

Integrated empirical-hydrodynamic assessment of sediment regime transformation in a tropical cascade reservoir system

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Abstract: Reservoir sedimentation threatens the long-term performance of multipurpose dams, especially in cascade systems where upstream flushing may intensify downstream deposition. This study aimed to diagnose sediment regime transformation in Sutami Reservoir within the Sengguruh-Sutami cascade system, East Java, Indonesia. An integrated framework combining the Borland–Miller empirical area reduction method (EARM), bathymetric differencing, and two-dimensional hydrodynamic modelling using the two-dimensional hydrodynamic-sediment transport solver in iRIC (Nays2DH) was applied using historical profile data (1972–2021) and bathymetric surveys from 2016 and 2021. The analyses showed that approximately $8.50 \cdot 10^6 \text{ m}^3$ of sediment was redistributed during 2016 to 2021, with about 62% accumulating below elevation 240 m, while the zero-capacity elevation rose by 0.24 m. Bathymetric differencing indicated a net storage loss of $7.06 \cdot 10^6 \text{ m}^3$ and confirmed downstream migration of deposition into the mid-reservoir and near-dam zones. The hydrodynamic simulation was used qualitatively to identify transport mechanisms rather than to hindcast the cumulative five-year sediment budget, and it showed that density-driven sediment plumes generated during upstream flushing can bypass shallow delta zones and promote deposition in deeper parts of the reservoir. The combined evidence indicates that the sediment distribution pattern in Sutami Reservoir has shifted from predominantly upstream/delta deposition toward increasing deposition in the deeper parts of the reservoir, broadly corresponding to a transition from Type I toward Type III–IV Borland–Miller distribution characteristics. So sedimentation in Sutami cannot be interpreted as an isolated single-reservoir process and support the need for coordinated cascade scale sediment management.

Keywords: bathymetric differencing, cascade reservoir, empirical area reduction method (EARM), flushing-induced transport, hydrodynamic modelling, reservoir sedimentation, sediment regime transition

INTRODUCTION

Sedimentation of reservoirs is well recognised as a major threat to the long-term health and operation of water infrastructure. Continued sedimentation further decreased live water storage, compromising the capacity for reservoir functions and increasing deterioration of infrastructure. Reservoirs worldwide

average a loss of 0.5 to 1.0% of their live storage annually up to four times higher in catchments with land-use change and watershed disturbance (Annandale, Morris and Kark, 2016). This means such impacts are especially critical with regards to multi-purpose reservoirs as sediment fills hydropower generation and flood attenuation or function water supply reliability (Morris, 2020).

Sedimentation processes are becoming more complex in cascade reservoir systems due to upstream interventions directly modify downstream sediment dynamics. A single reservoir, sediment analysis is mainly evaluating internal trapping, storage loss, and reservoir deposition patterns. In contrast, cascade reservoir analysis must consider inter-reservoir sediment transfer, especially when upstream flushing redistributes sediment to downstream reservoirs. Such interactions create operational tradeoffs that cannot be explained through isolated single reservoir assessment alone.

Prior research has investigated delta progradation, density currents, and near dam aggradation (Wan *et al.*, 2021). Empirical methodologies, such as the Borland–Miller empirical area reduction method (EARM), are extensively employed to assess long-term storage loss, whereas GIS based bathymetric differencing provide spatial evidence of erosion and deposition. Numerical modelling complements these methods by identifying transport sediment and distribution mechanisms, particularly during flushing sediment events (Li *et al.*, 2024). However, these approaches are often applied separately, producing fragmented interpretations. Therefore, a major gap remains in integrating these methods within a single framework capable of diagnosing sediment regime transition in tropical cascade reservoirs.

This study develops an integrated empirical-spatial-numerical framework to diagnose sediment regime transformation in a tropical cascade reservoir system. This study focuses on Sutami Reservoir. It is a downstream reservoir in the Sengguruh–Sutami cascade system in the Brantas River Basin, East Java, Indonesia (Sisinggih *et al.*, 2023a). Sutami was originally constructed in 1972 as a Type I (lake-type) reservoir with dominant upstream sediment trapping (Directorate General of Water Resources, 2019). There have been repeated flushing operations at Sengguruh Reservoir which have altered sediment delivery to Sutami. Accordingly, the study aims to diagnose whether Sutami has

shifted from a Type I to a Type III–IV sedimentation regime. This transition has important implications for storage capacity, intake safety, and hydropower reliability (Ran *et al.*, 2023). It is also to provide evidence relevant for coordinated sediment management at the cascade scale.

