International Journal of Sustainable Development and Planning
Vol. 18, No. 2, February, 2023, pp. 541-548
Journal homepage: http://iieta.org/journals/ijsdp

Discharging Sediment Downstream: The Opportunities and Challenges of Sediment Management in Sutami Reservoir, Indonesia

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https://doi.org/10.18280/ijsdp.180223

Received: 15 November 2022
Accepted: 3 January 2023

Keywords:
dredging, downstream discharging, reservoir, sediment management

ABSTRACT

There is no flushing outlet facility and limited disposal sites for dredged material sediment in Sutami Reservoir. One preferable alternative to evacuate the sediment is directly downstream discharging dredged material. New research into such dredging techniques is therefore essential. This research focused on the technical opportunities and challenges of downstream discharging sediment from Sutami Reservoir. In addition, the HEC-RAS model was used to look at the impacts on the river downstream of the dam. Results showed that 400,000 m^3 should be dredged at two sites (Dempok and Sumberpetung), extended the pipeline to release the slurry material downstream, and two booster pumps installed to maximize dredging productivity. There were no significant impacts on the riverbed alteration downstream of the dam. The slurry material flowed and deposited in Wlingi Dam and could be flushed periodically to avoid excess deposits. There were opportunities to save the cost of disposal area and support the replenishment of sediment. Meanwhile, the challenges were the need to monitor the environmental issues related to water quality downstream, cost investment, and water loss, which cannot re-enter the storage as conventional dredging. Finally, discharging sediment downstream was technically feasible and the best solution for sediment management in Sutami Reservoir.

1. INTRODUCTION

Reservoir sedimentation is challenging in almost all countries managing dams/reservoirs [1]. It is because sedimentation will result in a loss or reduction of reservoir storage volume, which decreases the value of the use of the reservoir [2]. However, there are prevention measures by reducing the rate of land erosion (by reforestation), restraining the sediment from erosion from entering the reservoir by building check-dams, and reducing the slope by making gully plugs [3-6].

Mechanical devices can be used to remove sediment. A reservoir's lost storage capacity due to silt deposition can be recovered through dredging [7]. Dredging can work to handle sediment already entering the reservoir [8]. Dredging is the process of removing submerged sediment that has been deposited [9]. This highly specialized job is primarily employed in ports, rivers, and estuaries to clear navigation routes [10]. This sediment dredging must be based on the most recent mapping and survey results to establish priorities for recovering reservoir dead storage capacity [11].

Different techniques for the dredging of reservoirs exist. Several types of dredging equipment are available for the dredging of reservoirs. The required size depends on the amount of sediment that has to be removed. Due to the additional handling required to move equivalent amounts of material, dredging is frequently more expensive than excavation.

There are benefits of dredging. First, sediment may be removed while the reservoir is still in use. The second is the ability to dispose of the material at a particular site. The majority of reservoirs' basins do not need to be dredged entirely. Sediment is removed from where it is quickly collected by tactical dredging of the reservoir's upper ends or significant embayments.

Additionally, settling basins that act as sediment traps are made when upper basins are excavated deeper than their initial contour. Dredging has the added benefit of allowing for controlling the amount of sediment that returns to the river downstream. The fourth benefit of dredging is that its results can be measured. Finally, it may be done in a wide range of environments. Investments into additional infrastructure, such as bypassing tunnels, can be saved by dredging an existing reservoir.

The fact that dredging cannot be done all year round may be a possible disadvantage of dredging. It becomes a problem, for example, if water is allowed to overflow from the reservoir. It is hazardous to use dredging equipment close to an overflow when the overflow is active because there is a chance that the dredger will be thrown over the dam or will, at the very least, sustain substantial damage to both the equipment and the dam's structure.

Dredging expenses and dredged material disposal are the two critical issues concerning the dredging of reservoir sediment. In conventional sediment dredging in the reservoir, the material is usually temporarily collected in a sediment storage pond (spoil bank) adjacent to the reservoir [12]. The material has to be de-watered. Once the material has settled, the extra water can be returned to the reservoir. Generally, it takes years for the removed sediments to dry completely. Therefore, this dredging method works well if there is enough open land for spoil banks.

