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Regional Case Study

Quick Assessment of Landslide Potential Using Satellite Imagery in Bili-Bili Reservoir Catchment Area

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Abstract

Landslides are among the most unpredictable and destructive sediment-related disasters, especially in mountainous regions with complex terrain and limited field accessibility. In 2004, a catastrophic landslide from the Mount Bawakaraeng Caldera delivered more than 100 million cubic meters (MCM) of sediment into the Bili-Bili Reservoir, filling its dead storage and threatening its long-term functionality. his study uses Sentinel-1A satellite imagery and Differential Interferometric Synthetic Aperture Radar (DInSAR) to perform a rapid, spatially driven assessment of landslide hazards in the Bili-Bili Reservoir Catchment Area. The results reveal surface deformation of up to ±1.55 meters, concentrated in upstream zones. High-risk areas span 71.00 km², with an estimated mobilizable volume of 110.04 MCM and a potential sediment yield of 27.14 MCM per year, nearly equal to the reservoir's dead storage. To mitigate this threat, the study proposes an integrated mitigation framework. Structural interventions include rehabilitating existing sediment control systems and constructing new sabo dams. Non-structural strategies such as slope revegetation and bioengineering are also recommended. This study demonstrates how remote sensing can identify subtle ground deformation and provides actionable insights for safeguarding critical water infrastructure in sediment-prone tropical watersheds.

Keywords: Bili-Bili reservoir catchment area; DInSAR; landslide potential; mitigation

1. Introduction

Landslides are sediment-related natural disasters that frequently occur in Indonesia, particularly in mountainous regions (Alimuddin et al., 2013) and pose significant risks to local populations and infrastructure (Samsonov and Blais-Stevens, 2024). The primary factors contributing to landslides include high and steep slopes with loose material support, impermeable subsurface layers, and high rainfall intensity (Suripin, 2004; Alimuddin et al., 2013). Landslides represent a form of erosion characterized by the movement of large volumes of soil mass (Suripin, 2004).

Many landslides are unpredictable without warning; however, early signs can often be detected as temporary surface deformations (Dille et al., 2022; Samsonov and Blais-Stevens, 2024). A landslide represents a form of ground deformation, involving changes in the position, shape, and dimensions of objects on the Earth's surface (Saputra et al., 2017). This deformation can be monitored using remote sensing technologies, such as Interferometric Synthetic Aperture Radar (InSAR), which is capable of mapping surface changes over large areas with millimeter-level precision (Amedeo et al., 2022; Hanif et al., 2024). Based on this, Differential InSAR (DInSAR) has emerged as a highly effective tool for mapping surface displacements, including those caused by landslides. By comparing the phase differences between pairs of SAR images captured at different times, DInSAR can accurately determine elevation changes at specific locations on the Earth's surface (Riska et al., 2017; Occhipinti et al., 2024). Numerous studies have presented that DInSAR is a reliable and efficient method for detecting and mapping ground movements associated with landslides (Alimuddin et al., 2013; Hanif et al., 2024 Samsonov and Blais-Stevens, 2024).

DInSAR has been widely applied across Indonesia to monitor pre-landslide deformations, particularly at the Bawakaraeng Caldera, Mount Merapi, and Mount Sinabung. Alimuddin et al. (2013) utilized Japanese Earth Resources Satellite (JERS-1) data (1993–1998) and DInSAR to detect slope movements preceding the 2004 Bawakaraeng Caldera wall landslide in the Jeneberang River Basin. Similarly, Nurtyawan dan Utami (2020) employed DInSAR to monitor volcanic activity-induced deformation at Mount Merapi in Central Java. Recent research by Hanif et al. (2024), applied DInSAR to analyze deformation at Mount Sinabung, North Sumatra, revealing continuous deformation averaging 0.197 cm/month and an inflation rate of 0.54 cm/month for 2024–2027. These studies underscore DInSAR's critical role in landslide mitigation and early warning systems in mountainous regions.

Several studies have also utilized DInSAR and/or Sentinel-1A imagery for landslide detection and monitoring. For example, Sharma et al. (2024) revealed DInSAR's ability to detect slope instability in valley regions. Similarly, Samsonov and Blais-Stevens (2024) demonstrated DInSAR's capability to detect slow-moving, deep-seated landslides in Northern Canada using Sentinel-1 imagery (2017–2022), estimating landslide thicknesses of up to 100 meters and mapping hazards in remote areas. A similar study was conducted by (Reyes-Carmona et al., 2020), which demonstrated that the application of DInSAR techniques in the Rules Reservoir case study in Spain was effective in detecting and monitoring slope instabilities around critical infrastructure such as dams. The study focused on monitoring landslide instabilities to evaluate dam stability. However, the integration of deformation analysis with sediment yield estimation in tropical volcanic catchments, such as the Bili-Bili Reservoir Catchment Area, remains underexplored, particularly in Indonesia.

In 2004, a landslide occurred on the caldera wall of Mount Bawakaraeng in the upper reaches of the Jeneberang River, specifically within the Bili-Bili Reservoir Catchment Area. This event became the primary cause of severe sedimentation problems in the reservoir (Achsan et al., 2015). By 2019, the combined effects of the landslide and ongoing upstream land erosion had reduced the storage capacity of the Bili-Bili Reservoir by 99.72 MCM. Since its initial operation in 1999 with a capacity of 347.81 MCM, the reservoir's volume has declined to just 248.09 MCM in 2019 (Safaa et al., 2023). Bathymetric measurements in 2023 indicated a continued decrease, with the capacity dropping further to 243.84 MCM (BBWS Pompengan Jeneberang, 2023). As a result, the planned dead storage capacity of 29 MCM became fully occupied, causing the reservoir's service life to end after 26 years, well short of its intended 50-year design life (Rahim et al., 2017). Sedimentation is expected to remain an issue due to the ongoing risk of landslides, especially considering the reservoir's location in the mountainous region. If further landslides occur, large volumes of sediment could be transported downstream during heavy rainfall, increasing the risk of high-concentration debris flows (Asrib et al., 2011). These debris flows, characterized by high viscosity and velocity, have the potential to cause significant damage to infrastructure along the river (Sumaryono, 2011).

