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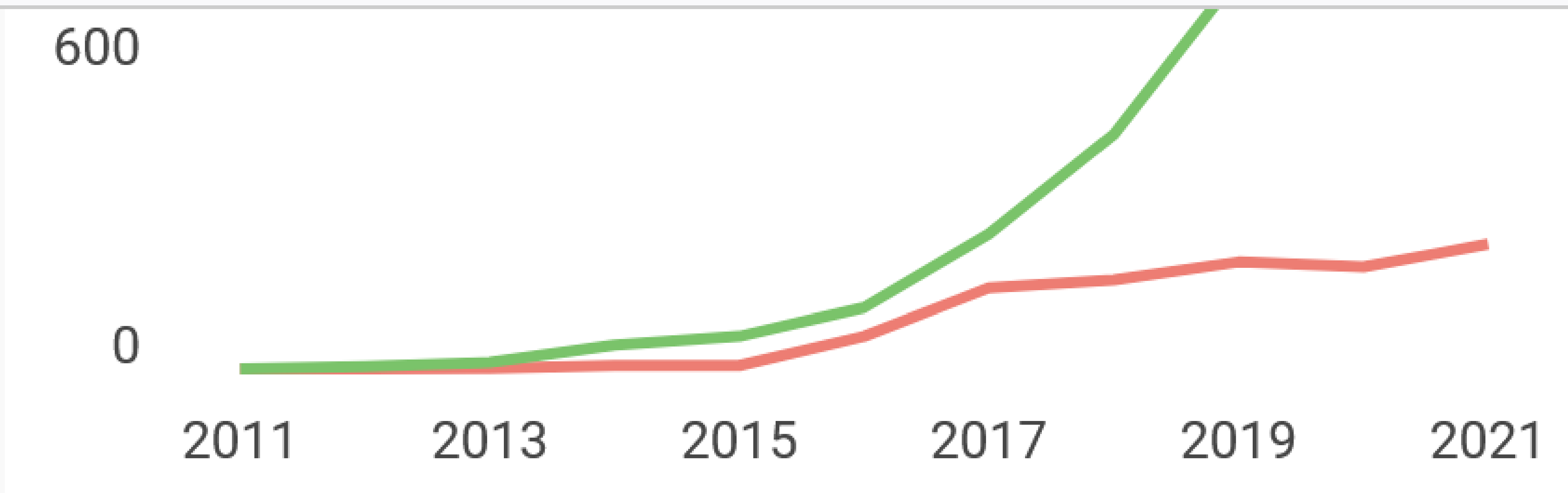