Another dredging method is to dispose of the dredged sediment downstream of the dam. In general, dam-building can harm the structure and habitat of the channel beneath the dam and the aquatic life that resides there [13]. Changes brought on by a disruption in the flow regime are typically accompanied by decreased sediment load in rivers and dams [14]. Sediment trapped in the dam generates a deficiency in sediment supply just beneath the dam, which can result in drastic changes to aquatic and riparian biota [15, 16]. In addition, this deposition and sediment reduction will change the flow and downstream alluvial channel morphology and riverbed composition [17-20]. Here, the natural sediment flows can be replicated similarly to before the dam's construction.

However, to determine if this method is a workable approach, the discharging of the dredged material downstream of the dam must be examined. Saving money on dredged material transportation, finding a disposal site, and potentially resolving downstream bed erosion are all advantages of releasing downstream sediment. But, first, it needs to be determined whether the downstream river can take the additional material or if the river would get choked. Also, It must be investigated because disposal must be done at specified times, depending on the place.

A Cutter Suction Dredge (CSD) consists of a pontoon with a large pump and a long suction pipe. Dredging machinery cuts and pumps up material sediment dumped in a particular place [21]. A standard suction dredger can only transport loose material, but a CSD can break up hard or compacted dirt so that it can be sucked up and pushed by pumping by employing a cutter head [22]. Dredges can be connected to floating pipelines, and the dredged material is pumped to the back of the dredge so that the slurry can be pumped to the desired place. Boosters (additional pump stations in the line) can be employed to extend the distance the material can be delivered, depending on how far it needs to go.

The optimum productivity depends on the applied working area, mainly head losses. The volume of material transported per unit of time defines a dredge's production rate. The output rate is calculated by combining the specified cycle limiting factors, non-dimensional pump features, and slurry transport theory. Calculations are first performed to choose the best booster pump [23], align the pipeline, and establish how much slurry material should be discharged following the dredger specification. Then, the optimum elevation of the downstream outlet is required to determine the total hydraulic head of the dredger instead of the pipe length. Based on previous research [24], many head losses are caused mainly by:

a. Losses in CSD ladder
b. Losses in delivery pipes and accessories (type of pipe, length, etc.)
c. Head between dredger pump and outlet.

Reservoir dredging is indeed costly; however, Smith [25] demonstrated that, on an annually per unit basis, it is not altogether prohibitively expensive. Mechanical dredging takes longer to complete than hydraulic dredging because it cannot pump continuously. This kind of dredging can be difficult if the dredging site is far from the dumping site. Furthermore, consolidation may require longer if dredged materials are dumped on land. Additionally, the disposal site would need to be cleaned up, hauled, graded, and stabilized. For some dredging methods, using locally available equipment is also possible.

The sediment dredging in the Sutami Reservoir is conducted with the Cutter Suction Dredge. Due to the limited availability of land for spoil banks, this study examined the opportunities and challenges of reservoir sediment management in the Sutami reservoir by discharging material sediment downstream.

2. DATA AND METHODS

2.1 Site description

This study was conducted in the Brantas basin, East Java Province, Indonesia (Figure 1). Figure 2 shows a cascade reservoir system, namely Sengguruh, Sutami, and Wlingi Reservoirs [26].