MATERIALS AND METHODS

STUDY MATERIALS

The Brantas River Basin in East Java, Indonesia, contains a cascade of multipurpose reservoirs that support water supply, hydropower, and flood regulation (Hidayat *et al.*, 2017). This study focuses on the Sutami reservoir, as seen in Figure 1, the most functionally interdependent part of the Sengguruh–Sutami cascade subsystem. Here, Sengguruh serves as an upstream sediment trap equipped with flushing outlets (Sisinggih *et al.*, 2023b). Meanwhile Sutami, located downstream, was constructed for multipurpose operation without sediment-flushing facilities. Sutami is approximately 12 km long and exceeds 86.5 m in depth near the dam.

For spatial interpretation, the reservoir was divided into three functional zones. There are upstream delta (>6 km from the dam), mid-reservoir (2–6 km), and near-dam (0–2 km). These zones represent the initial sediment deposited, the flow-transition reach, and the critical infrastructure zone, respectively. Historical capacity-area curves, longitudinal profiles from 1972 onward, as shown in Figure 2, and bathymetric surveys conducted in 2016 and 2021 provided the empirical basis for evaluating long-term sedimentation in Sutami Reservoir. These datasets were complemented by inflow and operational records from Sengguruh Reservoir to interpret downstream sediment redistribution under cascade operation.

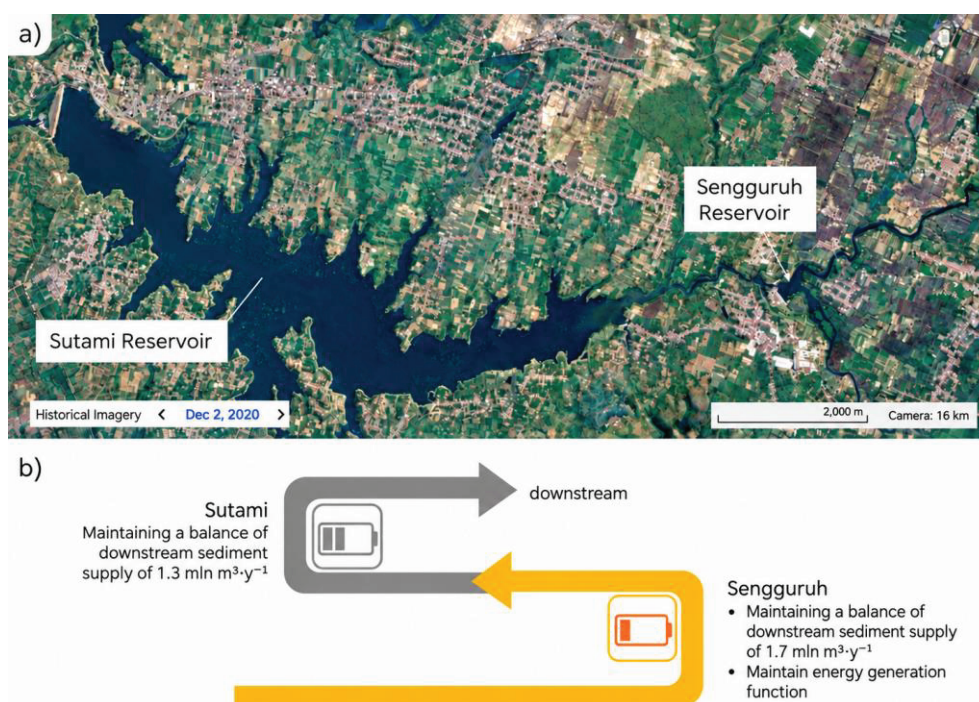


Fig. 1. The Sengguruh–Sutami cascade system in the Brantas River Basin, East Java, Indonesia: a) location, b) scheme; source: a) Google Earth, December 2, 2020 (Maxar Technologies, 2020), modified, b) Jasa Tirta I (2023), modified