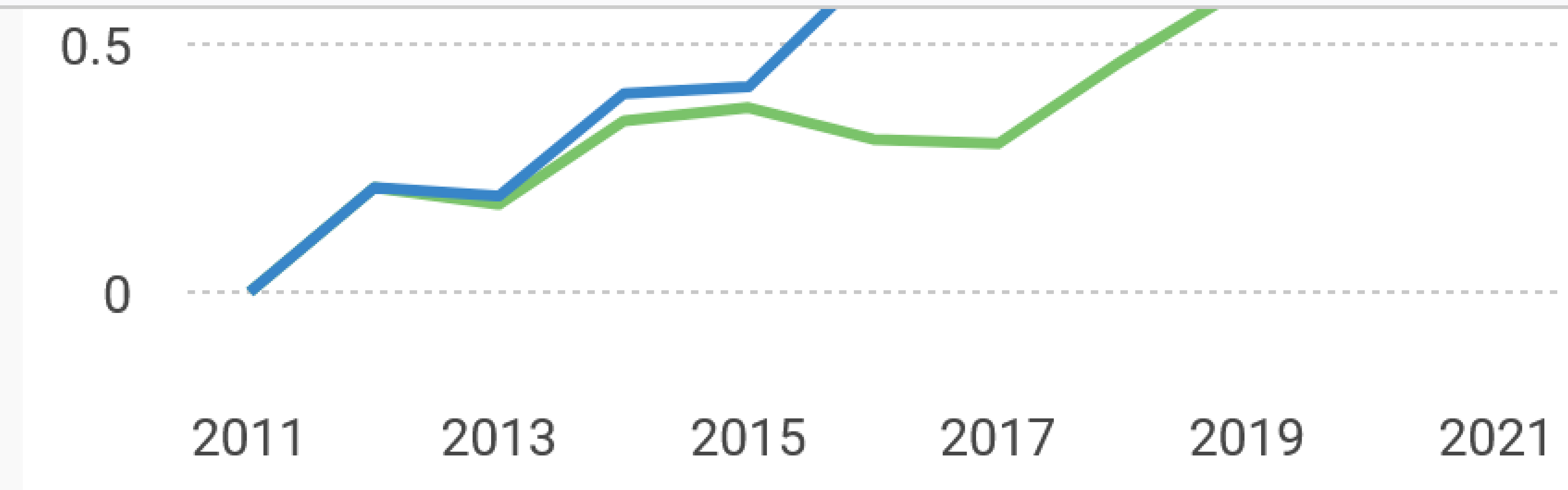

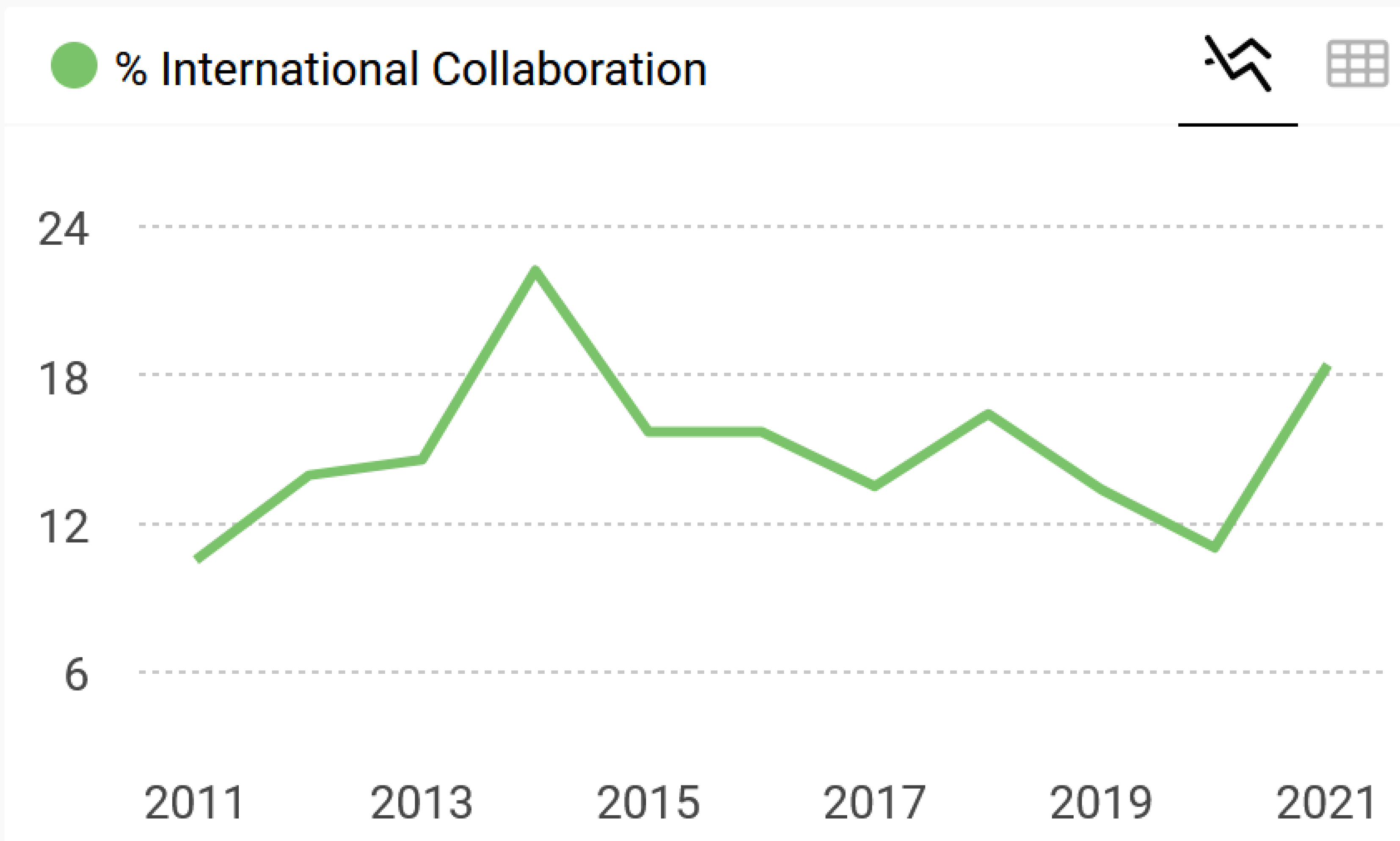

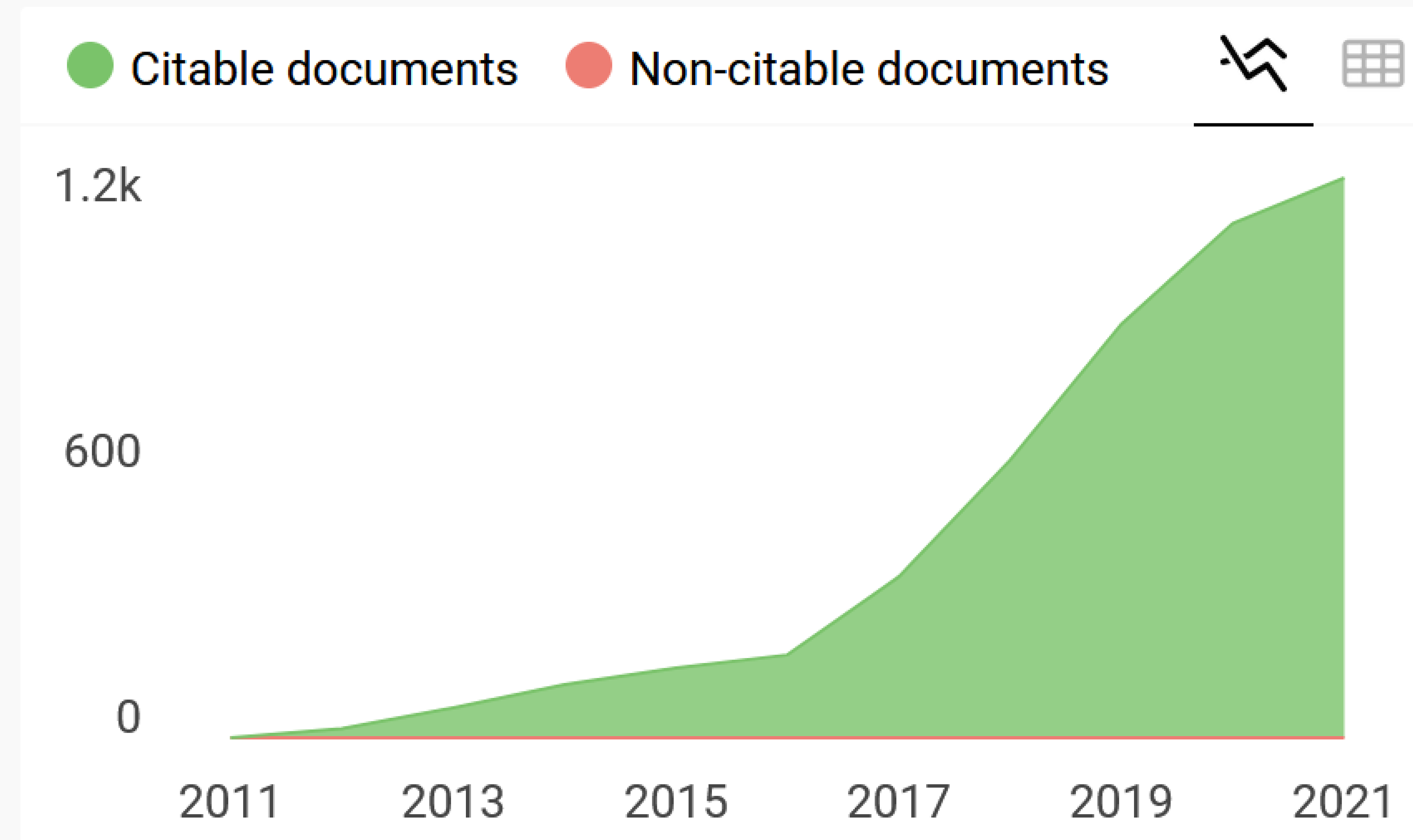

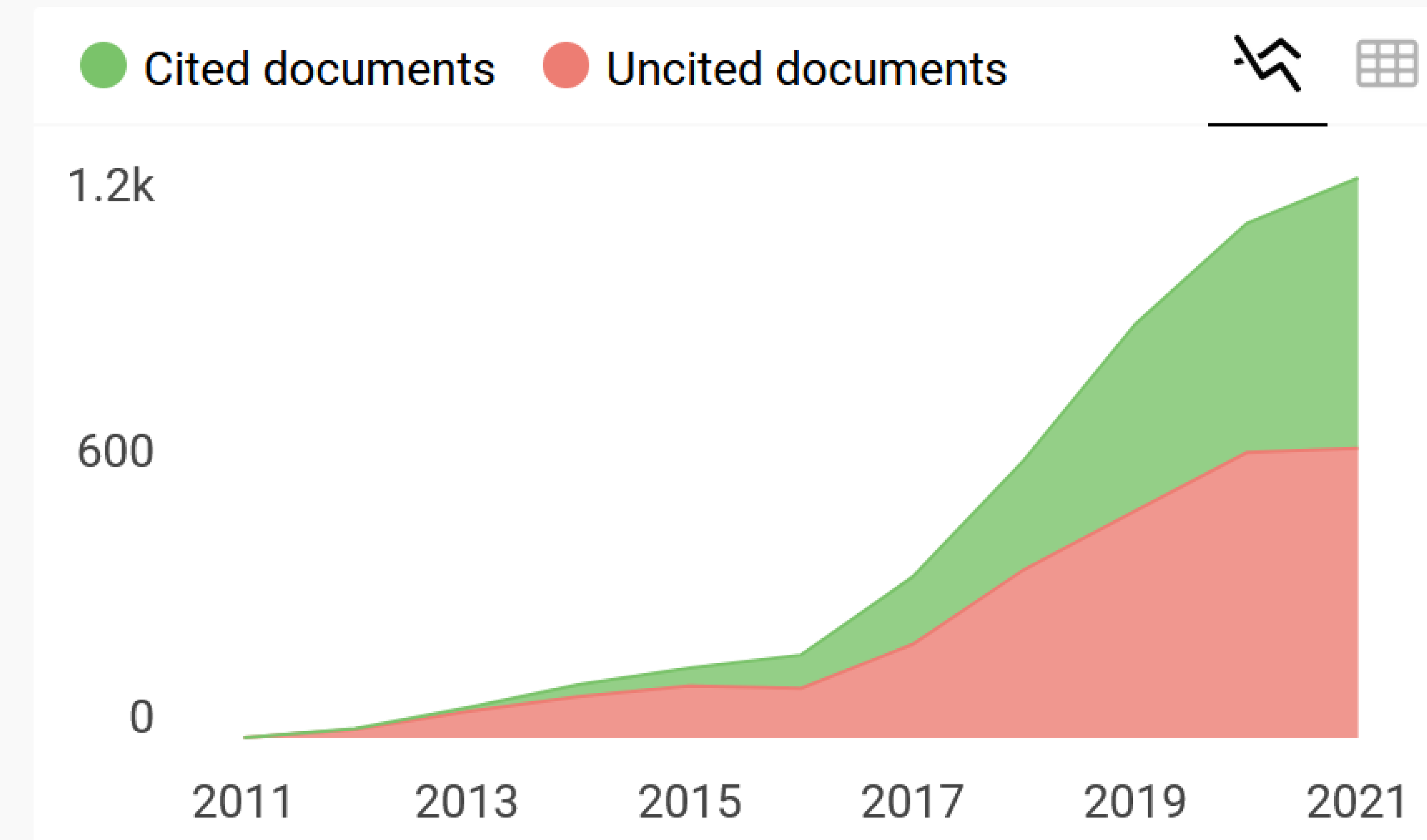

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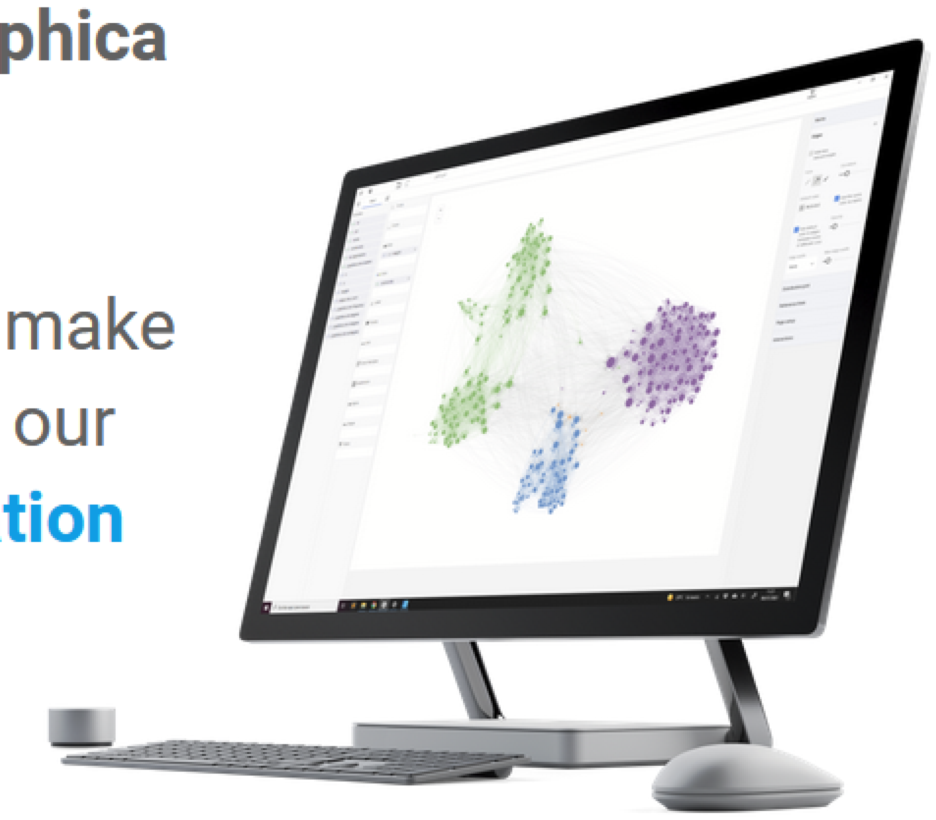

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Naoto Naito, Tatsuya Matsuda, Kinya Miura, Takumu Omura, Arif Daniel Bin 1-8

Azmi

PDF

RESPONSE SURFACE MODELLING OF PERFORMANCE OF CONCRETE WITH BAUXITE LATERITE SOIL AND FLY ASH

Joenel Galupino, Mary Ann Adajar 9-16

PDF

LONG-TERM DEFLECTION OF PRESTRESSED CONCRETE BOX GIRDER BRIDGES DUE TO CREEP AND SHRINKAGE

Luki Hariando Purba, Bambang Supriyadi, Bambang Suhendro 17-24

PDF

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107-114

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Dian Sisinggih, Sri Wahyuni, Mokhammad Farid Maruf, Fahmi Hidayat

