Performance of Flushing Efficiency of Sediment Evacuation from Wlingi and Lodoyo Reservoirs

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Abstract. The sediment evacuation from the reservoir should be carried out when it disturbs the dam development's functional design. There are issues regarding the objection to releasing sediment from the reservoir, especially related to potential environmental degradation of the river downstream. The sediment source entering the reservoirs is considerably variable, depending upon the catchment characteristics and the hydrological triggers. When limiting the erosion yield and controlling the sediment in the catchment, evacuating sediment from the reservoir could be the only alternative to avoid environmental degradation. Several issues showed that sediment evacuation from reservoirs is a cost-effective solution. Therefore, assessing the efficiency of sediment evacuation from a reservoir through flushing has become of high interest. This paper presents the analysis of the flushing efficiency performance of the flushing operation of Wlingi and Lodoyo Reservoir that was carried out on 10-17 March 2019. The flushing efficiencies are found to be 0.005 and 0.003 for Wlingi and Lodoyo Reservoirs, respectively. These figures are lower than that of Mrica Reservoir and other world reservoirs at higher than 0.1. Further analysis suggests the critical timing of the sediment evacuation schedule considering the inflow condition.

Keywords: Disturbances, sediment evacuation, flushing efficiency, functional design.

1. Introduction
The Brantas River has springs in Sumber Brantas Village, Bumiaji District, Batu City, which originates from the water storage of Mount Arjuno, then flows into Malang, Blitar, Tulungagung, Kediri, Jombang, Mojokerto. In Mojokerto Regency, this river branches into two Surabaya River or Mas River (towards Surabaya) and Porong River (towards Porong, Sidoarjo Regency). Brantas River has a basin covering 11.800 km² or of the area of East Java Province. The main river is 320 km long and flows around an active volcano, Mount Kelud. The average rainfall reaches 2.000 mm per year, and of that amount, around 85% falls in the rainy season. Therefore, the potential for surface water per year is 12 billion m³ on average. The exploited potential is 2.6-3.0 billion m per year. Therefore, the Brantas River and its
tributaries are an excellent source of water. The Brantas River management system is supported by several reservoirs or dams in the upstream area of the Brantas River, including the Wlingi and Lodoyo Reservoirs (see Figure 1).

![Figure 1. Brantas River Basin [1]](image)

The environmental quality of several rivers in Indonesia (including the Brantas River) has decreased drastically during the last decades. The decline in river environment quality is followed by an imbalance in the socio-economic conditions of the community, especially the poor along the river [2]. The role of housewives or women is believed to be a failure in implementing water resource management. At the same time, their involvement in the decision-making process is generally very limited. Such conditions will widen the gap between social groups to obtain healthy water sources. Cooperation and willingness among stakeholders to deal with environmental conditions have begun to appear. However, along the way, it is very vulnerable due to various reasons such as overlaps between institutional authorities, poor water quality monitoring networks, and limited commitment from industry actors to treat waste before it is disposed to the river. An Indonesian-Dutch consortium once developed a project based on the understanding that water problems in the world identify the causes and create cooperation or collaboration. Cooperation is an iterative process that needs to be maintained together among collaborating stakeholders. Partnership-based cooperation is a collaboration that is agreed to play an active role under their respective capacities. One of the important issues in building partnerships is developing procedures and routines to monitor river water quality along the Brantas River. Participatory-based monitoring is the key creates sustainable river management, and transdisciplinary monitoring issues are the challenges.

Apart from the problem of river water quality along the Brantas River that can affect human needs for water, environmental issues also arise in the form of the river's function as a place for the life of specific flora or fauna. Previous studies on genotoxicity showed that the delta of Brantas Delta was the most polluted area [3]. Numbers of micronuclei were found, especially in fish samples in the river basin in the Brantas Delta. The results of the analysis also showed that genotoxicity occurred in fish living in
Brantas Delta. It is also evidence that sediment in the Brantas Delta is the primary source/carrier of pollution for several species that live in this area. In various parts of the world, sediment derived from river dredging has been used extensively to meet various needs, including building materials, reclamation, coastal filling, habitat restoration, and others [4]. However, the use of dredged sediment has problems related to the heterogeneity that depends on locality. Thus, the characteristics of the utilization of the dredged sediment cannot be generalized. Another study said that river sediment can be polluted because of an activity that produces phosphorus materials that enter the sediment, either from aquaculture activities or from industrial and or agricultural waste [5]. Some of these components are released back into the water flow through biological decomposition, while others will remain in sedimentary deposits for long periods.