Previous studies and the historical landslide at Mount Bawakaraeng serve as references for developing the research framework and methodology. Earlier research in the Bili-Bili Reservoir Catchment Area had been conducted, but it was limited to identifying slope movements prior to the caldera wall landslide using Japanese satellite imagery (JERS-1) (Alimuddin et al., 2013), which has been non-operational since 1998. This study aims to build upon the previous research by conducting a quick assessment and identifying the locations and volumes of landslide potential in the Bili-Bili Reservoir Catchment Area using the DInSAR method with more recent Sentinel-1A satellite imagery. In addition to identifying landslide-prone areas and estimating their volume, this study also calculates the estimated volume of mobilizable landslide material that may contribute to sediment yield entering the Jeneberang River and Bili-Bili Reservoir. This analysis is critical for anticipating further landslides, which pose a threat to the sustainability of the Bili-Bili Reservoir, now heavily filled with sediment from the 2004 landslide. Should the reservoir fail to operate effectively, it would compromise several essential services, including the flood reduction capacity of 1,000 m^3/s along the Jeneberang River, the provision of 3.3 m^3/s of raw water, irrigation for 24,858 hectares, and the operation of a 20.1 MW hydroelectric power plant.

The quick assessment approach was selected due to the challenging topography of the study area, which limits field accessibility, and the availability of easily accessible Sentinel-1A satellite data. Unlike previous studies, this is the first to integrate landslide potential prediction using the DInSAR method with the subsequent estimation of sediment yield volume generated by landslides. The findings of this study are expected to serve as a reference for landslide hazard mitigation efforts in the Bili-Bili Reservoir Catchment Area, particularly through the development of landslide potential maps and the implementation of both structural and non-structural mitigation strategies to reduce sediment inflow into the Jeneberang River and Bili-Bili Reservoir.

2. Methods

2.1. Study Area and Data Requirements

The Jeneberang River is classified as a national strategic river under the Ministry of Public Works (Kementerian Pekerjaan Umum dan Perumahan Rakyat, 2015), originates from Mount Bawakaraeng in the east and flows into the Makassar Strait in the west. Located in the midstream of Jeneberang River within Gowa Regency, Bili-Bili Dam is geographically positioned at coordinates 05°15'S–119°37'E. The reservoir's catchment covers 383.64 km^2, comprising 13 sub-basins, with a river extending 108.04 km across the study region. Figure 1 delineates the study area boundaries and the Bili-Bili Reservoir Catchment Area.

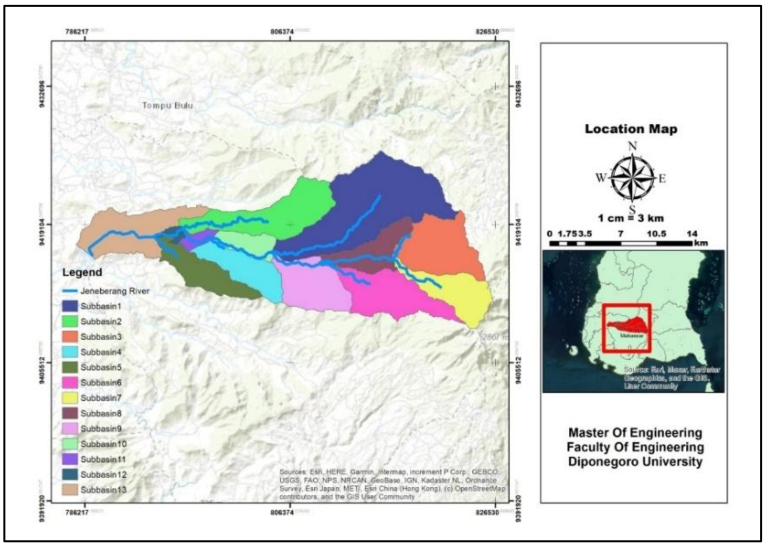

Figure 1. Bili-Bili reservoir catchment area

Sentinel-1 satellite imagery was utilized to identify landslide potential zones in the Bili-Bili Reservoir Catchment Area through visual analysis. Data from Sentinel-1A with ascending orbit, single-look complex (SLC) processing, and Vertical Vertical – Vertical Horizontal (VV-VH) polarization were acquired for January 22, 2021, and January 24, 2023, via the Copernicus Data Space Ecosystem (https://dataspace.copernicus.eu), the successor platform to the Copernicus Open Access Hub. This imagery provides high-resolution day-and-night earth surface observations, with a 12-day revisit cycle and robustness against cloud cover and adverse weather (Nugraha et al., 2022; Dwinita et al., 2024).

The datasets utilized in this study include: (1) Sentinel-1A imagery for deformation analysis; (2) surface monuments data from the Bili-Bili Dam for validation; and (3) National Digital Elevation Model for topographic reference. Detailed specifications of the data are provided in

Table 1. Data Requirements

No.	Data	Description
1	Sentinel-1A	https://scihub.copernicus.eu/, the period of 2021 – 2023
2	Surface Monuments of Bili-Bili Dam	Data provided by BBWS Pompengan Jeneberang, the period of 2021 – 2023
3	National Digital Elevation Model	Watershed delineation (https://tanahair.indonesia.go.id/portal-web/) accessed on April 1, 2025

2.2. Data Analysis

The DInSAR method was selected for landslide potential prediction due to its proven effectiveness in mapping landslide potential areas, as demonstrated in prior studies (Hanif et al., 2024). This remote sensing technique measures ground surface elevation changes by analyzing phase differences between two SAR images (primary and secondary) acquired at different times. The primary image captures pre-event conditions, while the secondary image records post-event conditions, either at the same spatial position (differential SAR) or slightly different positions (terrain height InSAR) within the target area (Riska et al., 2017; Occhipinti et al., 2024). The DInSAR process generates digital elevation models (DEMs) or earth surface displacement data (Riska et al., 2017; Fadhlurrohman et al., 2020).