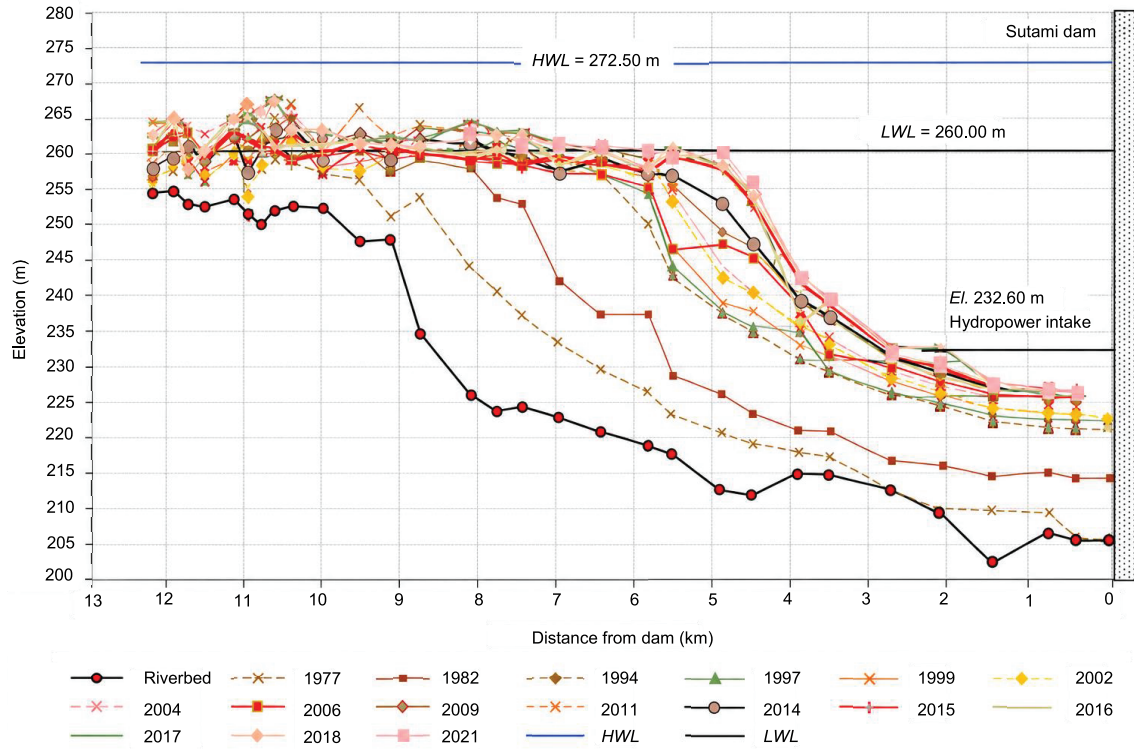


Fig. 2. Long-term morphological evolution of Sutami Reservoir based on historical longitudinal profiles, showing the downstream migration of the depositional front from the upstream delta toward the mid-reservoir and near-dam zones; HWL = high water level, LWL = low water level, El. = elevation; source: Jasa Tirta I (2023)

STUDY METHODS

The analysis integrated three complementary components: (i) EARM for long-term volumetric redistribution, (ii) bathymetric differencing for spatial validation of erosion and deposition, and (iii) two-dimensional hydrodynamic-sediment transport solver in iRIC (Nays2DH) hydrodynamic modelling to identify flushing-induced transport mechanisms.

Empirical sediment distribution analysis

The empirical area reduction method (EARM) developed by Borland and Miller (1960) was used to estimate long-term sediment redistribution and revised storage characteristics in Sutami Reservoir. This method classifies reservoirs into four standard types according to reservoir geometry and sediment-deposition characteristics. For each reservoir type, the relative sediment area is expressed as a function of relative depth (p), using the empirical relationship $A_p = Cp^m(1 - p)^n$. The empirical coefficients C , m , and n corresponding to the four reservoir types are provided in Supplementary Table S1, based on the formulation summarised by Strand and Pemberton (1982).

The standard Borland–Miller classification distinguishes four reservoir types based primarily on reservoir geometry: Type I (lake), Type II (floodplain–foothill), Type III (hill), and Type IV (gorge) (Borland and Miller, 1960; Strand and Pemberton, 1982).