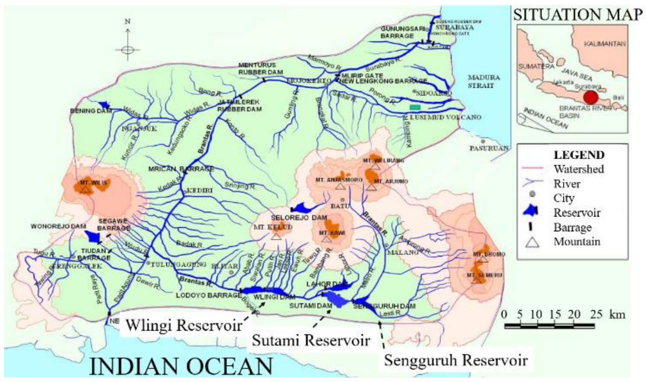

Figure 1. Location of the cascade reservoirs of Sengguruh, Sutami, and Wlingi in the Brantas River Basin, East Java, Indonesia [27]

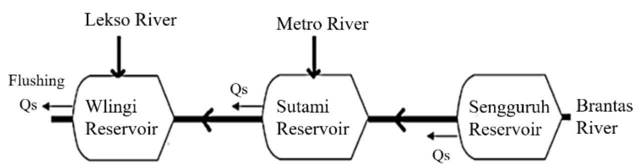

Figure 2. Schematic of a cascade reservoir system of Sengguruh-Sutami-Wlingi Reservoirs

The Sengguruh Reservoir was built in 1990 (Figure 3). It is the most upstream reservoir in the Brantas basin, with about 2.5 million m^3 of effective storage. It traps about 2 million m^3 of annual sediment inflow from the upstream catchment before entering Sutami Reservoir [28]. Sutami Reservoir (Figure 4) has a 100 m height and was built in 1972. It is located approximately 14 km downstream of the Sengguruh Reservoir. It has a reservoir catchment area of 2,052 km^2. It is the largest multi-purpose reservoir in the Brantas basin, with about 175 million m^3 of effective storage and serving for Surabaya flood control, hydropower, irrigation, and raw water [29]. Approximately 1.7 – 1.8 million m^3 of sediment is deposited in Sutami Reservoir annually. There are no outlet facilities to release sediment downstream [30].

Figure 3. Sengguruh Reservoir [31]

Figure 4. Sutami Reservoir [31]

Figure 5. Wlingi Reservoir [31]

Since a vast sediment inflow is trapped in the Sutami Reservoir, hydraulic dredging is carried out at the upstream bay of the reservoir basin. The slurry material with 10-30% solid has been disposed of in surrounding banks. This temporary disposal area allowed drain and release back the excess water to the reservoir. It takes about two years to overhaul the disposal site, then new dredged material to be filled in. Approximately 300,000 to 400,000 m^3 of silty sand has been removed from storage during the current sediment dredging. Downstream of the Sutami Reservoir, there is the Wlingi Reservoir (Figure 5). This reservoir is equipped with radial gates to have the ability to flush. Some 1.2 million cubic meters of sediment deposited are annually removed through dredging, dry excavation, and flushing downstream [27].

Given the limitations in providing land for spoil banks for the Sutami Reservoir in the future and rising land costs, the efforts to remove sediment in the Sutami Reservoir should consider the alternative of downstream discharging. The dredged sediment is directly released downstream. In addition, this downstream disposal method is expected to be supported by flushing at the Wlingi Reservoir. Further, it provides the balance of sediment supply downstream positively.

2.2 Data

In this study, the necessary data needed were inflow, reservoir sedimentation, bathymetry data, dredging material, dredger type and capacity, and river section below the dam. All of the data were collected from the river basin authority (Jasa Tirta 1). Field observation was conducted for additional data, such as potential dredging sites, spoil banks, outlets, downstream river reach, and land availability.

2.3 Evaluation of discharging sediment downstream

The first step of the study was analyzing the existing sediment dredging and assessing the technical possibility of downstream discharging of dredged material sediment.

The second was estimating dredging location and productivity. The calculation was done by considering the capacity of the existing dredger, accessories, and equipment for delivering slurry material downstream [31].

Third was the evaluation of releasing downstream discharge of sediment concerning changes in river morphology below the dam. The sediment transport modeling was also carried out to check the impact downstream river morphology and to identify whether the flow transported the slurry material to the Wlingi Reservoir. Hence, the sediment flow was modeled by employing the package program of the Hydrologic Engineering Center - River Analysis System (HEC-RAS) [32]. HEC-RAS is designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels.