The accuracy of deformation measurement in this method is achieved by eliminating the topographic phase from SAR interferograms. An interferogram represents the phase difference (ϕ), which correlates with variations in radar line-of-sight (LOS) distance. The phase difference comprises four primary components: topography, orbital shifts, surface deformation, and atmospheric disturbances. The relationship is formulated in Equation 1 (Hassen, 2001 dalam Castañeda et al., 2011). Deformation values are derived through differential interferometry, which removes the effects of topography, orbital discrepancies, and atmospheric interference by analyzing differences between two interferograms.

$$\phi = \phi_{topography} + \phi_{orbits} + \phi_{deformation} + \phi_{atmosphere} \quad (1)$$

Where, ϕ is the phase difference, $\phi_{topography}$ is the topography difference; ϕ_{orbits} is the orbital shifts; $\phi_{deformation}$ is the surface deformation; and $\phi_{atmosphere}$ is the atmospheric disturbance.

The study started with data collection, followed by analysis using the DInSAR method, processed through the Sentinel Application Platform (SNAP) software. The detailed workflow of the research is illustrated in Figure 2. The SNAP analysis generated topographic deformation maps by comparing phase differences between two Sentinel-1A SAR images. To identify potential landslide zones, deformation values were thresholded based on the maximum observed displacement. A deformation threshold was applied to delineate areas with significant deformation. Pixels exceeding this threshold were grouped into polygons representing critical areas for further analysis. Spatial overlays were then performed with the delineated Bili-Bili Reservoir Catchment Area using Geographic Information System (GIS) tools. Areas exhibiting significant surface deformation were delineated as landslide-prone zones using polygon-based mapping. To validate the accuracy of the delineated zones, the deformation results were compared with field-based displacement data collected from surface monuments installed at Bili-Bili Dam. These instruments are used to monitor vertical movements of the dam structure and are routinely observed by dam operators.

Model accuracy was evaluated by comparing simulation results with observational data using the Root Mean Square Error (RMSE) and RMSE-Observations Standard Deviation Ratio (RSR) statistical tests. RMSE, a widely used indicator of simulation error (Singh et al., 2004; Moriasi et al., 2007) approach zero when the model perfectly matches observations. However, Singh et al. (2004) noted that RMSE values below 0.5 times the observational standard deviation (SD) still indicate low agreement. To standardize interpretation, Moriasi et al. (2007) developed RSR, calculated as the ratio of RMSE to SD (Equation 2), providing a normalized metric for model performance assessment.

$$RSR = \frac{\sqrt{\sum_{i=1}^{n}(Q_{oi}-Q_{mi})^2}}{\sqrt{\sum_{i=1}^{n}(Q_{oi}-Q_{mavg})^2}} \quad (2)$$

Where Q_{oi} is the observation parameter, Q_{mi} is the model parameter, and Q_{mavg} is the average model parameter. The criteria for the RSR statistical test values are presented in Table 2.

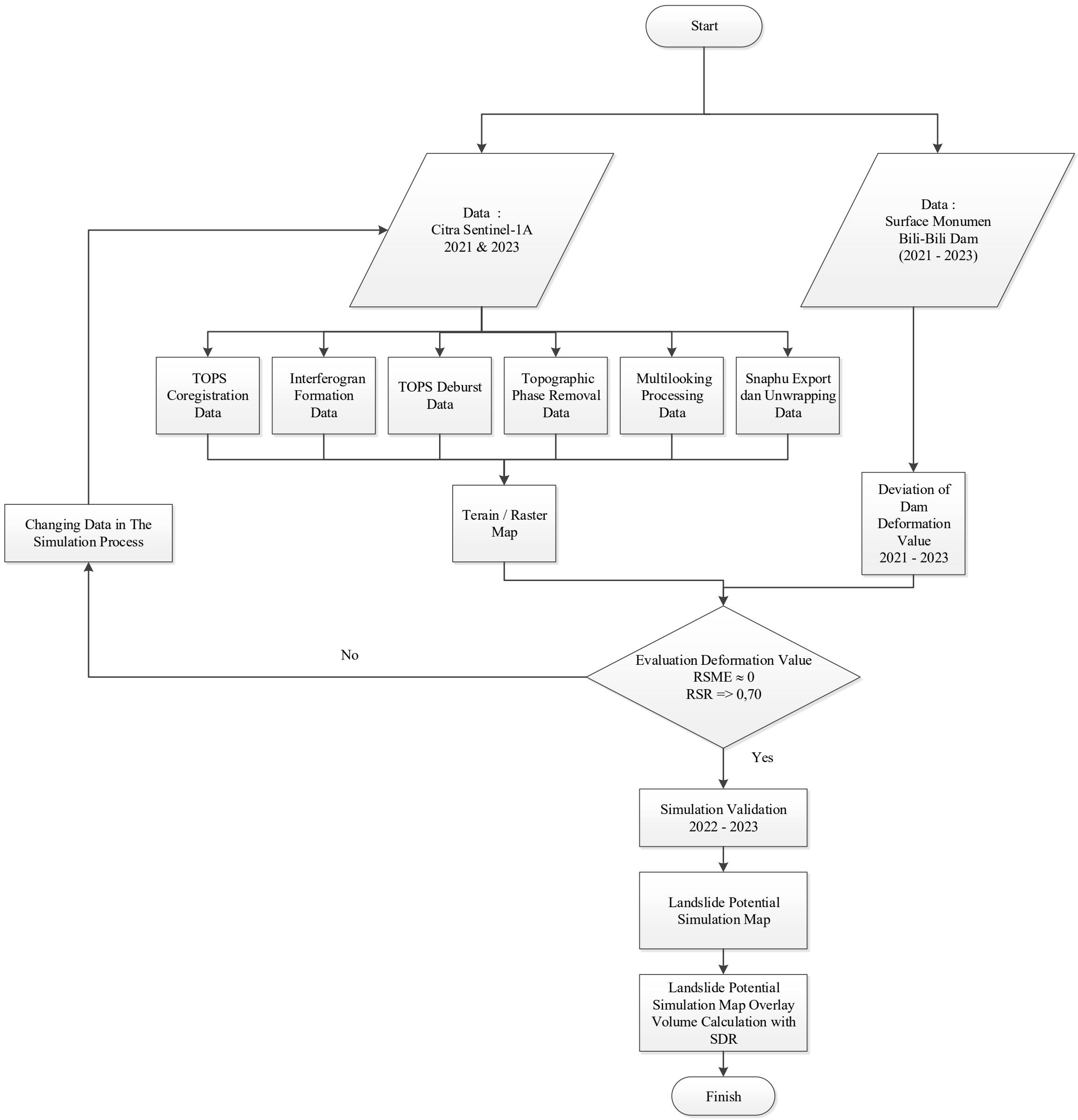

Figure 2. Research flowchart

Table 2 . RSR criterion values

Statistical Test	Evaluation Criteria			
	Very Good	Good	Satisfy	Not Satisfy
RSR	0,00 < RSR ≤ 0,50	0,50 < RSR ≤ 0,60	0,60 <RSR ≤ 0,70	RSR ≤ 0,70