The procedure used in the Borland–Miller EARM followed the standard sequence below.

1. Determine the sediment inflow volume to be redistributed within the reservoir.
2. Select the design curve corresponding to the reservoir type.
3. Compute the new zero-capacity elevation at the dam using the original elevation-area-capacity relationships.

4. Evaluate the dimensionless function $F = (S - V_h)/(H \cdot A_h)$.
5. Compute relative depth $p = (h - h_{\min})/H$.
6. Plot the resulting F and p values on the standard type curves to determine p_0 .
7. Calculate the new zero-capacity elevation using $h_0 = p_0H + h_{\min}$ (see Tab. S2).
8. Redistribute the specified sediment volume according to the selected design curve.
9. Recalculate the revised area and capacity curves (see Tab. S3).

The EARM requires reservoir capacity-area data and cumulative sediment volume and is suitable for large reservoirs with limited long-term monitoring. The relative depth (p) is expressed as:

$$p = \frac{h - h_{\min}}{H} \quad (1)$$

where: H = total depth, $h_{\min}$ = the lowest bed elevation.

The relative sediment area (A_p) follows the generalised empirical distribution (Morris and Fan, 1998):

$$A_p = Cp^m(1 - p)^n \quad (2)$$

where: C , m , and n = coefficients varying according to reservoir type.

In this study, EARM was used as a reduced-order tool to estimate depth-dependent sediment redistribution and to evaluate whether the observed pattern remained consistent with Type I behaviour or shifted toward Type III–IV (Tangi *et al.*, 2023). In the EARM application, the central task was the determination of the new zero-capacity elevation (h_0) using the dimensionless function (Strand and Pemberton, 1987):

$$F = \frac{S - V_h}{H \cdot A_h} \quad (3)$$

where: F = the dimensionless function F at several different pool elevations of the reservoir, S = total sediment deposition, V_h = reservoir capacity at each elevation h , A_h = reservoir area at a given elevation h .

The resulting p_0 yields $h_0 = p_0 H + h_{\min}$. The resulting h_0 was used as an indicator of bed rise at the dam section and of its potential operational significance for hydropower head and intake safety. Next, the specified volume of trapped sediment is distributed within the reservoir according to the selected type of curve (Chaudhuri, 2017). Further, the revised area and capacity curves are determined.

Bathymetric survey and spatial analysis

Bathymetric surveys conducted in 2016 and 2021 provided the spatial basis for evaluating morphological change in Sutami Reservoir. Surveyed depth data were transformed into bed-elevation surfaces. Then they were analysed within a GIS framework to produce comparable DEM/TIN representations for both years. The workflow consisted of interpolation, grid resampling, and elevation differencing in producing sediment-thickness maps. Bathymetric differencing provided zone-based and reservoir-wide estimates of net storage change, which were used to cross-check EARM-derived sediment volumes. Because EARM represents gross redistributed sediment volume whereas bathymetric differencing reflects net morphological change, differences between the two estimates were interpreted as the combined effect of scour, bypass, and survey/interpolation uncertainty.

Numerical modelling of flushing-induced sediment transport

Empirical methods cannot resolve event-scale transport pathways or local depositional mechanisms. Therefore, the Nays2DH solver in the iRIC platform (iRIC Software, 2013) was used to simulate the hydrodynamic behaviour of sediment released from Sengguruh Reservoir and entering Sutami Reservoir. In this study, the model was applied qualitatively to identify transport mechanisms and likely deposition pathways. It was not to reproduce the full five-year cumulative deposition volume.

The numerical model domain is illustrated in Figure 3. It covered approximately 12 km from the Sutami inflow to the dam and was discretised into 161×41 non-uniform cells. The model was initialised using the 2016 bathymetric data. Boundary conditions included a flushing-related inflow of about



Fig. 3. Conceptual setup of the two-dimensional hydrodynamic-sediment transport solver in iRIC (Nays2DH) model for Sutami Reservoir; source: own study

$50 \text{ m}^3 \cdot \text{s}^{-1}$, a free-outflow downstream boundary, and sediment input representing material released from Sengguruh. Because flushing plumes are typically dominated by finer fractions, the simulation should be interpreted as a mechanism-oriented representation of sediment transport. The grain-size information used in the simulation, including the sediment fractions from Sengguruh Reservoir and the representative bed material in Sutami Reservoir, is provided in Supplementary Table S4. The initial bed material in Sutami Reservoir is set uniformly as representative grain size ($D_{60} = 1.2 \text{ mm}$).

