flood susceptibility (Setiawan et al., 2021).

Previous studies have indicated that land-use changes from forests to intensive agricultural areas significantly increase surface runoff and soil erosion (Chang et al., 2024). Agricultural expansion without proper conservation techniques

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leads to soil degradation, decreasing water retention capacity and intensifying flood risks (Lal, 2001). Research conducted in the Brantas watershed by Setiawan et al. (2021) confirmed that forest-to-plantation conversion without soil and water conservation measures led to a 40% increase in peak flood discharge. Similarly, the impact of poor watershed management in other regions of Southeast Asia has been found to accelerate flooding due to rapid land-use changes and deforestation (Dadson et al., 2017).

On a global scale, watershed conservation strategies have gained recognition as effective flood mitigation measures. Studies in China's Loess Plateau highlight the success of ecohydrology-based approaches, such as reforestation and green infrastructure development, in reducing flood risks by enhancing infiltration capacity and decreasing runoff rates (Huang et al., 2020). In Europe, integrated flood management approaches that combine engineering solutions with nature-based strategies have been effective in improving flood resilience (Falkenmark, 2003).

Given the importance of sustainable water management, this study aims to identify the primary causes of flooding in the Upper Kuncir River and propose mitigation strategies based on ecohydrology and watershed conservation. The findings of this study are expected to serve as a foundation for sustainable water resource management planning and support the development of green infrastructure in the region. Additionally, the study will provide insights into the potential application of adaptive flood control measures in similar watersheds across Indonesia, promoting long-term resilience to hydrological disasters.

2. Method

This study employs a quantitative and qualitative approach to analyze the causes of flooding and evaluate mitigation strategies. The research methods include data collection, hydrological and hydraulic analysis, sedimentation assessment, optimization simulation of the Margopatut Dam, and watershed conservation evaluation. The following steps were conducted:

2.1. Data Collection

The study utilizes both primary and secondary data sources to ensure comprehensive analysis:

Hydrological Data: Daily rainfall data and river discharge records from the Meteorology, Climatology, and Geophysics Agency (BMKG) and the Brantas River Basin Organization. Geospatial and Land Use Data: Satellite imagery from Landsat, Digital Elevation Models (DEM), and land-use maps analyzed using Geographic Information Systems (GIS) (Li et al., 2019). Soil Characteristics: Soil permeability, texture, and erodibility data collected from field surveys and laboratory analysis. Community Interviews and Stakeholder Consultation: To gather insights on flood occurrences, risk perception, and existing mitigation efforts (Yamamoto et al., 2021).

2.2. Hydrological and Hydraulic Analysis

Rainfall Frequency Analysis: The Generalized Extreme Value (GEV) method was used to determine design rainfall intensity (Coles et al., 2001). Flood Discharge Estimation: The Log Pearson Type III and Rational methods were applied to estimate peak discharge events (Stedinger, 1993). Flood Simulation Modeling: HEC-RAS was used to assess the river's flood-carrying capacity and to model different flood scenarios (Brunner, 2002). Runoff Coefficient Assessment: The impact of land-use changes on runoff characteristics was evaluated using hydrological models.

2.3. Erosion and Sedimentation Analysis

Soil Erosion Estimation: The Universal Soil Loss Equation (USLE) model was applied to quantify soil loss rates based on rainfall erosivity, soil erodibility, slope, and land use (Wischmeier & Smith, 1978). Sediment Transport Modeling: The impact of sediment movement on river capacity and dam performance was assessed using sediment transport equations and GIS analysis (Morgan, 2005). Reservoir Sedimentation Assessment: The rate of sedimentation in the Margopatut Dam was calculated to determine its impact on long-term reservoir functionality (Seno, 2013).

2.4. Margopatut Dam Optimization Simulation

Dam Feasibility Review: The study incorporated findings from the Margopatut Dam feasibility study to evaluate its effectiveness in flood mitigation (Bappeda, 2024). Reservoir Operations Modeling: HEC-ResSim software was utilized to simulate different reservoir management scenarios and their impact on reducing flood peaks (USACE, 2015). Adaptive Reservoir Management: Scenarios including controlled water release and real-time monitoring systems were tested to optimize dam operation during extreme rainfall events.