115-122

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EVALUATION OF SUSTAINABLE SEDIMENT MANAGEMENT IN SENGGURUH RESERVOIR CONSIDERING AGE AND TRAPPING EFFICIENCY

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ABSTRACT: Trap efficiency is essential in governing the sedimentation process, as the volume of sediment trapped in a reservoir depends on it. The trap efficiency values were a tool to evaluate sustainable reservoir sediment management scenarios in Sengguruh. Theoretically, the reservoir could trap much sediment with higher trap efficiency values. However, along with the age of a reservoir, the sediment trap efficiency decreased. This paper aims to analyze long-term historical records of sediment trap efficiency and to evaluate the scenarios of sustainable sediment management in the Sengguruh Reservoir. Results indicated that after its completion in 1988, the sediment trap efficiency of Sengguruh Reservoir has continued to fluctuate yearly instead of conservation efforts. The trap efficiency sharply reduced during the initial impounding in 1988–1989. Later, in 1990–1994, the depletion rate became mild as introduced sediment dredging works. In February 2004, a massive landslide and flash flood in the upper catchment produced more sediment transported to the Sengguruh reservoir. Therefore, the trap efficiency remained low, between 15 and 20%. The predicted value of future trap efficiency with Brown's method yielded slightly lower values than the Churchill method but still gave good results compared to observed values. With the dredging-only scenario, the future trap efficiency varied between 15% and 20%. In contrast, the combination of dredging and flushing yielded a value between 20% and 35%. Further, dredging 310,000 m^3 annually and flushing 1,200,000 m^3 every three years provided better trap efficiency results for future sustainable sediment management in the Sengguruh Reservoir.

Keywords: Trap efficiency, Brown, Churchill, Sedimentation, Dredging, Flushing

1. INTRODUCTION

On a worldwide scale, reservoir sedimentation is a significant problem because it reduces reservoir capacity by depositing material from watersheds [1]. Regardless of the purpose, reservoirs created after the building of dams affect the flow regimes (or sediment transport regimes), which reduces their storage capacity. According to the World Commission on Dams, 2000, sedimentation is attributed to the 0.5–1% annual loss of storage capacity in reservoirs around the globe [2]. Therefore, global reservoir storage capacity may be lost by almost 25% over the next 25 to 50 years without reducing sediment deposition. Consequently, it is essential to know how many sediments have accumulated in a reservoir using various estimating techniques [3].

Over time, reservoirs continue to accumulate silt and water, which reduces both their storage capacity and the reliability of the water supply. Even though the benefits are not as great as in the original project, most operators are interested in preserving the infrastructure and continuing to produce economic and social benefits, including water supply, hydropower, and flood mitigation management. When a reservoir is finished, the water level, depth rise, and flow rate decline. Later, the reservoir's capacity gradually decreases due to silt buildup [4].

The long-term risk caused by reservoir sedimentation must also be considered while planning, building, and maintaining dam and reservoir projects. Adopting a new design and operational standard focusing on controlling the reservoir and watershed system to balance sediment inflow and outflow helps prolong the dam's life [5,6].

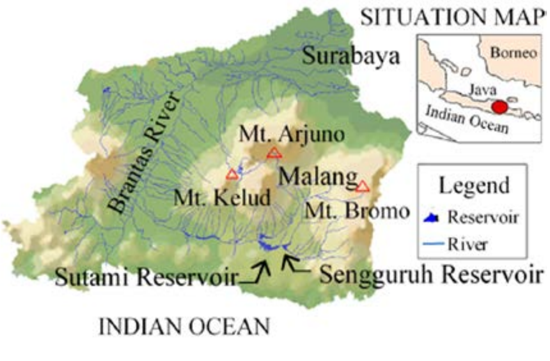

Fig.1 Location of Sengguruh and Sutami Reservoirs in the Brantas River Basin, East Java, Indonesia

Almost all Brantas River Basin reservoirs also have sedimentation issues. Reduced storage capacity impacts how much water is allocated for energy production, how much raw water need for agriculture during the dry season, and the effectiveness of flood management during the rainy season. Sengguruh Reservoir is a daily reservoir whose position is the most upstream in the Brantas basin (Fig.1). The Sengguruh Dam is a rock-fill dam with an upright core with a height of 37 m and a peak length of 700 m. It has a catchment area of 1,659 km^2 and is built at the downstream confluence of the Brantas and Lesti Rivers. The initial gross storage volume is 21.5 million m^3. The dam generates electricity with an installed capacity of 2 x 14.5 MW and holds back sediment entering the Sutami Reservoir to extend its economic life.

The Sengguruh Reservoir is experiencing high sedimentation of 1.81 million m^3/year due to land use changes in the upstream catchment and erosion of eruption material on Mount Semeru [7]. Since its completion in 1988, sediment accumulation in the Sengguruh Reservoir has reduced the effective storage capacity to 76.8% of the original storage capacity. The sedimentation rate was high immediately after the initial operation; around 15 million m^3 of sediment entered the reservoir in the first five years. In addition, lost storage capacity reduces the sediment efficiency trap value of the reservoir, reducing its ability to catch sediment. Therefore, it is needed to keep the reservoir's useful life and improve services. The authority (Jasa Tirta I) also makes efforts to remove sediment from the reservoir by dredging 300,000 m^3 per year (Fig.2) despite watershed conservation [8].

Fig.2 The activity of sediment dredging in Sengguruh Reservoir

2. RESEARCH SIGNIFICANCE

Trap efficiency is the ratio of deposited sediment to the total inflow over a certain period. As the age of a reservoir increases, the sediment trap efficiency decreases in most reservoirs. Because the volume of sediment trapped during the design life must be considered in the reservoir capacity, reasonable estimations of a reservoir's sediment trap effectiveness are required. If the estimated trap efficiency is lower than expected, the reservoir's usable life will be cut short. In contrast, if the estimate is higher than required, the reservoir is overdesigned and might not perform as well as it could.

Focusing on the Sengguruh Reservoir in the Brantas River basin, this study aimed to analyze long-term historical records of sediment trap efficiency, predict future sediment trap efficiency based on various sediment management scenarios, and evaluate sustainable sediment management by considering the future sediment trap efficiency.

3. DATA AND METHOD

3.1 Data

In this study, the primary data needed were discharge inflow, sediment inflow, sediment dredging, sediment flushing, and sediment material properties. The data were collected from the basin authority (Jasa Tirta I) and by conducting field investigation [8].