Although the flushing operation extended beyond one day, the simulation was restricted to the first day because peak entrainment and strongest hydrodynamic forcing occur during the initial drawdown phase (Reckendorfer, Badura and Schütz, 2019). This setup was intended to capture the dominant plume-dispersion and depositional processes rather than to reproduce the cumulative multi-year sediment budget (Mackie, Stevenson and Burgess, 2024).

Validation and uncertainty interpretation

To assess agreement between the empirical sediment redistribution analysis and the bathymetry based volumetric estimate, a percentage error metric was used. This comparison was intended as an agreement check between two independent estimates with different physical meanings. The EARM represents gross redistributed sediment volume, whereas bathymetric differencing represents net storage loss.

RESULTS AND DISCUSSION

LONG-TERM MORPHOLOGICAL EVOLUTION AND STORAGE LOSS

Over five decades, the longitudinal profiles of Sutami Reservoir show a clear morphological transition. In the early operation period (from 1970s to 1980s), sedimentation was concentrated in the upstream reach and remained consistent with Type I behaviour. It was characterised by deltaic deposition and limited disturbance near the dam. By the period from 1990s to 2000s, the sediment front had migrated into the mid-reservoir reach. It was indicating a departure from the original Type I pattern and a progressive reduction in effective depth. In the most recent period (2016–2021), bed aggradation extended into the near dam zone. There were some sections approaching the intake elevation at 232.6 m. The occurrence of deposition in these deeper operationally sensitive areas indicates a transition toward Type III–IV behaviour. It was consistent with downstream transport of finer sediment during upstream flushing events.

SEDIMENT DYNAMICS IN CASCADE RESERVOIR SYSTEMS

The average annual sediment inflow at Sutami was approximately $1.70 \cdot 10^6 \text{ m}^3$ (Jasa Tirta I, 2021). Furthermore, there were flushing events at Sengguruh in 2016 and 2018. They introduced additional sediment pulses of around $2.00 \cdot 10^6 \text{ m}^3$. During the period 2016 to 2021, EARM calculated a cumulative redistributed sediment volume of $8.50 \cdot 10^6 \text{ m}^3$. It resulted $p_0 = 0.005$ and $h_0 = 224.24 \text{ m}$, indicating a bed rise of 0.24 m at the dam section.

The EARM demonstrates that the vertical sediment distribution significantly deviated from the expected Type I pattern (Fig. 4). Approximately 62% of the redistributed sediment settled below an elevation of 240 m, 28% between 240 and 260 m, and just 10% above 260 m (Tab. 1). This pattern has transitioned to deeper zones instead of remaining concentrated in the upstream delta. Furthermore, the progressive sediment accumulation concentrated in the mid reservoir and near-dam zones. They are validating a transition from Type I to Type III–IV.

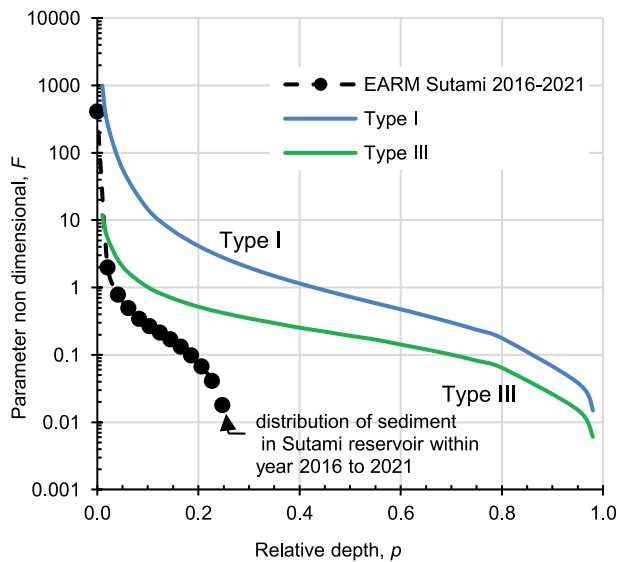


Fig. 4. Empirical area reduction method (EARM) distribution curve for Sutami Reservoir (2016–2021) compared against standard Borland–Miller curves (Type I and Type III); source: own study