2.5. Watershed Conservation Strategy Evaluation

Effectiveness of Conservation Measures: Comparative analysis of different conservation techniques, including check dams, reforestation, and agroforestry (Chang et al., 2024). Scenario Analysis: Evaluation of watershed conditions under various intervention scenarios, such as land restoration, afforestation, and infrastructure improvements (Lal, 2001). Implementation Feasibility: Assessment of financial and institutional feasibility for conservation projects based on local policies and community engagement (Supangat et al., 2021). Impact of Land Use Changes: Evaluating the long-term effects of land management practices on flood reduction and soil stability.

2.6. Model Validation and Sensitivity Analysis

The validation process was conducted by comparing simulated flood discharges with historical flood records over the past ten years. The Nash-Sutcliffe Efficiency (NSE) score of 0.85 confirms the model's high accuracy, while the Root Mean Square Error (RMSE) and Coefficient of Determination ($R^2 = 0.92$) indicate strong correlation between observed and simulated values. These metrics demonstrate the model's reliability in predicting flood events.

A comprehensive sensitivity analysis was performed to assess the influence of hydrological parameters on flood severity. Key findings indicate that a 10% increase in rainfall results in an 18% rise in peak discharge, while reduced Soil Infiltration capacity due to land degradation increases runoff by 30%. Additionally, sediment accumulation has led to a 15% reduction in river channel capacity, exacerbating flood risks. These insights highlight the importance of land conservation measures in mitigating flood hazards.

Validation: The hydrological model was validated using historical flood data over the past 10 years, with accuracy assessed through the Nash-Sutcliffe Efficiency (NSE) coefficient (Moriasi et al., 2007). Statistical Metrics: Root Mean Square Error (RMSE) and Coefficient of Determination (R^2) were used to verify model reliability. Sensitivity Analysis: Key hydrological and land-use parameters were tested to identify their influence on flood peaks and conservation effectiveness (Dadson et al., 2017). Climate Change Impact Assessment: Evaluating potential future shifts in flood frequency under changing precipitation patterns.

This methodological approach provides a comprehensive assessment of flood dynamics in the Upper Kuncir River and supports the development of integrated flood mitigation solutions.

3. Results and Discussion

This section presents the findings of the hydrological analysis, erosion and sedimentation assessment, dam optimization simulations, and watershed conservation evaluation. The results provide insights into the flood dynamics in the Upper Kuncir River and the effectiveness of proposed mitigation measures.

3.1. Hydrological Analysis

Rainfall data analysis from BMKG indicates that the Upper Kuncir River basin receives an annual average precipitation of 2,100 mm, with peak rainfall occurring from December to February. These months account for over 60% of the total annual precipitation, significantly increasing the flood risk. Analysis of long-term rainfall trends suggests an increasing frequency of extreme rainfall events, which aligns with findings in other tropical watersheds where climate change has led to higher rainfall intensities and more frequent flood events (Chang et al., 2024).

Extreme rainfall events are identified as a key driver of flooding, with a 50-year return period rainfall event reaching 150 mm/day (Kurniadi et al., 2021). Additionally, a 100-year return period event is projected to reach 180 mm/day, indicating a potential increase in flood severity under future climate conditions. The Rainfall-Runoff Analysis confirms that these extreme precipitation events produce significant surface runoff due to limited infiltration capacity in the watershed's steep terrain and clayey soils (Azizah et al., 2022).

Flood peak discharge modeling using the Log Pearson III method estimated that a 25-year return period flood event generates a peak discharge of 125.905 m^3/s, which exceeds the river's capacity of 85.4 m^3/s, leading to overflow and flooding (Brunner, 2002). Furthermore, for a 50-year return period flood event, the peak discharge is projected to increase to 150.432 m^3/s, exacerbating flood risks in low-lying areas.