Finally, a conclusion has been drawn for the opportunities and challenges of future reservoir sustainable sediment management in the Sutami Reservoir by considering the downstream discharge of sediments.

3. RESULT AND DISCUSSION

3.1 The existing sediment dredging

The sediment deposits in the Sutami reservoir were often found upstream bay of the dam. This was because the region between the dam and six kilometers upstream was very stable, and sedimentation did not grow much. However, in the meantime, the area beyond six kilometers downstream was experiencing a substantial increase in sedimentation. Generally, it was consistent with the essential characteristics of major dams with suitable storage depth (H > 50 m) and storage capacity.

Since 2004, sediment has been dredged out of the Sutami Reservoir to keep the storage capacity high. It was conducted during the dry season with an annual dredging volume of

400,000 m^3. There were two units of CSD dredgers being operated, IHC Beaver 1200 [33] and SKK 06 Dixie, with Vessel production of 150 m^3/hour and 60 m^3/hour, respectively.

The ideal location for dredging placement was determined by taking into account the depth arm range of each dredger (maximum 8-10 m). Two sites selected for such criteria were Sumberpetung. Both were located between 7,000 meters and 10,000 meters from the dam.

The dredging activity and temporary disposal site of dredged material at the Sutami Reservoir is shown in Figure 6. (i). There were 14 (fourteen) spoil banks situated nearby the Sutami Reservoir (Figure 6. (ii)). Due to increasing land prices and availability, there is a shortage of new spoil banks. Therefore, carrying out sustainable dredging operations becomes a challenge. As a result, the number of dredging operations will be constrained by the amount of land available for spoil banks (Figure 6. (iii)). Sediment transfer (hauling) at the spoil bank is generally feasible after the sediment is deposited for 1.5 – 2 years (Figure 6. (iv)).

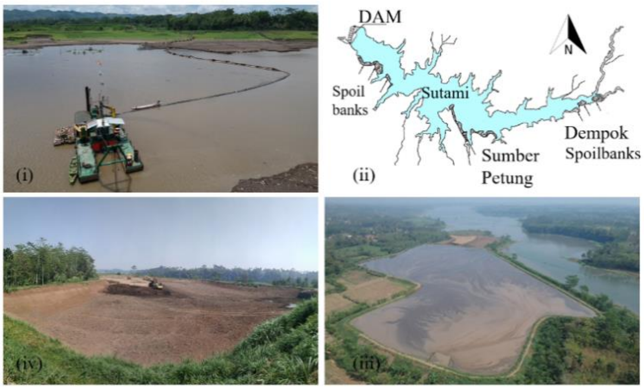

Figure 6. (i) The dredging in the upper bay of Sutami Reservoir (ii) The disposal sites surrounding Sutami Reservoir (iii) The temporary disposal sediment of dredged material (iv) Overhauling the disposal site

3.2 Sediment dredging with downstream discharging

In the Sutami reservoir, the imminent problem in dredging activities was the limited land for spoil banks. The availability of land for a spoil bank would also restrict the amount of dredging efforts. Therefore, disposing of the dredge material downstream of the Sutami Dam becomes an alternative strategy.

When sediment is being dredged up, a mixture of water and solid slurry travels through the exhaust pipe. The percentage of sludge usually ranges from 10-20% of the volume. The amount of material removed is a function of the pipe's flow velocity. If the velocity is too high, it causes a large number of head losses due to friction; on the other hand, if the velocity rate is too low, a lot of material is retained in the pipe. For mud-type material, the recommended velocity is 2.5 m/s.

3.2.1 Calculation of head losses

The CSD's big front beam is referred to as the cutting ladder. The cutting head is fastened to the front of this ladder. The ladder is lowered to the ground with the help of a winch. The cutter is activated at the bottom and cuts the material that needs to be dredged. The material is then suctioned up using the ladder's built-in suction tube. The dredged material is piped to the dredge's back, which can be linked to a floating pipeline to pump the slurry to the desired place. To enhance the distance the material can be transported, boosters (additional pump stations in the line) may be utilized.