3.2 Methodology

First, the analysis has been done for historical changes in reservoir storage and trap efficiency from construction to the last observation data. Second, we predicted the value of trap efficiency based on the sediment management scenarios in the Sengguruh Reservoir. Here, the Brown and Churchill methods were used and verified with the observed value. Finally, we evaluated the future reservoir sustainable sediment management by considering the future sediment trap efficiency to reservoir life.

3.2.1 Trap Efficiency

Sediment trap efficiency is an essential parameter for determining the loss rate of a reservoir's storage capacity. It is defined as the percentage ratio of retained sediment to the amount of sediment entering the reservoir. It is formulated as [9]:

$$TE = 100 \left[\frac{Q_{si} - Q_{so}}{Q_{si}}\right] \quad (1)$$

where TE denotes sediment trap efficiency (%), Q_{si} and Q_{so} are total sediment inflow and total sediment outflow, respectively.

There are empirical relationships such as Brown (1944), Churchill (1948), Brune (1953), Borland (1971), and many others available for estimation of the sediment trap efficiency of reservoirs. These empirical relationships are widely used for estimating reservoir sediment trap efficiency, but they have the limitation that the characteristics used to develop them were entirely different. For example, Brown suggests a method based on reservoir storage capacity and catchment area relationship (C/W). Churchill proposes the reservoir's sedimentation index (SI) (water retention time ratio to the reservoir's mean velocity). The Brune estimates the trap efficiency value using the capacity-inflow ratio (C/I). However, the Brune curve is unsuitable for calculating trap efficiency in the Sengguruh Reservoir because of the lower C/I for small fluctuating reservoirs (daily reservoirs) such as the Sengguruh Reservoir [10].

Hence, it used the empirical methods of sediment trap efficiency developed by Brown and Churchill to assess the impacts of future scenarios of sediment management. The considerations were:

- Brown method is the simplest because it only requires reservoir capacity and watershed area.
- Churchill method is appropriate for estimating sediment release efficiency in continuously sluiced reservoirs such as stilling basins, small reservoirs, and flood control structures.

3.2.2 Brown Curve

Brown (1943) developed a curve that relates sediment trap efficiency (TE_{Brown}) to a capacity–watershed area ratio (C/W). C is the reservoir storage capacity expressed in m^3, and W is the catchment area represented in km^2 (Fig.3). The Brown curve is helpful when watershed area and reservoir capacity are the only known parameters.

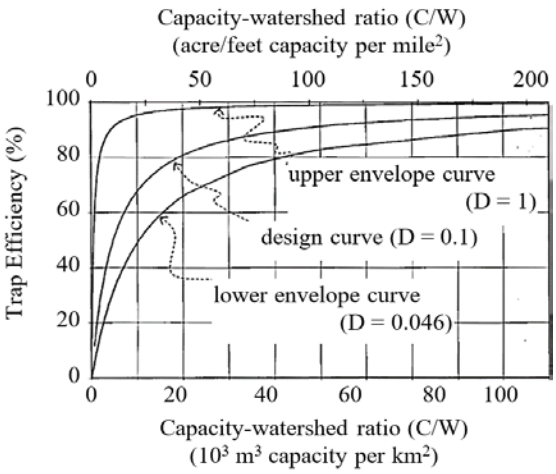

Fig.3 Relationship between trap efficiency and capacity-watershed ratio according to Brown [11]

The empirical value of Brown's trap efficiency is formulated below [12].

$$TE_{Brown}=100\left(1-\frac{1}{1+0.0021D\frac{C}{W}}\right) \quad (2)$$

Values of D range from 0.046 to 1, with a mean value of 0.1, and they depend on a reservoir's characteristics. Brown suggests that values for D are close to 1 for reservoirs in regions with smaller and more variable runoff and for those that hold back and store flood flows [13].

3.2.3 Churchill Curve

Churchill, in 1948 presented a relationship relating the sedimentation index to trapping efficiency (Fig.4). The Sedimentation Index (SI) expresses the ratio of retention time to mean flow velocity in the reservoir [2].

$$SI=\frac{S_{gross}^2}{L.Q_m^2} \quad (3)$$

where S_{gross} denotes gross reservoir storage (m^3), L is the length of reservoir (m), and Q_m is the mean annual inflow discharge (m^3/s).

$$TE_{Churchill}=100-(1600[SI.g]^{-0.2}-12) \quad (4)$$

where $TE_{Churchill}$ is trap efficiency according to Churchill (%), g is the gravitational acceleration (9.81 m/s^2), and SI stands for sedimentation index (s^2/m).

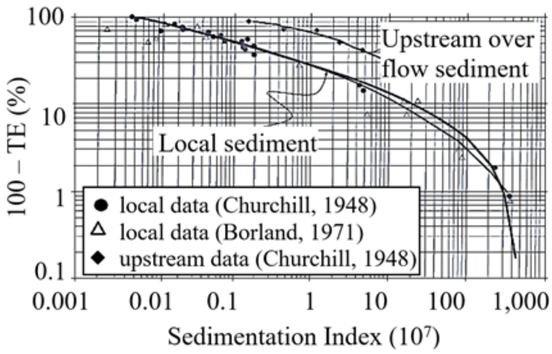

Fig.4 Churchill's curves for determining reservoir trap efficiency [2]

The Churchill curve better assesses trap efficiency for a broader range of reservoir types and reservoirs where sediment management is applied.

4. RESULT AND DISCUSSION

4.1 Observed Sediment Trap Efficiency

Sediment buildup has been significantly decreasing the Sengguruh Reservoir's useful storage capacity since it was finished in 1988. Massive storage losses appeared to have resulted from bank landslides during initial impoundment in 1988-1989 at the start of reservoir operation (Fig.5). Later, from 1990 to 1994, the depletion rate became mild. Since 1994, reservoir dredging has been introduced to remove deposited material. As a result, the trap efficiency increased in 1997-1998, allowing more sediment to be deposited.

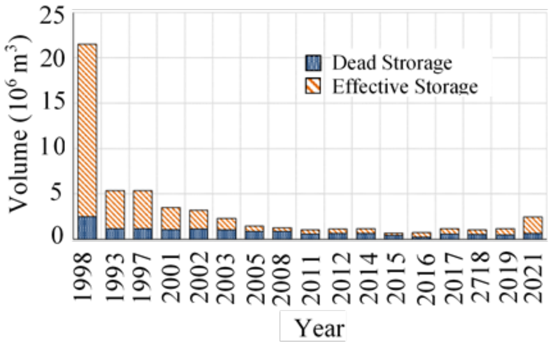

Fig.5 Temporal variation of storage changes in Sengguruh Reservoir (1998 – 2021)

Figure 6 shows that from 2000-2004, the sediment trap efficiency decreased by reducing the dredging capacity. Later, dredging capacity increased again, but trap efficiency remained low. Furthermore, according to the record data, in February 2004, there was a massive landslide and flash flood at the origin of Brantas, which produced additional amounts of sediment transported to the Sengguruh Reservoir [14].