The HEC-RAS model simulation confirmed that the river's current drainage system is inadequate for managing high runoff volumes, with flood-prone areas identified along the midstream and downstream segments, particularly in agricultural and residential zones (Kim et al., 2020). The model output indicated that floodwater depths could reach up to 2.5 meters in the most vulnerable areas, particularly where natural floodplains have been converted into urban or agricultural land without adequate drainage infrastructure.

Further analysis of infiltration rates in different land-use types showed that:

- Forested areas have an average infiltration rate of 30-40 mm/hour, significantly reducing surface runoff.
- Agricultural lands exhibit moderate infiltration rates of 15-25 mm/hour, depending on soil conditions and crop type.
- Urbanized areas have the lowest infiltration capacity, with rates as low as 5 mm/hour, leading to rapid surface runoff accumulation.

The runoff coefficient analysis indicated that urban expansion and deforestation have contributed to a 15% increase in total runoff over the past decade, further intensifying flood hazards. These findings are consistent with global studies that link urbanization with increased flood susceptibility (Falkenmark, 2003).

Additionally, peak flood discharge analysis showed that deforested and degraded land in the upper watershed contributes up to 40% of total runoff, highlighting the importance of reforestation in mitigating floods (Waskitho & Wibowo, 2024). Similar results were found in studies on other Indonesian watersheds, where deforestation accelerated runoff generation and flood occurrence (Lal, 2001).

Based on these findings, it is evident that a combination of land-use planning, enhanced drainage capacity, and ecosystem-based adaptation strategies is necessary to mitigate flood risks in the Upper Kuncir River basin.

3.2. Erosion and Sedimentation Analysis

Soil loss estimation using the USLE model revealed that erosion rates in the Upper Kuncir watershed range from 50 to 80 tons/ha/year, with the highest rates occurring on slopes exceeding 20% (Morgan, 2009; Rabin et al., 2024). The dominant land uses contributing to erosion are intensive agricultural lands lacking soil conservation practices (Waskitho & Wibowo, 2024). Areas with bare soil experience accelerated erosion, increasing sediment transport into river channels and reservoirs.

Field observations indicate that gully erosion and sheet erosion are prevalent in the upper watershed. Gully erosion is particularly severe in deforested zones and abandoned agricultural plots, with erosion depth reaching 1.5 meters in some locations. These eroded channels act as conduits, rapidly transporting sediments into the river system ((Lal, 2001). Sheet erosion, on the other hand, has been observed on cultivated lands with slopes exceeding 10%, where raindrop impact dislodges soil particles and accelerates sediment transport during heavy rainfall events (Wischmeier & Smith, 1978).

Sedimentation assessments indicate that the river receives an annual sediment load of 18,500 m^3, reducing its capacity and exacerbating flood risks. The sediment transport analysis using the Modified Universal Soil Loss Equation (MUSLE) model confirmed that 60% of sediment inflow originates from upstream agricultural areas, necessitating urgent soil conservation efforts. Without intervention, continued sedimentation is expected to lower the river's storage volume by 15% within the next decade (Bappeda, 2024).

The deposition of sediment within the riverbed and at the Margopatut Dam reservoir has reduced flow efficiency and storage capacity. A comparative sediment yield analysis found that:

- Upstream erosion hotspots contribute to 40% of total sediment load, primarily from steep agricultural fields lacking contour planting.
- Midstream sedimentation zones account for 35% of total sediment deposits, particularly in areas where river meandering slows water velocity.
- Reservoir sedimentation contributes to 25% of the problem, reducing dam effectiveness over time.

Further analysis revealed that sedimentation rates have increased by 25% over the past 15 years, correlating with land-use changes that replaced forested areas with cash crops and settlements (Chang et al., 2024). The increasing fine sediment load also contributes to riverbed aggradation, which raises flood risks in lowland areas by reducing channel capacity (Waskitho & Wibowo, 2024).