Table 1. Comparative sediment distribution in Sutami Reservoir during 2016–2021 based on EARM versus the Type I theoretical model

Depth zone	Elevation range (m)	Observed EARM distribution (2016–2021)	Type I theoretical distribution	Deviation
Upper	260–272.5	~10%	~30–35%	from –25 to –20%
Middle	240–260	~28%	~40–45%	from –17 to –12%
Lower	224–240	~62%	~20–25%	from +37 to +42%

Source: own study.

SPATIAL VALIDATION USING BATHYMETRIC DIFFERENCING

Bathymetric validation is important because it shows operational risks (Specht *et al.*, 2021). Bathymetric differencing in Figure 5 provided direct spatial evidence of downstream migration of deposition zones. The elevation-surface comparison confirmed that sediment accumulation had extended into the mid reservoir and near dam pools, consistent with the empirical interpretation of regime transition (Kasprak, Sankey and Butterfield, 2021).

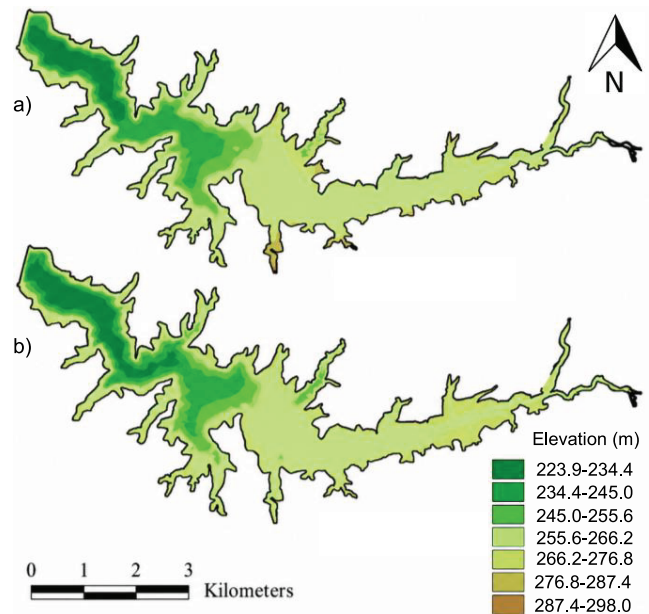


Fig. 5. Bathymetric comparison of Sutami Reservoir, showing downstream migration of deposition into the mid reservoir and near dam zones: a) in 2016, b) in 2021; source: own study

The sediment-thickness maps derived from this analysis are shown in Figure 6. These maps showed limited retention in the delta and increased deposition in the mid reservoir and near dam reaches. The significant accretion observed in these zones supports the empirical evidence of a shift from Type I deposition behaviour toward Type III–IV behaviour (Fig. 6). For 2016 to 2021, the net storage loss derived from bathymetric differencing was $7.06 \cdot 10^6 \text{ m}^3$, compared with $8.50 \cdot 10^6 \text{ m}^3$ estimated from EARM. This level of discrepancy (20.44%) is within acceptable engineering tolerance for reservoir-scale sediment assessment (Moriassi *et al.*, 2007; Moriassi *et al.*, 2015; Dong and Lu 2015). This difference also indicates that not all incoming sediments were retained as net storage loss. It suggests the combined influence of bypass, localised scour, and methodological uncertainty (Singh *et al.*, 2023). Despite localised capacity gains at some elevation bands, the reservoir-scale response remained strongly depositional. These results also provide strong evidence of regime change by showing where deposition occurs as well as how it threatens reservoir function.