Source: Moriasi et al. (2007) dan Moriasi et al. (2015)

After fulfilling the evaluation criteria, the landslide potential simulation results were utilized to estimate the sedimentation volume potentially entering the Jeneberang River and Bili-Bili Reservoir using the Sediment Delivery Ratio (SDR) equation. This calculation aimed to predict the sediment yield from potential landslides in the Bili-Bili Reservoir Catchment Area. The SDR formula was referenced from Equation 3, developed by Suripin (2004).

$$\text{Log SDR} = 2{,}31 + 3{,}07 \text{ Log } D_d + 0{,}41 \text{ Log } S - 1{,}26 \text{ Log } (F_L + F_w) \quad (3)$$

Where SDR is Sediment Delivery Ratio; D_d is the drainage density, S is the average slope of the catchment area (%); and $F_L + F_W$ is the percentage of forest and rice fields (%).

3. Results and Discussion

3.1. Quick Assessment of Landslide Potential

This study utilizes two satellite images acquired on different dates (January 22, 2021, and January 24, 2023) to analyze deformation over the study period. The initial simulation phase involved coregistration through subswath and burst area trimming, along with polarization selection for each image. The coregistration results are presented in Figure 3.

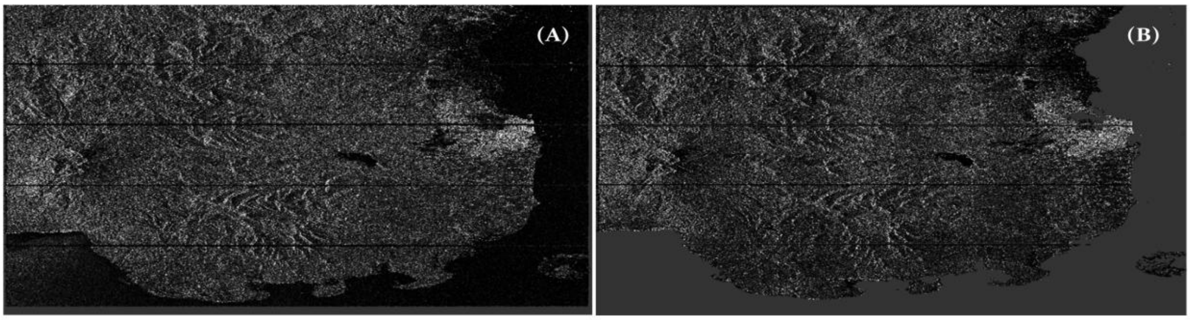

Figure 3. Coregistration results : (A) 2021, (B) 2023

The landslide potential simulation begins with interferogram formation, which initially generates separate burst data segments. These bursts are merged using the TOPS Deburst process to create a continuous interferogram. Subsequent phase reduction steps (Equation 1) include: (1) topographic phase removal to eliminate elevation-related artifacts, (2) Goldstein Phase Filtering for noise reduction, and (3) Multilooking to optimize unwrapping by averaging pixels. The unwrapping process in SNAP requires exporting data to the Statistical-cost, Network-flow Algorithm for Phase Unwrapping (SNAPHU) software, with intermediate results visualized in Figure 4. These steps collectively produce a terrain map displaying pixel-based deformation.

The simulated terrain map was spatially overlaid with the delineated catchment boundary to generate a comprehensive deformation map highlighting pixel-based elevation changes. Displacement magnitudes were visualized using a yellow-to-red gradient, with red zones indicating critical deformation hotspots. The resulting deformation map revealed elevation changes across the catchment, with maximum displacements of approximately ±1.55 meters concentrated in upstream areas of the Jeneberang River and near the Mount Bawakaraeng Caldera, while smaller scattered deformations were also observed throughout other parts of the catchment (Figure 5)

These deformations are interpreted as early indicators of slope instability, which are significant for disaster mitigation planning as they help prioritize areas for field investigation, early warning system deployment, and targeted structural interventions to prevent or minimize potential landslide impacts. The red zones on the map represent critical areas where significant ground movement has occurred, likely triggered by factors such as weakened slope materials, steep slopes, high rainfall intensity, or land use changes. This spatial pattern corresponds closely with the area most affected by the 2004 landslide, suggesting persistent geohazard vulnerability in the region. The deformation data, therefore, serve not only as an early warning signal for future landslide activity but also as a decision-support tool to identify priority areas for monitoring and targeted mitigation.