The impact of sedimentation on Margopatut Dam is particularly concerning, as it threatens the reservoir's long-term operational efficiency. Current estimates suggest that without sediment management, the dam's effective storage volume will be reduced by 8-10% within 20 years (Kim et al., 2020). In similar cases, reservoir sedimentation in tropical regions has been mitigated using sediment flushing techniques, check dams, and vegetative buffer zones, all of which should be considered for the Upper Kuncir watershed (Widyasasi et al., 2024).

To mitigate erosion and sedimentation impacts, several conservation strategies are recommended:

- Check Dams and Retention Basins: These structures can trap up to 60% of sediments before they reach critical flood zones (J. Zhang et al., 2022a).
- Reforestation and Buffer Strips: Increasing Forest cover by 20% in critical upstream zones can reduce sedimentation by 30-40% over a decade.
- Agroforestry and Contour Farming: The adoption of agroforestry techniques on sloped farmlands has been shown to reduce soil erosion by 50% in comparable watersheds.
- Riverbank Stabilization and Riparian Vegetation: Strengthening riverbanks with native vegetation can reduce channel erosion by 25%.
- Sediment Flushing at Margopatut Dam: Periodic flushing operations can prevent excessive sediment buildup, maintaining reservoir efficiency over time.

The combined implementation of these measures is expected to stabilize the watershed, reduce sedimentation, and enhance the resilience of flood management efforts. Similar approaches have been successfully implemented in Indonesia's Citarum and Brantas watersheds, demonstrating their effectiveness in controlling sediment-related flood hazards (Narulita & Ningrum, 2018).

3.3. Margopatut Dam Optimization Simulation

Simulation results for the Margopatut Dam's flood control function suggest that the dam's effective storage capacity of 21.68 million m³ can reduce peak flood discharge by 35% when operated with controlled water release mechanisms (Bappeda, 2024). The HEC-ResSim model indicated that the dam can lower peak flood discharge from 125.905 m³/s to 81.3 m³/s, significantly reducing downstream flood risks (J. Zhang et al., 2022b). Additionally, simulation results for extreme flood events, such as those with a 50-year return period, show that the dam is capable of mitigating peak discharges, preventing severe flooding in downstream areas.

Further optimization of the dam's operation using real-time monitoring systems and predictive hydrological models can enhance flood mitigation capabilities. The implementation of automated spillway control and adjustable sluice gates has been shown in other case studies, such as the Jatiluhur Dam in Indonesia, to improve reservoir efficiency by 20-30% (Waskitho & Wibowo, 2024). Adopting similar technologies in the Margopatut Dam could optimize water retention and controlled release, minimizing flood impact while maintaining adequate water storage for other uses.

Beyond flood mitigation, the Margopatut Dam provides substantial benefits for irrigation, supporting water supply for 1,885 hectares of farmland and increasing the cropping index from 200% to 300% (X. Zhang & Song, 2014). This increase in agricultural productivity aligns with the findings from other multipurpose reservoirs, such as those in the Citarum watershed, where regulated water storage has significantly improved food security and rural livelihoods (Agaton et al., 2016; Narulita & Ningrum, 2018). Additionally, improved irrigation water availability will enhance drought resilience, reducing dependency on groundwater extraction during dry seasons.

However, sedimentation buildup poses a long-term risk, requiring comprehensive sediment management strategies. Current estimates indicate that sediment deposition in the dam reduces storage capacity by 8-10% per decade, a significant challenge for long-term dam functionality (Bappeda, 2024). If left unaddressed, sedimentation could lead to a 25% reduction in reservoir efficiency within 30 years, necessitating proactive interventions.

To maintain optimal performance, the following sediment control measures are recommended:

- Periodic Dredging and Sediment Flushing: Regular removal of deposited sediments can maintain reservoir capacity. The Sediment Management Plan at Jatigede Dam demonstrated that annual dredging prevents long-term sediment accumulation by 30-40% (Bappeda, 2024).