Relationship between cumulative change in reservoir capacity and elevation for 2016–2021 is shown in Figure 7

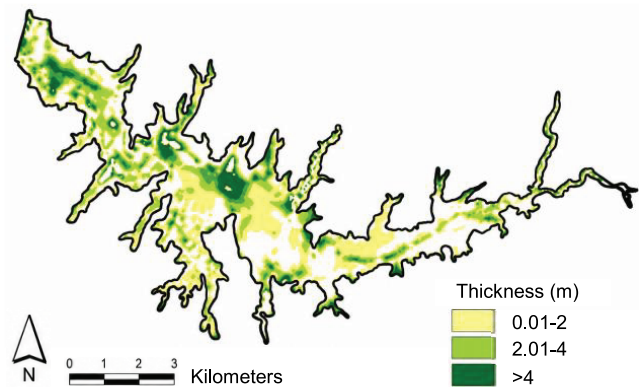


Fig. 6. Sediment-thickness map derived from bathymetric differencing between 2016 and 2021; source: own study

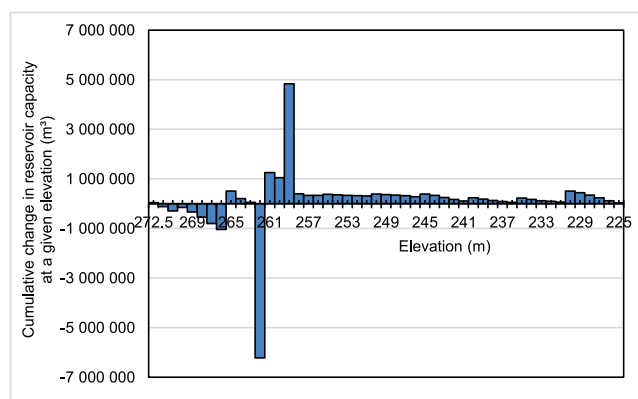


Fig. 7. Relationship between cumulative change in reservoir capacity and elevation for 2016–2021; source: own study

(positive values represent capacity loss associated with sediment deposition, whereas negative values indicate localised scour or sediment evacuation).

HYDRODYNAMIC INFLUENCE ON SEDIMENT REDISTRIBUTION

Two-dimensional hydrodynamic-sediment transport solver in iRIC (Nays2DH) simulations were used qualitatively to identify transport mechanisms associated with Sengguruh flushing. The model showed that suspended sediment plumes propagated rapidly from the Sutami inlet toward the mid reservoir (Fig. 8). That density driven transport could move fine sediment beyond the upstream delta and into deeper zones. The simulated bed elevation changes indicated localised scouring near the inflow and

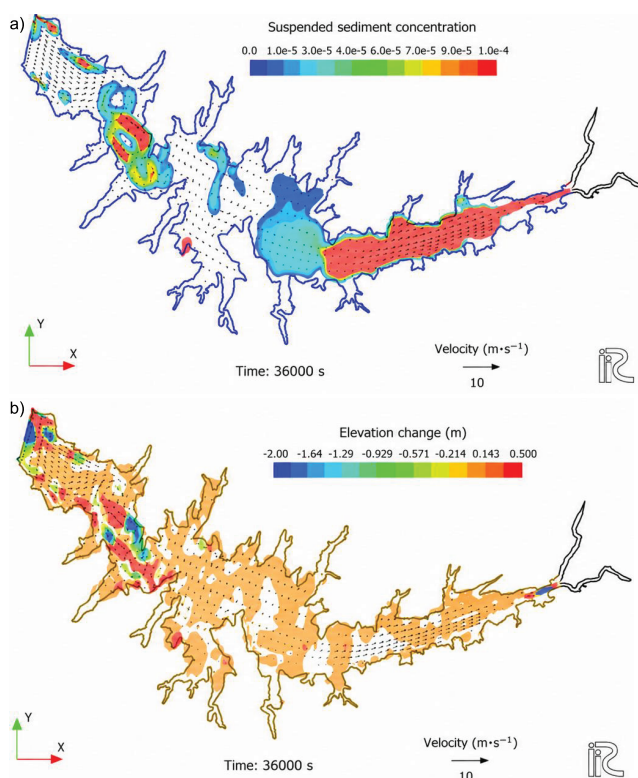


Fig. 8. Two-panel hydrodynamic simulation output: a) suspended sediment plume propagation, b) simulated bed-elevation response during upstream flushing; source: own study

deposition farther downstream. A zone-based comparison between the observed bathymetric tendencies and the simulated deposition behaviour is provided in Supplementary Table S5. These outputs show process-based evidence of likely transport pathways. There are not as a predictive hindcast of the entire 2016 to 2021 sediment budget.