This paper evaluates the effect of reservoir sediment flushing activities on environmental quality along the river downstream, especially from the physical aspect, where the amount of sediment that has been successfully removed from the reservoir might be considered efficient and feasible. Two reservoirs in the Brantas River Basin to be studied are Wlingi Reservoir and Lodoyo Reservoir (see Figure 2). The sediment flushing implementation requires various considerations, including the essential criteria for flushing planning and the realizations. At the same time, a negative impact should accompany the review of possible changes in physical environmental parameters due to flushing activities which might be significant and burdensome on ecological quality in the waters of the Brantas River downstream of the Wlingi and Lodoyo Dams. Table 1 and Figure 3 show the technical data and layout of the two dams.

![Figure 2. Wlingi and Lodoyo Dam in Brantas River System](image-url)
Table 1. Technical Data of Wlingi and Lodoyo Dams [6]

| No. | Parameter                     | Wlingi Dam     | Lodoyo Dam     |
|-----|-------------------------------|----------------|----------------|
| 1   | Year of Completion            | 1979           | 1983           |
| 2   | Types of Dam                  | Rockfill Dam   | Weir (Barrage) |
| 3   | Catchment Area (km²)          | 2.850          | 3.017          |
| 4   | Total Volume (m³)             | 24,000,000     | 5,200,000      |
| 5   | Effective Volume (m³)         | 5,200,000      | 5,000,000      |
| 6   | Sedimentation Storage (m³)    | 18,800,000     | 2,000,000      |
| 7   | Length of Dam Crest (m)       | 717.00         | 120.00         |
| 8   | Elevation of Dam Crest (m)    | +167.00        | +136.50        |
| 9   | Length of Spillway Crest (m)  | 85.50          | 9600           |
| 10  | Elevation of Spillway Crest (m)| +153.50      | +125.00        |
| 11  | Riverbed Elevation (m)        | +120.00m       | +123.00        |
| 12  | Installed Capacity (MW)       | 2 x 27.00      | 4.5            |

2. Research Methods

2.1. General

The regular sediment flushing program of a reservoir is an effort to reduce reservoir sedimentation, disrupting the sustainability of the reservoir function in the future. In general, there are two types of flushing sediment, namely by removing water through the bottom outlet, which is commonly called drawdown and without drawdown [7]. The schematic diagram is shown in Figure 4.

Figure 3. Layout of Wlingi and Lodoyo Dams
Types of Sediment Flushing in Reservoirs

With Drawdown
- More effects along and across the basin (flushing channel)
  - Complete
    - Flood season emptying
  - Partial
    - Non-flood season emptying
    - Under pressure minimum operation level
    - Free flow over spillway
Without Drawdown
- Very local effects (flushing cone)
  - Dam outlets are opened for very short time
    - Lateral, longitudinal, and in both directions
  - Auxiliary channel
  - Mechanically
    - Bulldozers to push deposits into flushing channel

Figure 4. Schematic diagram of sediment flushing types in a reservoir

Analysis of the flushing program's success has a significant advantage in evaluating the level of efficiency and effectiveness based on certain criteria. Sensitivity analysis of flushing generally adopts the parameters of the initial variation of time and duration of flushing. This paper utilizes the various methods of flushing efficiency and flushing feasibility criteria.