Head loss is the amount of energy lost while a slurry is conveyed through a piping system. Head losses should be determined to get the power needed to deliver a specific flow rate. The head losses in the CSD system are the total of the major head losses from frictional effects on the pipe and the minor losses from pipe accessories components. In addition, the energy lost as the fluid passes through pipeline elements such as valves, couplings, bends, and pipe entrance and exit conditions cause minor losses.

The CSD dredging, the pipeline network, and the index for calculating minor head losses (H_i) are shown in Figure 7. Following the manual book of the dredger machine, the head losses along the discharge pipe to the outlet and dredging production capacity were calculated [24]. A total head loss (H_{tot}) was summarized from the suction pipe to the end of the outlet above the spillway. The total head loss was given in Eq. (1). These minor head losses are characterized by the loss coefficient and calculated by the following equation recommended by Randall and Munson [34].

$$H_{tot} = \sum_{i=1}^{14} H_i \tag{1}$$

where, H_{tot} = total head loss and H_i = minor head losses.

As seen in Figure 7, head losses in the pipeline of sediment dredging are:

1. Operational depth
2. CSD
3. Inlet pipe
4. Ladder pipe
5. Bend of ladder pipe
6. Suction pipe
7. Outlet pipe
8. Outlet bend
9. Pipe reducer
10. Floating pipe and landline pipe
11. Bend of Floating pipe and landline pipe
12. Friction pipe
13. Outlet type
14. Difference outlet head

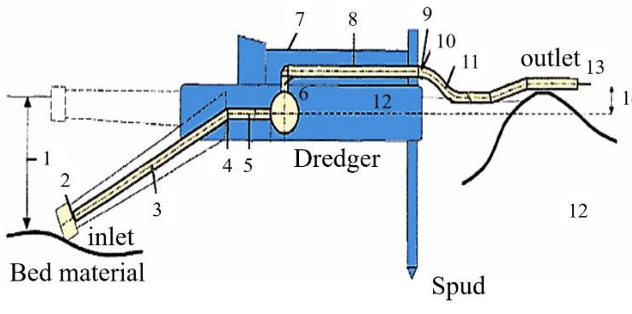

Figure 7. The pipeline system of a dredger to the outlet

On the left side of the reservoir, the dredge pipeline should be extended to the dam spillway in the Sutami reservoir for downstream disposal. A floating hose with a floater was designed for downstream delivery pipes. For a downstream disposal method, the outlet pipe of the dredger was connected to the delivery discharge pipe and its accessories and extended to reach the downstream. The longest distance from the dredging location to the outlet was about 9 km. The delivery pipeline used a combination of floating pipe (< 1.5 km) and land pipe (7.5 – 8 km). While the slurry material with sediment and water discharge ratio was about 0.1 to 0.2, the outlet discharge pipe was installed above the spillway level. A schematic of the pipeline construction from the dredger location to the outlet is shown in Figure 8.

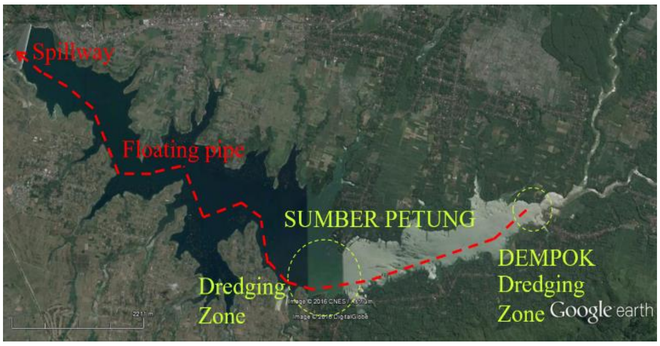

Figure 8. The dredging sediments and pipeline routes for downstream discharging in the Sutami Reservoir