SEDIMENT REGIME TRANSITION AND MANAGEMENT IMPLICATIONS

The empirical, spatial, and numerical analyses consistently indicate a transformation in the sedimentation regime of Sutami Reservoir. The integrated results reveal a clear transition from Type I (delta-dominated) to Type III–IV (deep-pool-dominated) sedimentation. The significance of this shift is that sediment accumulation is no longer confined to upstream reaches but increasingly affects deeper and near dam zones.

The EARM showed that most sediments were redistributed below elevation 240 m. Meanwhile the zero-capacity elevation rose by 0.24 m. The bathymetric differences confirmed substantial accumulation in the mid reservoir and near dam zones. The numerical model further supported the mechanism of density driven transport during upstream flushing. Together, these results indicate that deposition has moved into operationally sensitive areas, increasing risk to live storage and intake performance.

The Sutami–Sengguruh system illustrates the trade-off inherent in cascade reservoir operation. Flushing at the upstream reservoir may temporarily recover storage there. However, it can accelerate sedimentation in the downstream reservoir. The results therefore support coordinated sediment management rather than single reservoir intervention. Possible responses include improved timing of flushing operations, targeted dredging in high-risk zones. The timing of deposition spikes aligns with these events, showing that operational practices upstream have cascading effects downstream (Koshiba, Miura and Sumi, 2022). It is also necessary to consider structural or catchment-scale measures to reduce downstream sediment transfer (Ara and Yasar, 2022; Sueyoshi *et al.*, 2023; Blanckaert *et al.*, 2024). Maintaining the functional performance of Sutami Reservoir therefore contributes to broader sustainable development goals, particularly energy security (SDG 7), reliable water supply (SDG 6), flood resilience (SDG 13), and watershed integrity (SDG 15) (Morris *et al.*, 2023).

LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

Several limitations should be acknowledged. First, EARM is a simplified redistribution method. It does not resolve transient morphodynamical processes. Second, the numerical simulation is event scale and mechanism oriented. There is uncertainty related to boundary conditions, grainsize representation, and calibration. Third, the present assessment is based on Sutami Reservoir, although its interpretation explicitly incorporates cascade forcing from Sengguruh Reservoir.

Although uncertainty affects the absolute magnitude of some estimates, the overall trend of downstream migration and regime transition remains consistent across methods. Future research should focus on improved uncertainty quantification, grainsize characterisation of flushing material, point based validation of simulated deposition, and extension of the framework to additional reservoirs within the cascade.

CONCLUSIONS

This study shows that Sutami Reservoir has shifted from a Type I (delta dominated) sedimentation regime toward a Type III–IV (deep pool aggradation) regime. It is characterised by deeper-pool aggradation. Integrated analysis using empirical area reduction method (EARM), bathymetric differencing, and hydrodynamic modelling indicates that sediment redistribution during 2016 to 2021 increasingly affected the mid reservoir and near dam zones. It brought implications for storage loss, intake safety, and hydropower reliability. Although the direct assessment was conducted for Sutami Reservoir, the results demonstrate that its sedimentation behaviour is strongly controlled by sediment transfer from Sengguruh Reservoir during upstream flushing. Therefore, sediment management in the Sengguruh-Sutami system should be approached at the cascade scale rather than through isolated single reservoir measures.

ABBREVIATIONS

A_h	= reservoir area at each elevation h (m^2)
A_p	= relative sediment area
D_{60}	= representative grain size (mm)
DEM	= digital elevation model
EARM	= empirical area reduction method
GIS	= Geographic Information System
H	= reservoir depth (m)
h	= given elevation (m)
h_0	= zero capacity elevation (m)
h_{min}	= minimum reservoir bed elevation (m)
Nays2DH	= two-dimensional hydrodynamic-sediment transport solver in iRIC
p	= relative depth of reservoir measured from the bottom (–)
p_0	= relative depth corresponding to the zero-capacity elevation (–)
TIN	= triangulated irregular network

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at: https://www.jwld.pl/files/Supplementary_material_71_Sisingih.pdf.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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