2.2. Flushing Efficiency dan Flushing Feasibility

2.2.1. Flushing Efficiency

There are several ways to describe the degree of efficiency in flushing the sediment from the reservoir. The general requirements to meet the high efficiency of flushing consist of the following [8]:

- a) The amount of sediment transported through the bottom outlet during flushing.
- b) The volume of sediment deposition left in the reservoir after equilibrium is reached is small enough to obtain or form certain storage as desired.
- c) The flushing costs do not exceed the benefits obtained. These costs are the value of water that has been used for flushing the sediment plus the damage that may occur due to flushing. In contrast, the benefits are the amount of water that is accommodated from the new storage after the flushing. Other researchers utilize the different flushing efficiency criteria, i.e., by the ratio of the volume of sediment deposits that dissolve in the volume of water used during flushing at a specific time interval [9]. In general, the efficiency of the reservoir flushing could be written as the following relationship:

\[
F_e = f\{V_o, V_{so}, C_o, W_{so}, V_i, V_{si}, W_{si}, C_i, V_d, \rho, \}
\]

(1)

where:

- \( F_e \) = Flushing Efficiency
- \( V_o \) = Outflowing water volume during flushing (m³)
- \( V_{so} \) = Outflowing sediment volume during flushing (m³)
- \( C_o \) = Sediment concentration of outflow (kg/m³)
- \( W_{so} \) = Weight of sediment outflow (kg)
- \( V_i \) = Inflowing water volume during flushing (m³)
\[ V_{si} = \text{Inflowing sediment volume during flushing (m}^3) \]
\[ W_{si} = \text{Weight of sediment inflow (kg)} \]
\[ C_i = \text{Sediment concentration of inflow (kg/m}^3) \]
\[ V_d = \text{Volume of flushed out sediment (m}^3) \]
\[ \rho = \text{Mass density of sediment (kg/m}^3) \]

The followings are the value requirements that must be met to determine the level of flushing efficiency (see Table 2).

### 2.2.2. Flushing Feasibility

Flushing feasibility is a criterion to evaluate flushing performance on the sediment evacuation from a reservoir. So, it can be interpreted that flushing feasibility is a reference given to evaluate flushing performance through the specified value so that the calculated value can determine whether the flushing performance is considered feasible. There are several criteria for deciding flushing feasibility such as Sediment Balance Ratio (SBR), Long Term Capacity Ratio (LTCR), Drawdown Ratio (DDR), new SBR value (namely SBR with full drawdown or SBR\_d), Flushing Width Ratio (FWR), and Top Width Ratio (TWR). Like that of flushing efficiency, the feasibility of the reservoir flushing is dependent on several parameters that could be written as follows:

\[
F_f = f\{M_f, M_{dep}, A_f, A_r, El_f, El_{max}, El_{min}, W_f, W_{bot}, W_{td}, W_t \} \tag{2}
\]

where:
\[ F_f = \text{Flushing Feasibility} \]
\[ M_f = \text{Mass of flushed sediment (ton)} \]
\[ M_{dep} = \text{Mass of deposited sediment (ton)} \]
\[ A_f = \text{Cross-sectional area after flushing (m}^2) \]
\[ A_r = \text{Cross-sectional area before flushing (m}^2) \]
\[ El_f = \text{Water surface elevation during flushing (m)} \]
\[ El_{max} = \text{Water surface elevation at TWL (m)} \]
\[ El_{min} = \text{Reservoir bed elevation (m)} \]
\[ W_f = \text{Width of channel flushing (m)} \]
\[ W_{bot} = \text{Width of reservoir bottom (m)} \]
\[ W_{td} = \text{Width of scour valley (m)} \]
\[ W_t = \text{Width of reservoir on TWL (m)} \]

Flushing feasibility can be evaluated using the various parameter as shown in Table 2, provided with certain values or requirements that must be met. In contrast to flushing feasibility, flushing efficiency has no specific condition to indicate whether the flushing activity is considered efficient. This is because in almost all flushing activities are generally cost-effective, where the benefits obtained from flushing are not balanced with the value of the water used for flushing activities [8]. However, it is very interesting to know how much the sediment flushing operations have obtained efficiencies. Previous research stated that the water consumption for the sediment flushing was utilized during the entire drawdown period though the acceptable sediment discharge starts from the reservoir drawdown period. This water volume should therefore be included in the water consumption. The sediment flushing efficiency was found at about 0.01-0.10. It is thought to be decreased to about Fe = 0.05 or less when considering the river environment is essential [7,10].
Table 2. Flushing Efficiency and Flushing Feasibility.