3.2.2 Calculation of discharge of the pump

When the head loss was already determined, it was necessary to calculate the pump output discharge hourly. A booster pump was considered to increase the head and avoid blockage of the delivery pipe. The installation of a booster pump with a capacity higher than 500 HP was preferred at every 2,000 meters in distance. The following Eq. (2) is the formula for determining pump discharge.

$$Q_{sl} = \frac{P \ x\ 75\ x\ \eta}{1000\ x\ \gamma_{sed}\ x\ H_{tot}} x\ 3600 \qquad (2)$$

where, Q_{sl} = slurry discharge (m^3/hour), P = total power of pump and booster (Hp), η = pump efficiency (0.6), γ_{sed}= specific weight of sediment (ton/m^3), H_{tot}= total head losses (m).

3.2.3 Calculation of dredging productivity

The amount of dredged material removed throughout the dredging cycle was measured using the total production rate for a trailing suction dredge. Assuming the discharge of solid material was about 10 to 20% of total slurry discharge (Q_{sm}= $0.1Q_s$ to $0.2Q_s$), the following formula as equation (3) was taken for determining monthly dredging productivity [35].

$$DP = Q_{sm}\ x\ Et\ x\ WD\ x\ WH \qquad (3)$$

where, DP = Dredging productivity (m^3/month), Q_{sm} = solid discharge (m^3/hour), Et = Total efficiency, Total efficiency was the summation of efficiency factors due to Machine availability (0.85), Effectiveness of working time (0.83), and Operator efficiency (0.8). WH = Working hours per day, WD = working days within a month.

Since the sedimentation material's composition properties were silt-clay, the velocity inside the pipe should be taken for 1.5 m/sec; the specific gravity of the sedimentation material was 1.6 kg/m³. Here, the maximum dredging depth was about 10 m, with a disposal distance of about 7,000 to 10,000 m. Then the relationship between dredging production, depth, and disposal head for each dredger machine was established. Figure 9 shows an example of the monthly dredging production for each head disposal and dredging depth for IHC Beaver 1200.

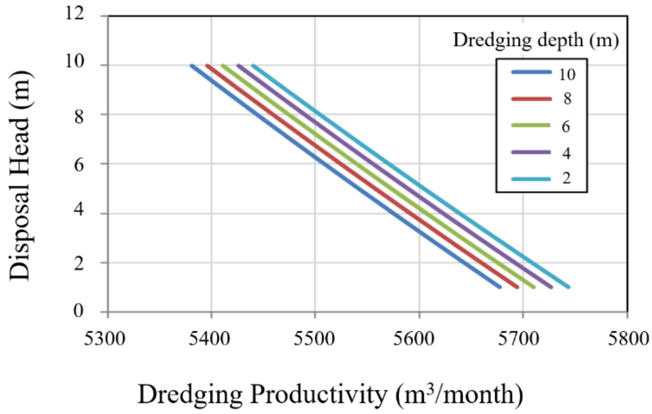

Figure 9. Monthly dredging production for each head disposal and dredging depth for IHC Beaver 1200

IHC Beaver 1200 dredger with one booster pump produced of sediment volume of 6,000 cubic meters in one month. In the same way, the SKK 06 Dixie type dredger has been determined. Assuming the dredging run continuously for 12 months (25 days/month and 12 hours/day), then the annual production capacity for each dredger was summarized as follows:

A. Dredger: SKK 06 Dixie with Booster Pumps Caterpillar C-27 596 HP.
   - A.1 Dredging location: Dempok (~10 km)
     126,819 – 133,190 m^3 (two booster pumps)
     81,613 – 85,713 m^3 (one booster pump)
   - A.2 Dredging location: Sumber Petung (~7km)
     175,674 – 188,142 m^3 (two booster pumps)
     113,053 – 121,077 m^3 (one booster pump)

B. Dredger: IHC Beaver 1200 with Booster Pumps IHC-Beaver 856 HP.
   - B.1. Dredging location: Dempok (~10 km)
     192,093 – 205,306 m^3 (two booster pumps)
     128,335 – 137,162 m^3 (one booster pump)
   - B.2. Dredging location: Sumber Petung (~7km)
     264,262 - 289,931 m^3 (two booster pumps)
     176,550 – 193,699 m^3 (one booster pump)

To achieve the target of annual dredging sediment with a volume of 400,000 cubic meters, the interconnection dredging with SKK 06 Dixie in Dempok and IHC Beaver 1200 in Sumber Petung equipped with two boosters on each meet the volume of annual sediment dredging. A schematic of the pipeline with the installed booster is shown in Figure 10 and Figure 11.