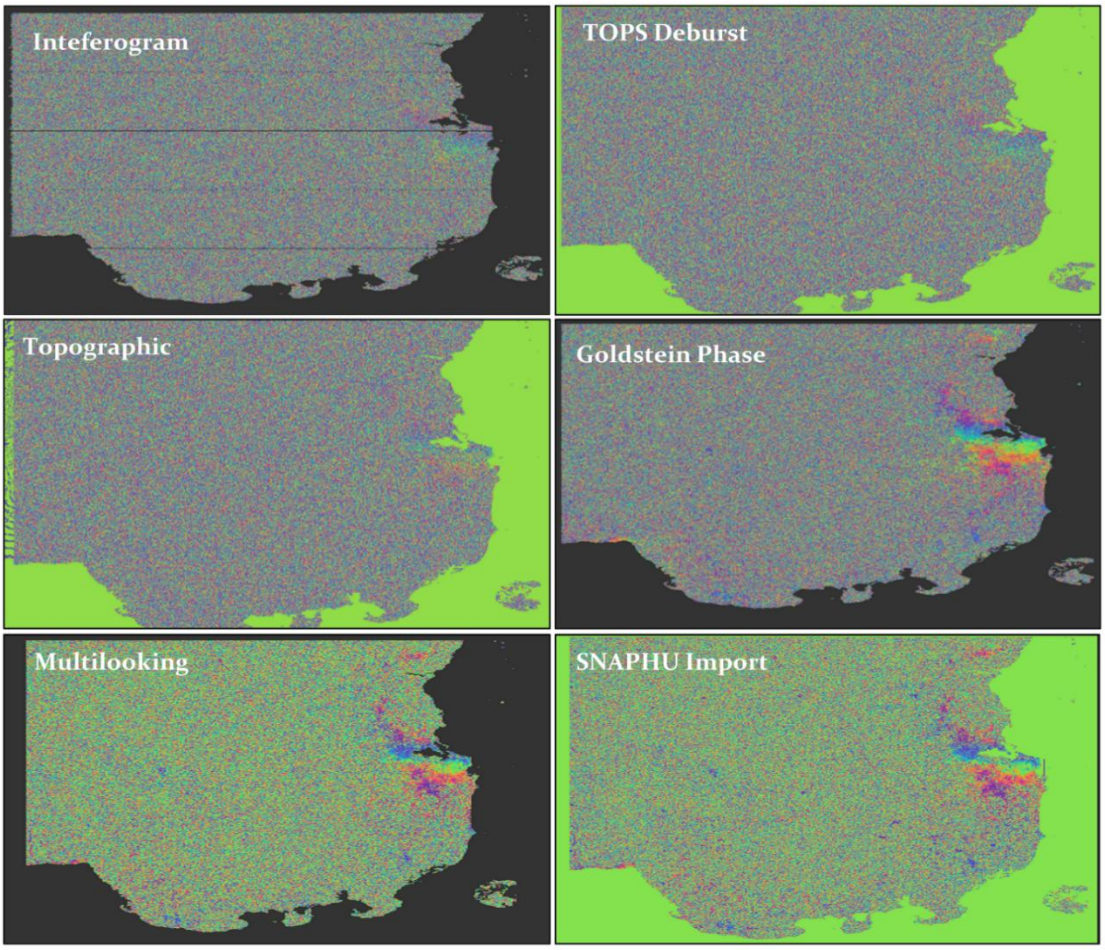

Figure 4. DInSAR processing steps using SNAP software

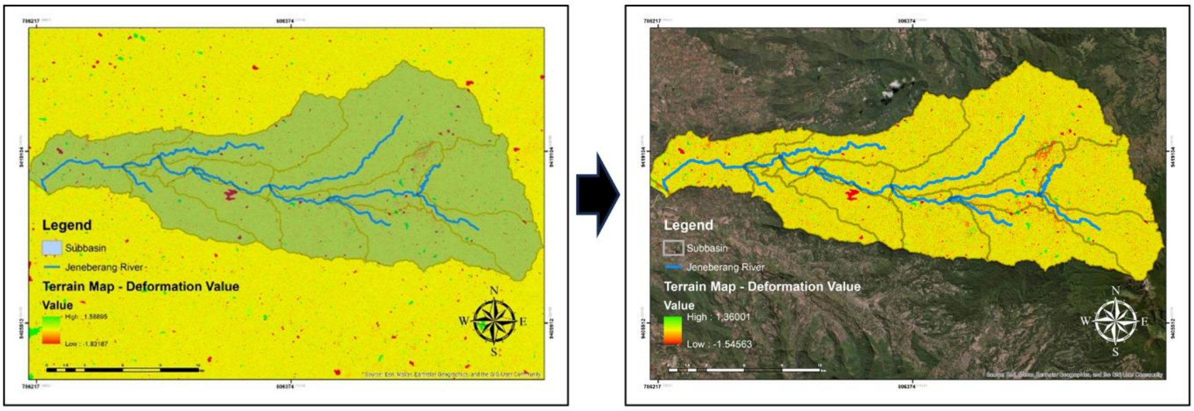

Figure 5. Overlay of landslide potential map and Bili-Bili Reservoir catchment map

To validate the quick assessment approach, deformation values from the DInSAR simulation were compared with displacement readings from surface monuments at the Bili-Bili Dam. The results are visualized in Figure 6, with a statistical comparison shown in Figure 7.

Validation using data from 2022–2023 yielded an RMSE of 0.120 and an RSR of 0.693, indicating a good agreement between the model and field observations. These values fall within the acceptable range (RSR: 0.60–0.70), suggesting that the DInSAR-based quick assessment approach is sufficiently reliable for preliminary decision-making in landslide risk mitigation, particularly in areas with limited field accessibility. These findings confirm the model's accuracy and support the use of Sentinel-1A-based DInSAR as a rapid assessment tool for slope deformation in remote or inaccessible terrains.

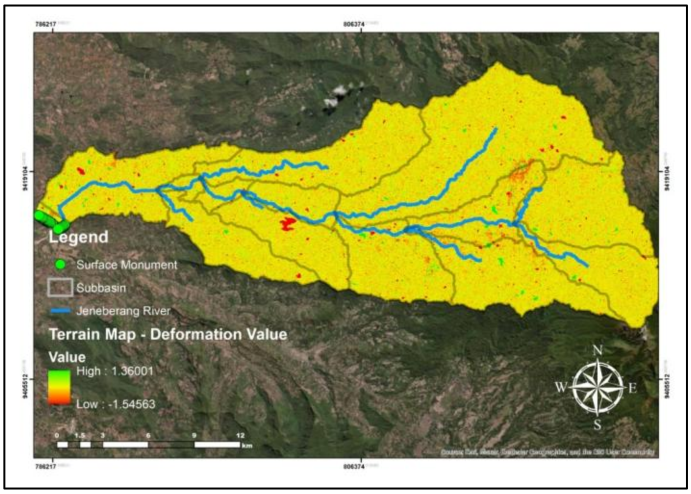

Figure 6. Terrain map (DInSAR result) and locations of surface monuments at Bili-Bili Dam