| No. | Parameter/ Reference   | Flushing Efficiency | Flushing Feasibility |
|-----|------------------------|---------------------|----------------------|
|     | Equation               | Required            | Equation             | Required            |
| 1   | Qian (1982)            | $F_e = \frac{V_o}{V_d}$, where $V_d = \frac{V_o C_o - V_i C_i}{\rho}$ | -                    | -                    |
| 2   | Ackers & Thompson (1987)| $F_e = \frac{L_o}{L_i}$ | -                    | -                    |
| 3   | Lai & Shen (1996)      | $F_e = \frac{V_{so} - V_{si}}{V_o}$ | -                    | -                    |
| 4   | Mors & Fan 1997        | $F_e = \frac{V_o C_o - V_i C_i}{\rho V_o}$ | -                    | -                    |
| 5   | Sediment Balance Ratio (SBR) | - | $SBR = \frac{M_f}{M_{dep}}$ | $> 1.0$ |
| 6   | Long Term Capacity Ratio (LTCR) | - | $LCTR = \frac{A_f}{A_r}$ | $> 0.5$ |
| 7   | Drawdown Ratio (DDR)  | -                    | $DDR = 1 - \frac{E_{l_r} - E_{l_{min}}}{E_{l_{max}} - E_{l_{min}}}$ | $> 0.7$ |
| 8   | Sediment Balance Ratio with Full Drawdown | - | $SBR_{f} = \frac{M_f}{M_{dep}}$ | $> 1.0$ |
| 9   | Flushing Width Ratio (FWR) | - | $FWR = \frac{W_f}{W_{bot}}$ | $> 1.0$ |
| 10  | Top Width Ratio (TWR)  | -                    | $TWR = \frac{W_{td}}{W_t}$ | $\geq 1.0$ |

3. Results and Discussion

3.1. General
Wlingi and Lodoyo reservoirs are daily reservoirs located Blitar Regency, East Java, Indonesia. Wlingi Reservoir was completed in 1977, functions as providing irrigation water for the Lodoyo and Tulungagung areas, covering an area of 13,600 ha, controlling the water discharge (afterbay) of the Karangkates Hydroelectric Power Plant, and a Hydroelectric Power Plant (PLTA) with a capacity of 2 x 27 MW [11,12,13]. Lodoyo Reservoir was completed in 1982, which functions as a hydropower plant with an installed capacity of 1 x 4.7 MW, controlling the water discharge (afterbay) of the Wlingi Raya hydropower plant, flood control, fisheries, and tourism. However, the high sedimentation rate causes the storage capacity of the Wlingi and Lodoyo reservoirs to decrease significantly. One of the contributors to sedimentation comes from Mount Kelud, which erupts at 15-year intervals and lastly in February 2014.
To maintain the reservoir storage capacity, annual dredging activities have been carried out using the dredgers. In addition to sediment dredging activities, other efforts made so that the reservoir continues to provide optimal benefits is to carry out sediment flushing activities [14,15]. The flushing activity of the Wlingi and Lodoyo Reservoir is a routine activity every year if conditions permit, which is an effort to remove the sediment deposited in the Wlingi and Lodoyo Reservoirs through the spillway gate by lowering the reservoir water level to the bottom elevation. By carrying out flushing activities, it is expected that the function of the reservoir for water supply to irrigation and hydropower can run more optimally.