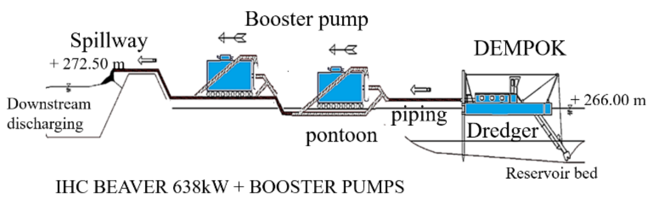

Figure 10. Schematic downstream discharging sediment dredging with installed booster pump for Dempok site

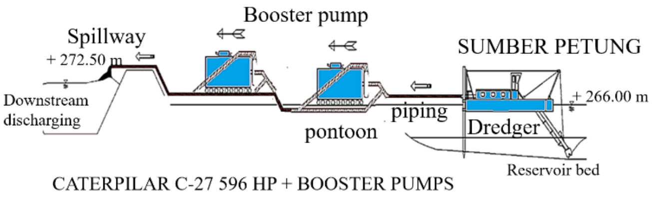

Figure 11. Schematic downstream discharging sediment dredging with installed booster pump for Sumber Petung site

3.3 Evaluation of river morphological changes downstream of the dam

Rivers, in general, is dynamic and characterized by morphological changes [36]. The changes occur due to natural and human factors, such as the construction of river structures, pillars, bridge abutments, ground sills, dams [37]. For example, the existence of a dam may affect the change in the water discharge pattern and sediment load. The discharge outflow of the dam becomes smaller or equal to the original river flow, but the sediment discharge release out of the dam may be close to zero. Changes caused by a breakdown in the flow regime are usually accompanied by a reduction in the sediment load in the river, resulting in a difference in the cross-sectional shape and composition of the base material in the downstream alluvial river.

Downstream discharging sediment becomes considered as sedimentary fillings fed into the river below the dam, commonly called replenishment/augmentation. Replenishing sediment below dams is promoted worldwide to compensate for downstream sediment deficits and improve habitat quality and ecological functions. This approach has been widely applied in Japanese rivers as a vital component of efforts due to its relative benefits, such as direct benefits, especially for restoring downstream habitats, especially concerning increasing fish spawning habitats [33]. The river is supplied through stockpiling of material in the channel, high-concentration sediment flows supply, and direct injection of high-concentration flow in combination with mechanical rehabilitation to recreate gravel bar features through fluvial processes.

Downstream discharging sediment scenarios might result in unintended morphological and ecological consequences and significant channel adjustments. So it was necessary to understand better the reversibility, direction, and timescale of change and sustainability of charging interventions before they were implemented. In this study, two scenarios of discharging sediment below the dam for 50% of maximum capacities (200,000 m^3/year) and 100% capacities (400,000 m^3/year) were simulated to assess the downstream impacts by employing the package program of the Hydrologic Engineering Center - River Analysis System (HEC-RAS). Figure 12 shows river bed changes due to downstream transporting of the sediment flux from dredging activities in the Sutami Reservoir. The river morphology did not have significant changes except at the dumping location (just below the stilling basin of the spillway of Sutami Reservoir) and in front of the Wlingi Dam.

Figure 13 shows how some deposited material was transported downstream and accumulated in front of the Wlingi Dam. The deposited sediment in front of the Wlingi Dam was supposed to be flushed periodically to avoid pilling up. There is an installed equipment facility in Wlingi Dam to conduct sediment flushing.