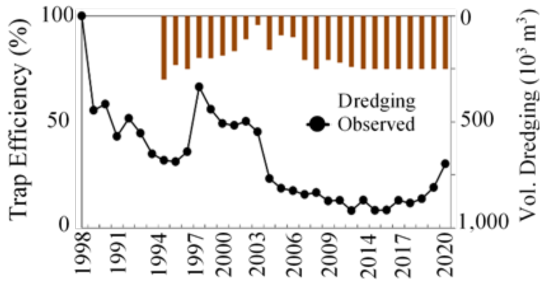

Fig.6 Observed trap efficiency in Sengguruh Reservoir (1988-2021)

Recently, the erosion rate of the upstream watershed has been reduced to 1.2 mm/year, but the reservoir trap efficiency remains low, between 15 and 20%. So then, to increase the trap efficiency value, sediment flushing was introduced. The first flushing attempt was in 2016, followed by 2018 and 2021 [8]. As a result, in 2019–2021, the gross storage changes varied from 1.2 to 2.47 million m^3, gaining a sediment trap efficiency value of 30.2%.

4.2 Sustainable Sediment Management in Sengguruh Reservoir

As the role of the Sengguruh Dam is mainly to serve as a sediment barrier for the Sutami Reservoir, the trap efficiency value must be kept high. The long-term reservoir sediment management in Sengguruh has prompted the consideration of maintaining existing storage by dredging and flushing annually instead of conserving the upstream catchment. They are scenario-1, which includes sediment dredging with an average dredging volume of 310,000 m^3/year, and scenario-2, which takes an average dredging volume of 310,000 m^3/year sediment combined with flushing every three years [8]. The following discussion presented the evaluation of sediment trap efficiency and its impacts on the reservoir's lifetime.

4.3 Future Scenario of Sediment Trap Efficiency

Particle size and distribution, reservoir size, and form, the rate and timing of runoff entering the reservoir, the position and depth of outlets, and the mechanism of reservoir drainage all affect the sediment trap efficiency. For example, the laboratory analysis of the sediment data in Sengguruh Reservoir showed that the D_{50} is about 0.5 mm for medium sediment grain sizes. Assuming that the deposit was sand with a mass density of 2.65 tons per cubic meter, the particle fall velocity was 0.030 m/s.

The Sengguruh is a daily reservoir and a long-term storage reservoir. The summarized data in 2021 [8] to determine the empirical value of trap efficiency are Catchment area, W = 1,659 km^2; Reservoir length, L= 4,000 meters; Gross storage capacity, S_{gross} = 2,470,000 m^3; Mean annual water inflow, Q_m = 57.59 m/s; Annual discharge inflow, I = 1,500,770,000 m^3, and Annual sediment inflow, Q_s = 2,000,000 m^3.

4.3.1 Brown Method

Considering the material properties of deposited sediment in Sengguruh Reservoir, the value of D was 0.15. Meanwhile, C/W is about 1488.85.

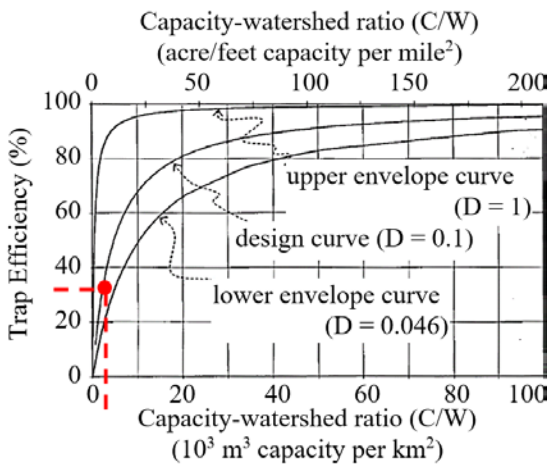

Fig.7 Trap efficiency value plotted on the Brown curve using observed data for 2021

The empirical value of Brown's trap efficiency was calculated as follows:

$$TE_{Brown}=100\left(1-\frac{1}{1+0.0021\ (0.15)^{\frac{2,470,000}{1,659}}}\right) \quad (5)$$

$$TE_{Brown}= 31.93\% \quad (6)$$

In Figure 7, for C/W, about 1488.85 and D, about 1.5, the value of trap efficiency was yielded by plotting on Brown's curve. Here, the sediment deposited in the Sengguruh Reservoir in 2021 was 31.93% of the total sediment inflow or about 638,518 m^3.

4.3.2 Churchill Method

The Sedimentation Index (SI) for Churchill was calculated as follows:

$$SI=\frac{S^2_{gross}}{L.Q^2_m}=\frac{(2.470.000)^2}{4000x\ (57.59)^2}= \ 454,128 \quad (7)$$

For the year 2021, SI value was 454,128. The empirical value of Churchill's trap efficiency was calculated as follows:

$$TE_{Churchill}=100-(1600[(454,128)x\ 9.81]^{-0.2}-12) \quad (8)$$

$$TE_{Churchill}=37.12\% \quad (9)$$

Similarly, utilizing the Churchill curve, the trap efficiency value was also plotted in Figure 8. For SI = 454,128, then (100-TE) = 63% or Churchill's trap efficiency close to 37%. Following the Churchill method, the sediment in the Sengguruh Reservoir in 2021 accounted for 37.12 percent of the total sediment inflow, or 742,453 m^3.

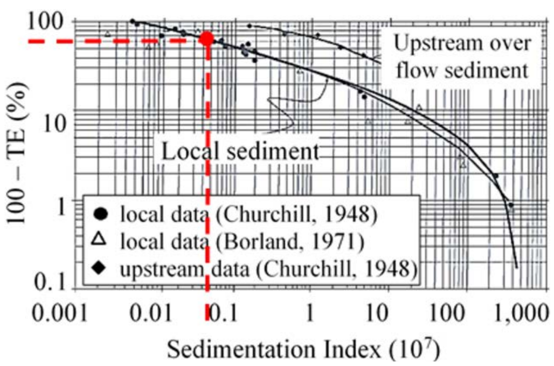

Fig.8 Trap efficiency value plotted on the Churchill curve using observed data for 2021

Brown and Churchill's methods were acceptable compared to the observed trap efficiency values in 2021, as seen in Figure 6. Thus, the Brown value was recommended as the lower limit and Churchill's as the upper limit value of trap efficiencies.