- Upstream Soil Conservation and Check Dams: Implementing erosion control practices in the watershed's upper catchment can reduce sediment yield by 40-50% over a 10-year period (Rinaldi, 2019). Check dams installed in high-sediment areas have proven effective in reducing sediment transport by 60% in comparable watersheds.
- Sediment Bypass Channels: Constructing sediment bypass tunnels or diversion channels can significantly reduce sedimentation rates in the main reservoir. Case studies in Japan and Switzerland indicate that bypass tunnels can divert up to 70% of incoming sediments away from the reservoir, prolonging its operational lifespan (Lal, 2001).
- Adaptive Reservoir Operations: Implementing flexible reservoir operation strategies that adjust water release timing based on real-time sediment loads and hydrological conditions can balance flood mitigation and sediment control (Kim et al., 2020).
- Riparian Buffer Zones and Reforestation: Increasing vegetative cover around the reservoir and along riverbanks can reduce soil erosion by 25-30%, preventing excessive sediment flow into the dam (Huang et al., 2020).

Additionally, the economic feasibility of sediment management interventions needs to be assessed. Long-term cost-benefit analysis should compare the investment in sediment control infrastructure versus potential loss of dam functionality and agricultural benefits (Agaton et al., 2016). Government and community-based conservation initiatives should be incorporated into sedimentation control programs, ensuring sustainable financing mechanisms for dam maintenance and watershed restoration efforts.

Overall, optimizing the operation and sediment management of the Margopatut Dam will enhance its effectiveness in flood control, irrigation supply, and long-term sustainability. By integrating hydrological monitoring, automated infrastructure, sediment management strategies, and community-driven watershed conservation, the dam can continue providing critical ecosystem services and economic benefits for the region.

3.4. Evaluation of Watershed Conservation Strategies

This section evaluates the effectiveness of structural and non-structural watershed conservation measures. Simulation comparisons between baseline conditions and intervention scenarios demonstrate that a combination of engineering solutions (check dams, river normalization) and nature-based strategies (reforestation, agroforestry) yields optimal flood mitigation outcomes.

Findings indicate that check dams reduce flow velocity by 40%, while reforestation increases Soil Infiltration rates, decreasing runoff by 35%. Agroforestry and vegetative buffer strips reduce soil erosion by 50%, significantly limiting sediment transport into river channels. Integrated watershed management approaches incorporating these strategies can reduce peak flood discharge by up to 50% and enhance long-term hydrological stability.

A comparative analysis of conservation techniques was conducted to evaluate their impact on reducing flood risks and improving watershed sustainability. Key findings include:

- Check Dams: Reduce flow velocity by 40% and enhance groundwater infiltration (Nugroho et al., 2022). Effective placement in high-erosion zones significantly reduces downstream sediment loads.
- Reforestation: Increasing vegetative cover from 30% to 50% in upstream areas can reduce runoff by 35% and improve soil moisture retention (Herawati & Santoso, 2011). The impact of reforestation programs on flood reduction has been demonstrated in previous studies in Indonesia's tropical watersheds.
- River Normalization: Sediment removal and widening of the river channel can enhance flow capacity by 20%, reducing flood risk in midstream and downstream areas (Agaton et al., 2016).
- Agroforestry and Vegetative Cover: Integrating agricultural activities with tree planting can reduce soil erosion by 50%, ensuring sustainable watershed management (Lal, 2001). Implementing buffer strips and cover crops significantly enhances soil stability and prevents excessive runoff.

Simulation comparisons between natural conditions, existing conditions, and conservation-based interventions demonstrated that a combined approach of engineering and ecohydrological solutions yields the most effective flood mitigation outcomes (Dadson et al., 2017)

3.5. Comparative Simulation of Conservation Scenarios

Simulation comparisons between natural conditions, existing conditions, and conservation-based interventions demonstrated that a combined approach of engineering solutions (check dams, river normalization) and ecohydrological strategies (reforestation, agroforestry, buffer zones) yielded the most effective flood mitigation outcomes. Model projections indicate that implementing a comprehensive watershed conservation plan can reduce peak flood discharge by up to 50% and increase infiltration rates by 30% (Dadson et al., 2017). These results support global findings on integrated watershed management, emphasizing the importance of balancing structural and ecological conservation strategies for long-term flood resilience (Lal, 2001).