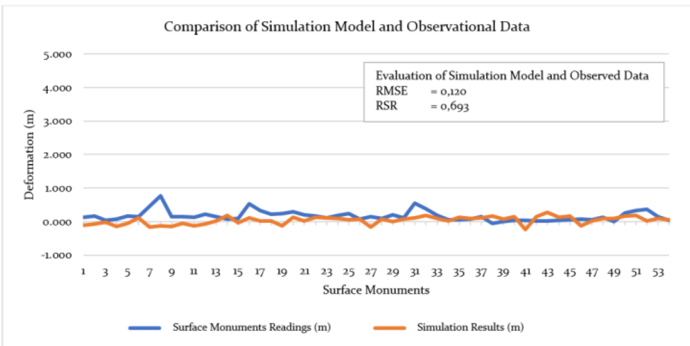

Figure 7 . Comparison of simulation model and observational data for the years 2022-2023

3.2. Determination of Landslide Potential Locations and Potential Sediment Yield

Using spatial overlay techniques in GIS, deformation thresholds were applied to delineate zones of landslide potential. A threshold of ±1.55 meters was uniformly applied across the deformation dataset to ensure consistency in spatial analysis. The potential landslide zones shown in Figure 8 were delineated based on this threshold. Polygons were drawn around areas with significant deformation, and volume estimates were calculated assuming an average depth of 1.55 meters. The total area identified with high landslide potential was 71.00 km², and the estimated volume of mobilizable material reached 110.04 MCM. Although this is lower than the 200–300 MCM generated by the 2004 event, it remains a substantial threat (Asrib, 2012). This threshold was consistently used to identify and quantify landslide-prone areas in both the deformation mapping and sediment yield estimation.

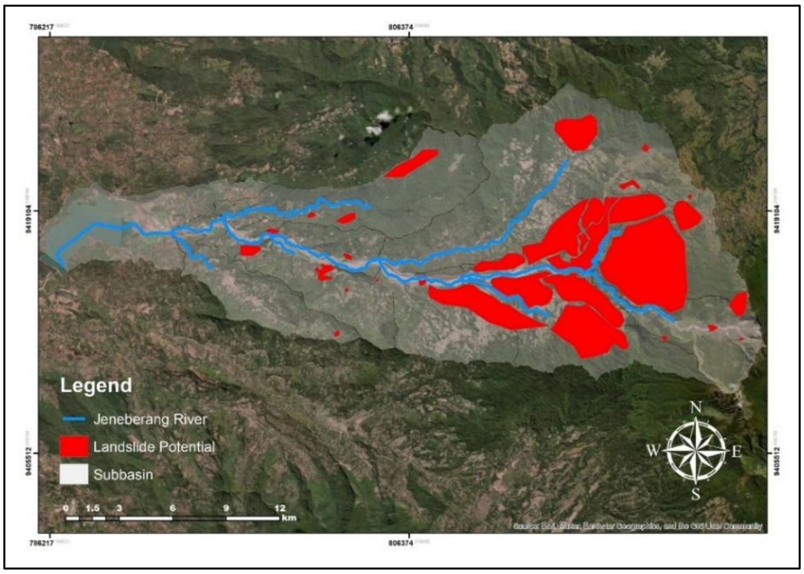

Figure 8. Landslide potential map of the Bili-Bili Reservoir catchment area

To estimate the actual sediment that could enter the reservoir system, the SDR was calculated. Using local drainage density, slope, and land cover data, the SDR was estimated at 0.247. This results in an annual sediment yield of 27.14 MCM, which is nearly equivalent to the current dead storage capacity of the Bili-Bili Reservoir (29.00 MCM). This highlights a critical implication: if left unmanaged, the landslide-induced sediment yield could directly impact essential public services by compromising the reservoir's ability to regulate floods, provide raw water, sustain irrigation systems, and support hydropower generation, one year of landslide-induced sediment yield could completely consume the reservoir's buffer storage, severely affecting its operational life. The summary of the calculations is presented in Table 3.

Table 3. Volume of landslide potential and sediment yield in the Bili-Bili Reservoir catchment area

Catchment area (km²)	Landslide potential		Volume (MCM)	SDR	Sediment yield (MCM/year)
	Area (km²)	Depth (m)			
383.64	71.00	1.55	110.04	0.247	27.14

These results provide concrete evidence that landslide activity remains a direct threat and underscore the urgency of translating these findings into actionable mitigation strategies, such as targeted sediment control infrastructure, revegetation programs, and early warning systems to ensure the long-term sustainability of the reservoir. Sediment yield resulting from landslides in the Bili-Bili Reservoir Catchment Area poses considerable environmental threats to both the Jeneberang River and the Bili-Bili Reservoir. The reservoir's effective storage capacity has declined to 243.84 MCM (BBWS Pompengan

Jeneberang, 2023), accelerating the loss of its usable capacity and threatening the reservoir's 50-year design life. This reduction severely compromises the reservoir's principal functions, including flood regulation, raw water supply, irrigation support, and hydropower generation. In addition, it heightens flood risk in downstream areas such as Gowa Regency and Makassar City, increasing the potential for extensive tangible and intangible damages. During periods of intense rainfall, landslide deposits within the catchment may be mobilized into high-viscosity debris flows capable of destructive velocities, further endangering infrastructure along the Jeneberang River. Therefore, the deformation map and sediment yield estimates presented in this study serve as essential references for the design and prioritization of integrated mitigation strategies combining engineering solutions with landscape-level interventions.

Unlike previous studies that primarily focused on monitoring deformation or protecting critical infrastructure, this study further integrates deformation mapping with sediment yield estimation. This combined approach provides a more comprehensive basis for disaster mitigation planning, especially in sediment-prone tropical watersheds where conventional field surveys are limited

2.1. Landslide Potential Mitigation

While landslides in volcanic mountainous regions cannot be entirely prevented, their risks can be mitigated through targeted interventions (Karnawati et al., 2009; Andersson-Sköld dan Nyberg, 2016; Maes et al., 2017; Kamal et al., 2023). Landslide potential mitigation in the Bili-Bili Reservoir Catchment Area is critical due to the catastrophic 2004 landslide event. Asrib (2012) demonstrated the efficacy of existing sediment control structures: seven upstream sabo dams reduced sediment inflow by 29.56 MCM (35% of total system reduction), seven midstream consolidation dams and five downstream sand pockets contributed 49.99 MCM (58%), while upstream dredging removed 7.70 MCM (7%).