Sediment flushing has been carried out in the Wlingi Reservoir since August 1990, immediately after the eruption of Mount Kelud in 1990. Sediment flushing is generally held twice a year, especially at the end of the rainy season. Sediment flushing has proven to be an effective measure to maintain reservoir storage capacity and simultaneously reduce riverbed degradation in the lower reaches of Wlingi Dam.

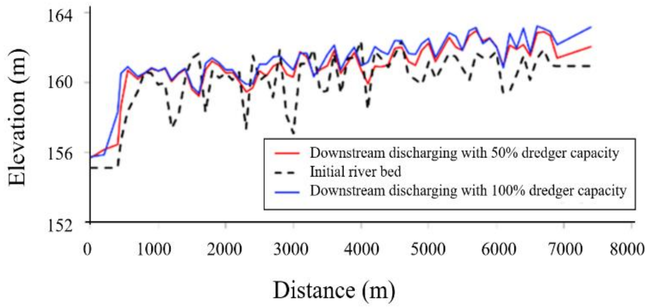

Figure 12. The morphological changes in the river reach below the Sutami Dam to the Wlingi Dam with additional sediment flux from discharging sediment downstream

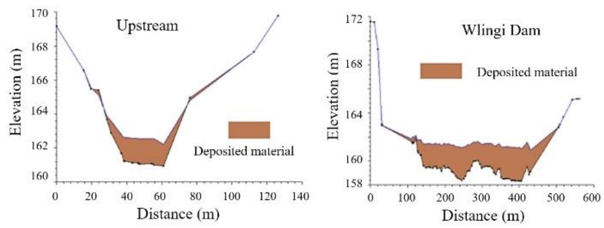

Figure 13. (a) Typical sediment deposited in the river reach below the Sutami Dam due to additional sediment flux from discharging sediment downstream (b) deposited sediment in front of the Wlingi Dam

3.4 The opportunities and challenges of discharging sediment downstream

It is technically feasible and the best solution for sustainable sediment management in Sutami Reservoir through dredging. The limited land availability and price encourage looking for an alternative to disposing dredged material. There is an opportunity to implement a dredging scheme with discharging sediment downstream. It saves the cost of disposal area, overhauling costs, and supporting the replenishment of sediment to the river below the dam to compensate for downstream sediment deficits and improve habitat quality and ecological functions. The flushing ability of the Wlingi Reservoir may support avoiding excess deposits in the Wlingi Reservoir.

However, the challenges are the need to monitor the environmental issues related to water quality downstream, cost investment and maintenance, also water loss which cannot re-enter the storage as conventional dredging,

4. CONCLUSION

Sustainable sediment management in Sutami Reservoir can be achieved by sediment dredging. Considering the large volume of sediment to be dredged yearly, keeping sediment disposal to the spoil bank is economically unfeasible in the long run because of high land prices and land availability. There is an opportunity with the dredging method to dispose of dredging material downstream of the Sutami Dam. Technically, it is feasible to run discharging sediment downstream in Sutami Reservoir. HEC-RAS modeling showed no significant impacts on the riverbed alteration downstream of the dam. Even though downstream discharging is an appropriate opportunity, there are challenges to monitoring the environmental issues related to water quality downstream, cost investment, and tolerated water loss due to dredging.

ACKNOWLEDGMENT

This work was supported by the Research and Community Service (BPPM), Faculty of Engineering, University of Brawijaya, and Jasa Tirta 1 Public Corporation.

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NOMENCLATURE

H	headloss, m
Q	discharge, $m^3.s^{-1}$
P	total power of pump and booster (Hp)
DP	dredging productivity, m^3/month
Et	total efficiency, the summation of efficiency factors
HP	a unit of measurement of the power of engines, horse power
WH	working hours per day, hour
WD	working days within a month, day

Greek symbols

η	pump efficiency, 0.6
γ	the specific weight of sediment, $ton.m^{-3}$

Subscripts

tot	total
i	minor
sl	slurry
sed	sediment
sm	solid material