Table 1. Summary of Recommended Conservation Strategies

Conservation Strategy	Expected Impact on Flood Mitigation
Check Dams	Reduces flow velocity by 40%, sediment retention up to 60%
Reforestation	Decreases runoff by 35%, improves soil retention
River Normalization	Increases channel capacity by 20%, reduces flood depth by 0.8m
Agroforestry	Reduces soil erosion by 50%, increases infiltration by 15-25%
Terracing	Reduces runoff by 40%, increases groundwater recharge
Infiltration Ponds	Reduces peak flood by 15-20%, enhances local water storage

Policy Recommendations for Watershed Conservation

1. Scaling Up Reforestation Initiatives: Prioritizing degraded upstream land for restoration to enhance water retention and flood control.
2. Incentivizing Sustainable Agriculture: Providing financial support and training for farmers adopting soil conservation techniques.
3. Integrated River Management: Combining river widening with natural floodplain restoration to sustain hydrological balance.
4. Community-Based Watershed Management: Engaging local stakeholders in conservation efforts to ensure long-term implementation and monitoring.
5. Technology-Driven Monitoring: Utilizing remote sensing and GIS tools for real-time assessment of watershed conditions and flood risk.

By integrating engineering solutions, nature-based interventions, and sustainable land management, watershed conservation efforts in the Upper Kuncir River can achieve long-term flood resilience, improved water security, and enhanced agricultural productivity.

3.6. Validation and Sensitivity Analysis

Validation of hydrological models was performed using 10 years of historical flood data, with a Nash-Sutcliffe Efficiency (NSE) score of 0.85, indicating high model accuracy (Moriasi et al., 2007). The validation process compared observed flood discharge data with the HEC-RAS simulated outputs, and the results demonstrated that the model effectively captures flood peak variations and timing within an error margin of ±7%.

Further validation using Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) metrics confirmed the model’s predictive reliability in simulating peak discharge events (Abbaspour et al., 2015; Baninajar et al., 2023; Kannan et al., 2019). Additionally, statistical assessments using Coefficient of Determination ($R^2 = 0.92$) showed a strong correlation between simulated and observed values, reinforcing the model's robustness in hydrological prediction (Stedinger, 1993).

Sensitivity Analysis of Key Flood Factors, Sensitivity analysis was conducted to evaluate the influence of various hydrological parameters on flood severity. The most critical factors identified include:

- Extreme Rainfall Events: A 10% increase in rainfall results in an 18% rise in peak flood discharge, indicating that the Upper Kuncir River basin is highly sensitive to extreme precipitation variability (Falkenmark, 2003). Climate change models project that rainfall intensity in the region could increase by 12-15% in the next 30 years, potentially exacerbating flood risks.
- Soil Infiltration Capacity: Areas with degraded land cover exhibit up to 25% higher surface runoff, as shown in field studies of deforested regions (Lal, 2001). Hydrological simulations confirm that reducing soil infiltration rates by 20% due to land degradation results in a 30% increase in flood volume.

- Sedimentation Impact: Increased sedimentation reduces river channel capacity, significantly aggravating flood risks. Analysis of riverbed aggradation over the past 15 years indicates that the mean sediment accumulation rate is 2.5 cm per year, leading to a 15% decrease in discharge capacity (Agaton et al., 2016). Without sediment control interventions, flood risk will escalate as channel storage diminishes.
- Land-Use Changes: Expansion of impervious surfaces and deforestation increases flood discharge by 30% over 10 years. Urban development and agricultural expansion without conservation practices accelerate surface runoff, intensifying flood hazard potential (Huang et al., 2020). Hydrological modeling shows that increasing urban areas by 10% results in an additional 5-8% rise in flood peak discharge.
- Reservoir Operation Efficiency: The Margopatut Dam's operational efficiency in reducing flood peaks was tested under different flood scenarios. Sensitivity analysis revealed that optimizing dam release schedules could further reduce peak discharge by an additional 10% without compromising irrigation supply (Bappeda, 2024). Implementing automated floodgate control and real-time hydrological monitoring can enhance dam effectiveness by 15-20% in extreme rainfall conditions.
- Vegetative Cover: Increasing forest and agroforestry land by 25% in the upper watershed could reduce runoff by 20% and flood peaks by 12% over a decade (Waskitho & Wibowo, 2024). Simulation results indicate that combining agroforestry with check dams is one of the most effective approaches for long-term flood mitigation.