The Pompengan-Jeneberang River Basin Organization (BBWS Pompengan Jeneberang) has constructed 28 sediment control structures, including sabo dams, consolidation dams, and sand pockets (Figure 9). However, 1 sabo dam, 4 consolidation dams, and 2 sand pockets are severely damaged due to sediment overload, reducing the system's capacity to intercept debris flows as originally designed. The remaining storage capacities of these structures are detailed in Table 4.

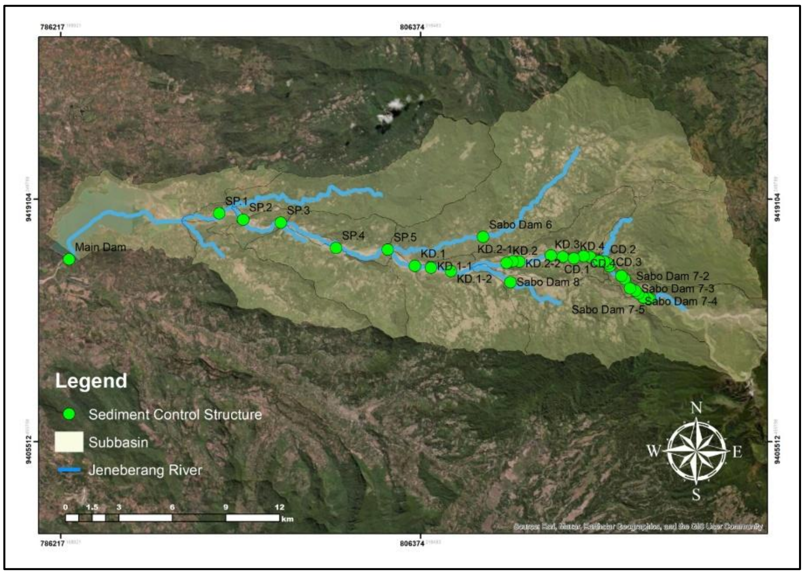

Figure 9. Map of existing sediment control structures in the Bili-Bili Reservoir catchment area
Source: BBWS Pompengan Jeneberang (2020)

Table 4. Existing sediment control structures in the Bili-Bili Reservoir catchment area

No.	Name	Capacity (m^3)	Description	No.	Name	Capacity (m^3)	Description
1	Sabo Dam 7-7	1.598.400		15	KD.4	705.800	Severely damaged
2	Sabo Dam 7-6	160.000		16	KD.3	925.200	Severely damaged
3	Sabo Dam 7-5	531.400		17	KD.2-3	375.000	
4	Sabo Dam 7-4	1.312.100		18	KD.2-2	375.000	
5	Sabo Dam 7-3	1.251.400		19	KD.2-1	375.000	Severely damaged
6	Sabo Dam 7-2	1.719.400	Severely damaged	20	KD.2	6.058.500	
7	Sabo Dam 7-1	2.681.120		21	KD.1-2	587.520	
8	CD.4	44.700		22	KD.1-1	587.520	
9	CD.3	1.523.000	Severely damaged	23	KD.1	11.657.800	
10	Groundsill CD.3	18.000		24	SP.5	347.200	
11	CD.2	1.094.700		25	SP.4	453.600	
12	CD.1-1	90.000		26	SP.3	235.900	
13	CD.1	1.642.200		27	SP.2	244.300	Severely damaged
14	KD.4-1	115.000		28	SP.1	878.900	Severely damaged

Source: BBWS Pompengan Jeneberang (2020)

The study conducted by Asrib (2012) constitutes a fundamental reference for formulating landslide mitigation strategies in the Bili-Bili Reservoir Catchment Area. The integration of sabo dams, consolidation dams, and sand pockets has proven effective in limiting sediment yield entering the reservoir, with a total reduction contribution of 75.55 MCM. Considering their role in capturing 29.56 MCM (35%) of the total landslide-derived sediment managed by the control system following the 2004 event, sabo dams should be prioritized and expanded as the primary structural defense against debris flow (Asrib, 2012; Kamal et al., 2023).

While previous studies have focused on the sediment yield after major landslide events, this study contributes new insights by integrating remote sensing-derived deformation analysis with sediment yield estimation to proactively identify high-risk zones. This approach provides a more comprehensive basis for intervention prioritization, especially in areas that show active surface movement but have not yet experienced failure. The delineation of deformation hotspots offers actionable spatial references for future placement of sediment control infrastructure.

Sabo dams serve not only as sediment control mechanisms for managing lahars and erosion , but also contribute to water conservation by elevating water levels (Asrib, 2012). These structures integrate civil engineering and ecohydrological principles, making them multifunctional solutions (Andersson-Sköld dan Nyberg, 2016; Maes et al., 2017). Future sediment control planning may adopt the established design configuration (Figure 10), which has demonstrated effectiveness: sabo dams upstream to block debris, consolidation dams midstream for flow stability, and sand pockets downstream as final sediment filters (Asrib, 2012). Additional structures can be strategically placed based on landslide potential locations identified through quick assessments.

Maintenance of sediment control structures, including dredging, can be carried out when site conditions allow adequate access. Nevertheless, dredging from existing structures requires careful deliberation, as it represents the most expensive and least cost-effective method of sediment management (Morris and Fan, 2010). To date, no rehabilitation efforts have been undertaken for the existing sediment control facilities. Before rehabilitation, a comprehensive assessment should first identify the extent of damage and evaluate repair feasibility, considering both structural safety and cost requirements.