4.3.3 Sediment Trap Efficiency for Scenario-1

In scenario-1, the reservoir storage conservation effort is carried out by dredging activities of 310,000 m^3 per year. Assuming that the annual inflow and sediment discharge was constant yearly, the future sediment trap efficiency (2022–2036) was estimated from the baseline data in 2021.

Here is an example of a calculation for the year 2002 with the Brown method. The gross storage in 2022 was predicted as the gross storage in earlier 2021 subtracted by sediment deposited in 2021 and adding the amount of sediment removed by dredging (2,470,000 - 638,518 + 310,000) m^3 or 2,211,482 m^3. Using the empirical formula (Eq.(2)) for sediment trap efficiency in the year 2022, Brown obtained a trapping efficiency of 21.87%. Then, the sediment deposited in 2022 was about 21.87% of the total sediment inflow, or about 437,420 m^3. The remaining 1,562,580 m^3 of sediment was flowing downstream (Sutami Dam). Similarly, the Churchill method achieved a sediment trap efficiency of 32.22 percent in the same year. The sediment deposited was about 644,311 m^3, while 1,355,689 m^3 was released. The detailed calculations for consecutive years are in Table 1, and the result of trap efficiency is in Figure 9.

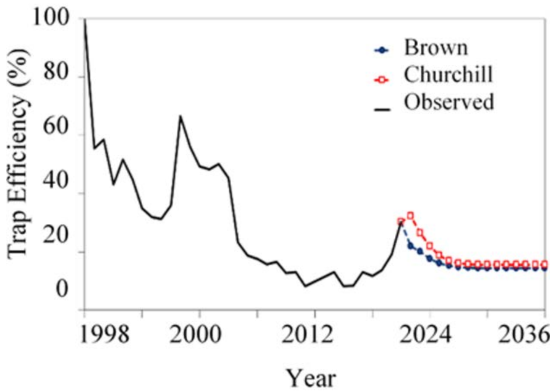

Fig.9 Observed and future predicted values of trap efficiency in Sengguruh Reservoir for scenario-1

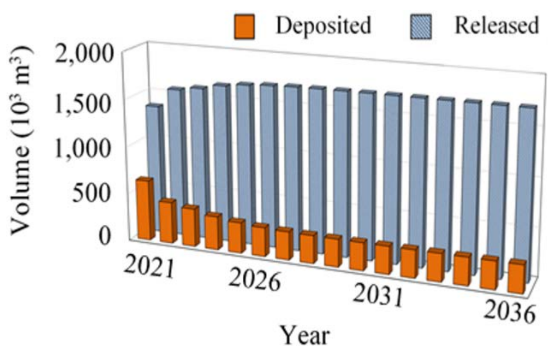

Fig.10 Retained and released sediment according to scenario-1 with the Brown method

Table 1 Trap efficiency and sediment balance in the Sengguruh Reservoir using the Brown and Churchill methods for years 2021 – 2036 with scenario-1

Year	Gross Storage (m^3)		Trap Efficiency (%)		Sediment (m^3)			
					Deposited		Released	
	Brown	Churchill	Brown	Churchill	Brown	Churchill	Brown	Churchill
2021	2,470,000	2,470,000	31.93	37.12	638,518	742,453	1,361,482	1,257,547
2022	2,211,482	2,107,547	21.87	32.22	437,420	644,311	1,562,580	1,355,689
2023	1,980,127	1,773,237	20.04	26.51	400,830	530,171	1,599,170	1,469,829
2024	1,682,406	1,553,065	17.56	21.85	351,145	437,051	1,648,855	1,562,949
2025	1,511,921	1,426,014	16.06	18.72	321,278	374,438	1,678,722	1,625,562
2026	1,414,736	1,361,577	15.19	16.98	303,763	339,611	1,696,237	1,660,389
2027	1,367,814	1,331,965	14.76	16.14	295,175	322,823	1,704,825	1,677,177
2028	1,346,790	1,319,142	14.56	15.77	291,299	315,390	1,708,701	1,684,610
2029	1,337,843	1,313,752	14.48	15.61	289,644	312,236	1,710,356	1,687,764
2030	1,334,108	1,311,516	14.45	15.55	288,952	310,922	1,711,048	1,689,078
2031	1,332,564	1,310,594	14.43	15.52	288,666	310,379	1,711,334	1,689,621
2032	1,331,928	1,310,215	14.43	15.51	288,548	310,156	1,711,452	1,689,844
2033	1,331,667	1,310,059	14.42	15.50	288,500	310,064	1,711,500	1,689,936
2034	1,331,560	1,309,995	14.42	15.50	288,480	310,026	1,711,520	1,689,974
2035	1,331,516	1,309,969	14.42	15.50	288,472	310,011	1,711,528	1,689,989
2036	1,331,497	1,309,958	14.42	15.50	288,468	310,004	1,711,532	1,689,996

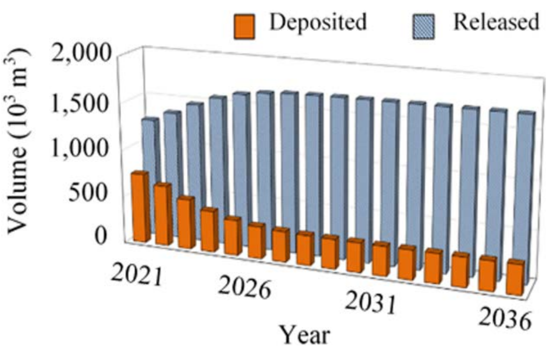

Fig.11 Retained and released sediment according to scenario-1 with the Churchill method

As shown in Figure 9, both Brown and Churchill's methods predicted that the sediment trap efficiency would decrease at the beginning of the first decade and remain constant at about 15% until 2036. However, scenario-1 still gives a lower trend in trap efficiency, as seen from the volume of sediment retained. Meanwhile, Figure 10 and Figure 11 presented retained and released sediment according to scenario-1. Deposition varied from 288,468 to 742,453 m^3/year. Allowing a large number of sediment to be released downstream became worse for the downstream cascade system of reservoirs.

4.3.4 Sediment Trap Efficiency for Scenario-2

In scenario-2, dredging and flushing are carried out to conserve the reservoir storage. The volume of sediment dredging is kept at 310,000 m^3 per year, and 1,200,000 m^3 of deposited sediment is flushed every three years. By employing the same calculating procedures as in scenario-1 with additional flushing every three years, the result of scenario-2 was in Table 2 and Figure 12.