3.7. Implications for Flood Management Strategies

The sensitivity analysis findings reinforce the need for an integrated flood management approach that includes:

- Enhanced Flood Forecasting Systems: Improved real-time hydrological monitoring and rainfall prediction tools can provide early warning alerts, enabling communities to take preventive measures ((Herawati & Santoso, 2011).
- Sustainable Watershed Management: Implementing erosion control, reforestation, and soil conservation can significantly mitigate surface runoff and sedimentation (Lal, 2001).
- Infrastructure Adaptations: Strengthening river embankments, optimizing dam operations, and implementing check dams can collectively reduce peak flood discharge by up to 50% (Dadson et al., 2017).
- Climate Adaptation Planning: Factoring climate variability into flood control planning ensures resilient water management strategies, preparing the Upper Kuncir River basin for projected increases in rainfall extremes (Huang et al., 2020).

Table 2. Summary of Sensitivity Analysis Results

Key Factor	Impact on Flooding
Extreme Rainfall	10% increase → 18% rise in peak discharge
Soil Infiltration	20% decline → 30% increase in runoff volume
Sedimentation	15% river capacity reduction → higher flood risk
Land-Use Changes	10% urban expansion → 5-8% higher flood peaks
Reservoir Optimization	Better dam operation → 10-15% flood reduction
Vegetative Cover	25% increase → 12% lower flood peaks

These findings emphasize that effective flood mitigation in the Upper Kuncir River requires an integrated approach combining structural flood control measures (dams, check dams, and river normalization) with nature-based solutions (reforestation, agroforestry, and watershed rehabilitation). Implementing these strategies can reduce flood risks by 40-50% over the next two decades, ensuring the long-term sustainability of water resources in the region.

4. Conclusion

The main causes of flooding in the Upper Kuncir River are high runoff due to low infiltration, high soil erosion rates (50-80 tons/ha/year), and sedimentation leading to a 7% narrowing of the river channel over the past five years. Hydrological modeling using HEC-RAS indicates that the 25-year return period peak flood discharge reaches 125.905 m^3/s, exceeding the river's maximum capacity of 85.4 m^3/s, highlighting significant flood risks during the rainy season. Watershed conservation strategies combining structural and vegetative methods are proven to be more effective than structural approaches alone. The application of check dams can reduce flow rates by 40%, upstream reforestation can decrease runoff by 35%, and river normalization can increase flow capacity by 20%. Optimization of

Margopatut Dam through staged water release management can reduce peak flood discharge by 35% while supporting irrigation for 1,885 hectares of farmland, increasing the cropping index from 200% to 300%. Hydrological model validation indicates an accuracy difference of 5-10% when compared with historical data, with a Nash-Sutcliffe Efficiency (NSE) score of 0.85, signifying excellent validation quality. Sensitivity analysis identifies the most influential factors in flooding as extreme rainfall, soil infiltration rates, sedimentation, and uncontrolled land-use changes.

Acknowledgments

To enhance flood management and watershed conservation in the Upper Kuncir River, several strategies should be implemented. Key measures include constructing check dams in high-erosion areas, dredging sediments to increase river capacity, and developing an integrated drainage system. Expanding reforestation and agroforestry can improve water absorption and prevent land degradation. Optimizing Margopatut Dam operations with real-time reservoir management and sediment traps will further reduce flood risks. Implementing IoT-based flood monitoring and early warning systems can enhance disaster preparedness. Strengthening watershed governance through policy incentives and multi-stakeholder collaboration is also essential. Additionally, further research on AI-driven flood prediction and climate change impacts will support adaptive mitigation strategies. These efforts will improve environmental resilience and socio-economic stability for the surrounding communities.

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