In addition to structural mitigation, integrating non-structural mitigation such as slope revegetation and bioengineering is strongly recommended for long-term mitigation optimization. Research demonstrates that vegetation significantly enhances soil shear strength and slope stability compared to bare slopes, depending on plant species and root characteristics (Zayadi et al., 2022; Asada dan Minagawa, 2023; Lann et al., 2024). Several plants have proven effective in erosion control and slope stabilization: (1) Vetiver (*Chrysopogon zizanioides*), known for its deep, robust root system (Badhon et al., 2021; Kumar dan Kumari, 2023); (2) Napier grass (*Pennisetum purpureum*), features dense, deep roots (Saidi et al., 2020); (3) Herbaceous vegetation, enhances slope stability through ground cover and root cohesion (Gong et al., 2024); (4) mahogany (*Swietenia macrophylla*), teak (*Tectona grandis*), and stink bean (*Parkia speciosa*), suitable for gentle slopes with proper drainage, and (5) Indian rosewood (*Dalbergia latifolia*), kaliandra (*Calliandra calothyrsus*), and galam (*Gliricidia sepium*), ideal for steeper slopes when combined with drainage systems or structural reinforcements like retaining walls, gabions, or crib walls (Trung, 2009). These plants can be applied through bioengineering, which integrates engineered solutions with natural vegetation to combat erosion and enhance slope stability naturally.

Figure 10. Condition of existing sabo dams in the Bili-Bili Reservoir catchment area
Source: BBWS Pompengan Jeneberang (2017)

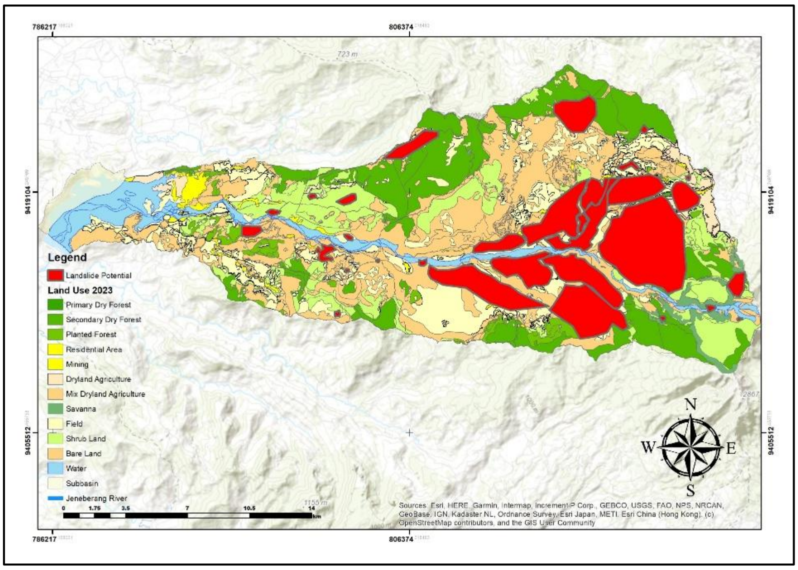

Figure 11. Land use map of the Bili-Bili Reservoir catchment area in 2023
Source: BPKHTL Wilayah VII Makassar (2024)

Based on the land use map in 2023 (Figure 11), landslide potential zones in the Bili-Bili Reservoir Catchment Area are concentrated in secondary dryland forests, shrublands, dryland agricultural areas with mixed shrubs, and rice fields. Vegetation strategies for slope stabilization must integrate climatic adaptability and land use compatibility. In secondary dryland forests, deep-rooted hardwood species such as mahogany, teak, stink bean, Indian rosewood, kaliandra, and galam are recommended, combined with optimized drainage systems to mitigate waterlogging risks. For shrublands and dryland agricultural zones, erosion-resistant grasses like vetiver and napier grass, paired with herbaceous ground cover, enhance slope cohesion. It will be difficult to plant other vegetation in the rice field area, but if it is possible to plant, grass and herbaceous species may be selected. This approach combines ecological suitability with practical agricultural needs, ensuring landslide risk reduction while maintaining the local land use.

This study strengthens the existing mitigation framework by introducing a spatially driven, deformation-based approach to proactively assess landslide hazards. By bridging remote sensing technology and sediment management planning, it supports a more adaptive, evidence-based strategy for protecting critical water infrastructure and downstream communities. By integrating spatial deformation analysis derived from remote sensing with sediment yield estimation, it offers a rapid assessment method capable of identifying risk before failure occurs. This is particularly important in the context of the Bili-Bili Reservoir Catchment Area, where challenging topography limits field accessibility. The mapped hazard zones provide a technical reference for prioritizing the rehabilitation of existing sabo dams or the construction of new structures. Moreover, this spatial information supports more responsive decision-making at the policy level, particularly in protecting critical water infrastructure and reducing risks in downstream areas. This approach is expected to serve as an entry point for integrating remote sensing methods into data- and spatial-driven disaster mitigation policies in Indonesia. Thus, this study not only complements previous research but also expands the scope of mitigation efforts by providing a scientific basis for the integration of spatial technologies, which have not yet been optimally utilized in watershed management planning in Indonesia.

4. Conclusions

Based on a quick assessment using the DInSAR method and Sentinel-1A satellite imagery, this study successfully fulfilled its objectives to (1) quickly assess, (2) identify the locations, and (3) estimate the volume of landslide potential in the Bili-Bili Reservoir Catchment Area. The analysis revealed maximum surface deformation of ±1.55 meters, with high-risk zones concentrated in the upstream areas, covering a total landslide potential area of 71.00 km² and an estimated mobilizable material volume of 110.04 MCM. Furthermore, sediment yield from potential landslides is projected to reach 27.14 MCM per year, nearly equivalent to the reservoir's dead storage capacity.

These findings highlight the urgency of strengthening landslide mitigation efforts in the region. Structural mitigation measures, such as sabo dams, consolidation dams, and sand pockets, have shown effectiveness in reducing sediment inflow into the Jeneberang River and Bili-Bili Reservoir. However, several existing structures are no longer functioning optimally. Therefore, expanding sediment control systems, particularly sabo dams, and rehabilitating damaged infrastructure should be prioritized based on feasibility and cost-effectiveness. Dredging may be considered where accessible. In addition, integrating non-structural strategies such as slope revegetation and bioengineering is strongly recommended to enhance slope stability and complement structural interventions. Together, these approaches form a comprehensive strategy for reducing landslide risks and preserving the functionality of the reservoir.

Beyond its technical contributions, this study provides actionable insights that can inform sediment management planning and disaster mitigation policy. The use of DInSAR and satellite imagery offers a replicable and cost-effective approach for early identification of landslide hazards, particularly in remote or data-scarce tropical catchments. This framework can serve as a model for other reservoir systems across Indonesia and similar geographies facing sediment-related challenges.

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