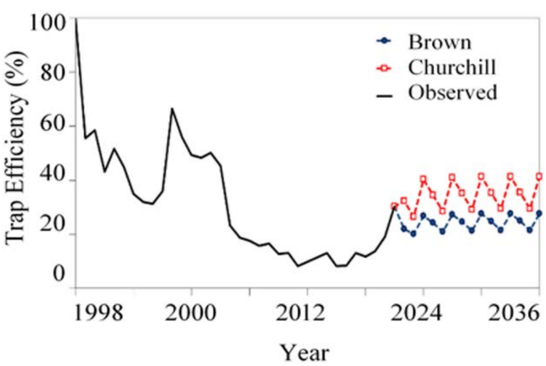

Fig.12 Observed and future predicted values of trap efficiency in Sengguruh Reservoir for scenario-2

Unlike scenario-1, the sediment flushing contributed to significant storage recovery and increased trap efficiency. There were short fluctuations in the sediment trap efficiency periodically after sediment flushing. However, they remained constant at about 25% until 2036 (Fig.12). Further, the useful life of the reservoir was constantly kept within an extended period [15]. Here, retention and released sediment as a result of continued sediment dredging through the year 2036 were also shown in Figures 13 and 14.

Table 2 Trap efficiency and sediment balance in the Sengguruh Reservoir using the Brown and Churchill methods for years 2021 – 2036 with scenario-2

Year	Gross Storage (m^3)		Trap Efficiency (%)		Sediment (m^3)			
					Deposited		Released	
	Brown	Churchill	Brown	Churchill	Brown	Churchill	Brown	Churchill
2021	2,470,000	2,470,000	31.93	37.12	638,518	742,453	1,361,482	1,257,547
2022	2,211,482	2,107,547	21.87	32.22	437,420	644,311	1,562,580	1,355,689
2023	1,980,127	1,773,237	20.04	26.51	400,830	530,171	1,599,170	1,469,829
2024	2,882,406	2,753,065	26.73	40.30	534,650	806,054	1,465,350	1,193,946
2025	2,528,416	2,257,011	24.25	34.37	484,909	687,449	1,515,091	1,312,551
2026	2,082,102	1,879,562	20.86	28.48	417,167	569,538	1,582,833	1,430,462
2027	2,972,395	2,820,024	27.34	40.99	546,778	819,772	1,453,222	1,180,228
2028	2,583,246	2,310,252	24.64	35.09	492,833	701,861	1,507,167	1,298,139
2029	2,127,419	1,918,391	21.22	29.16	424,320	583,145	1,575,680	1,416,855
2030	3,004,071	2,845,246	27.55	41.24	551,000	824,821	1,449,000	1,175,179
2031	2,604,246	2,330,425	24.79	35.36	495,846	707,201	1,504,154	1,292,799
2032	2,144,579	1,933,224	21.35	29.41	427,012	588,242	1,572,988	1,411,758
2033	3,016,212	2,854,982	27.63	41.34	552,611	826,753	1,447,389	1,173,247
2034	2,612,371	2,338,229	24.85	35.46	497,009	709,249	1,502,991	1,290,751
2035	2,151,220	1,938,980	21.40	29.51	428,052	590,205	1,571,948	1,409,795
2036	3,020,928	2,858,775	27.66	41.38	553,237	827,504	1,446,763	1,172,496

Note: shaded row is the year with sediment flushing.

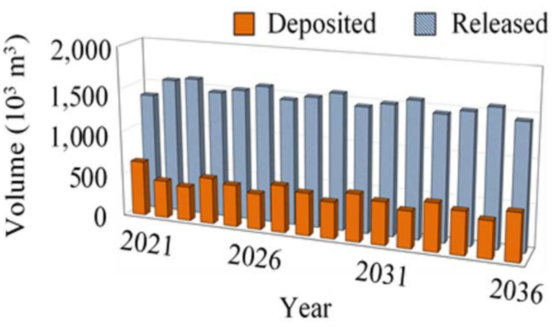

Fig.13 Retained and released sediment according to scenario-2 with the Brown method

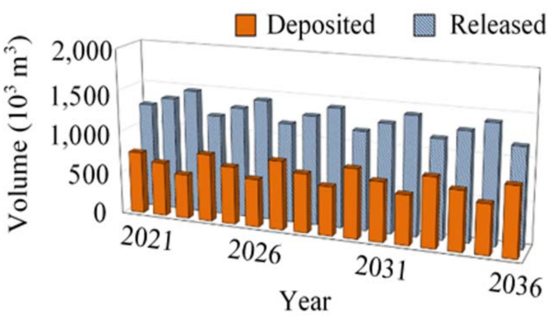

Fig.14 Retained and released sediment according to scenario-2 with the Churchill method

A combination of dredging and flushing gave an average constant trend of trap efficiency values at about 25%, with deposition sediment varied from 400,830 to 827,504 m^3/year. These actions are good for maintaining the sediment trap efficiencies and reducing sediment passed to the downstream reservoir. In addition, a lower number of sediment flows downstream minimizes the maintenance effort of storage conservation in downstream reservoirs. Lastly, scenario-2 was preferable to scenario-1 for the Sengguruh Reservoir's sustainable sediment management.

5. CONCLUSIONS

Along with the reservoir's age, the value of trap efficiencies in Sengguruh Reservoir has decreased through time, either due to increasing incoming sediment or possibly due to the bank's collapse at the start of reservoir operations. In the early-2000s, the sediment dredging recovered part of the storage. Later, it sharply declined again due to a vast landslide disaster at the upstream catchment in 2004.

Evaluating future scenarios of sustainable sediment management was done by considering the value of trap efficiency with Brown and Churchill's methods. In scenario-1, it dredged out of sediment at approximately 310,000 m^3 every year. As a result, the trap efficiency value fluctuated between 15% and 20%. Meanwhile, with the combination of dredging 310,000 m^3 every year and flushing 1,200,000 m^3 every three years (scenario-2), the trap efficiency values varied between 20% and 35%. Therefore, scenario-2 provided better trap efficiency results in a certain period for sustainable sediment management. Consequently, it was recommended for the future storage conservation of the Sengguruh Reservoir. Further, selecting the best value of trap efficiency should be addressed after examining economic and technical factors and the proper upstream sediment input controls to guarantee that the trap efficiency meets the primary objectives.

The limitation of the proposed methods is that they are designed for a small daily reservoir with a lower C/I value. Expanded use of this model for other reservoir types requires other empirical trap efficiency methods, calibration, and validation with site-specific field measurements for the model to be applied confidently. Future research on trap efficiency must thoroughly characterize and investigate (1) the inflowing water and sediment, (2) the size and layout of the reservoir storage, and (3) the characteristics of the deposited material sediment.

6. ACKNOWLEDGMENTS

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