3.2. Evaluation of Flushing Activity in March 2019.

3.2.1. Schedule of Flushing Implementation
There are several activities during the flushing, these include the reservoir emptying, the power plant stopping, sediment clearing, reservoir impounding, power plant re-operation, irrigation stops. The sequences of the activities are shown in Table 3.

| No. | Activities               | Date and Time          |
|-----|--------------------------|------------------------|
|     |                          | Lodoyo Dam             | Wlingi Dam             |
| 1   | Reservoir emptying       | 10 March 0:00 thru     | 11 March 01:00 thru    |
|     |                          | 11 March 07:00         | 11 March 07:00         |
| 2   | Power plant stopping     | 10 March 0:00 thru     | 10 March 24:00 thru    |
|     |                          | 16 March 18:00         | 13 March 16:00         |
| 3   | Sediment clearing        | 11 March 07:00 thru    | 11 March 07:00 thru    |
|     |                          | 16 March 22:00         | 12 March 23:00         |
| 4   | Reservoir impounding     | 16 March 23:00 thru    | 12 March 24:00         |
|     |                          | 17 March 08:00         | 13 March 10:00         |
| 5   | Normal Operation         | 17 March 18:00         | 13 March 16:00         |
| 6   | Irrigation stopping      | -                      | 11 March 04:00 thru    |
|     |                          |                        | 13 March 06:00         |

3.2.2. Sedimentation after Flushing
According to the reference sediment profile, the sediment elevation in the zone I before and after flushing decreased from the results of echo-sounding measurements. Flushing the Lodoyo Reservoir in 2019 was assisted by two units of long boom pontoon excavators and 2 units of amphibious excavators, which were placed in the Daily Storage Pool of the Lodoyo Power Plant and were able to clean the sediment that settled in the area through baling/slipping. The results of echo-sounding measurements before and after flushing in the Wlingi Reservoir are compared with a decrease in sediment elevation in Zone I before and after flushing. With the help of 1 unit of heavy amphibious excavator, 1 unit of long boom pontoon excavator, and 1 unit of standard boom pontoon excavator that cleans sediment in front of the hydropower intake (Zone I), it can clean sediment as wide as 45 meters and as long as 200 meters.

The sediment flushed out from the Lodoyo and Wlingi Reservoirs from 10–17 March 2021 were 310,284 m³ and 313,415 m³. Additionally, approximately 5,823 m³ and 3,625 m³ sediment has been taken out from Lodoyo daily detention pond and near the intake of Wlingi, respectively.
3.2.3. Performance on Flushing Efficiency
The flushing efficiency of the flushing operation of Wlingi and Lodoyo Reservoirs in 10–17 March 2019 is then calculated by considering the total water volume that has been released from the reservoir. 

Figure 5 shows the discharge of the flow that has been released during the 10-17 March 2019 [10]. The integration of the area under the curve of Figure 5 will result in the total volume of water released from the reservoir. Since the sediment volume was presented in the total volume within the flushing period, i.e., on 10-17 March 2019, only Lai & Shen equation is used to investigate the flushing efficiency. The efficiency mentioned earlier is found at 0.005 and 0.003 for the Wlingi Reservoir and Lodoyo Reservoir. Figure 6 shows the result of the assessment, i.e., the performance of the flushing efficiency plotted over the graph that has been produced by previous researchers [7].

![Figure 5](image1.png)

**Figure 5.** Discharge release from Wlingi and Lodoyo Reservoir during 10-17 March 2017 [10]

![Figure 6](image2.png)

**Figure 6.** Flushing efficiency of Wlingi and Lodoyo Reservoirs and other reservoirs [7]
4. Conclusions
The type sediment flushing of Wlingi and Lodoyo Reservoirs is categorized as flushing with a partial drawdown mechanism through the overflow of the spillway. Compared to that of the flushing efficiency of other reservoirs, i.e., Mrica Reservoir and world reservoirs (range from 0.01 – 0.10), the flushing efficiency of Wlingi and Lodoyo Reservoirs at 0.005 and 0.003 respectively, are relatively less efficient. Such conditions show that even the flushing efficiency is low, the flushing still needs to be implemented to support the functional design of the reservoir development. Moreover, further assessment of the flushing performance through other criteria, i.e., the flushing feasibility, is essential. However, as mentioned earlier, the examination requires a more structured monitoring system related to hydraulics and geometrical dynamics.

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