Assessment on the efficiency of sediment flushing due to different timings (a case study of Mrica reservoir, central Java, Indonesia)

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\textbf{Abstract}. The issue of the sedimentation problem of reservoirs has been growing significantly during the last two decades, particularly in areas where human activity increases pressure on the land. However, some researchers believe that such situation is also (partly) affected by the significant shift in hydro-meteorological conditions, accompanied with higher rainfall erosivity and hence an increase in land erosion. Various efforts have been suggested to control the erosion process, whether by sediment control at the catchment area or placing a ground sill and/or check dam in the stream. However, additional activities to remove sediment from reservoirs through sluicing, flushing, and dredging are often still necessary. This paper deals with the evaluation of the effectiveness of flushing at different timings. The results showed that the uncertainty of the sedimentation process and the hydrograph inflow characteristics are dominant factors affecting the problems. A further recommendation is to determine the procedure for establishing reliable advance timing that is considered most efficient for carrying out the flushing activities.

Keywords: Sedimentation, reservoir, flushing, timing, efficiency.

1. Introduction
The Mrica Reservoir (Panglima Besar Sudirman Dam) is located in Bawang Sub-District of Banjarnegara Regency in Central Java, Indonesia (Figure 1). The Mrica Reservoir is an artificial reservoir that was built in 1980 by damming the Serayu River in the Serayu-Bogowonto watershed. The spillway crest elevation of the reservoir is +231 m above mean sea level, with an initial reservoir capacity of 141.250 million m\textsuperscript{3} and an inundation area of 8.258 km\textsuperscript{2} [1]. The topography of the Mrica Reservoir catchment area is mountainous and hilly, undulating, and with steep reliefs [2]. The area resembles a basin, and thus sediments easily flow downstream and enter the reservoir. The rock formations found in the catchment area of the Mrica reservoir are Pre-Tertiary Hungarian Quaternary rocks due to volcanic eruptions and alluvial deposits. Old rocks, which are generally facies of shallow sea, are in the form of clay and/or limestone. This type of rock is easily destroyed and weathered, and furthermore would very potentially have high permeability.
The catchment area of Mrica Reservoir is a plateau area which has a high annual rainfall of approximately 4000-4500 mm. The number of wet months (with monthly rainfall greater than 200 mm) is approximately seven months, whereas the remaining five months are dry months (with monthly rainfall less than 200 mm). The annual maximum rainfall generally takes place within December to January. Much of the land in the catchment area is used for agricultural activities such as plantations and vegetable crops (such as corn, cassava, chili, spinach, and many types of beans). The planting of potatoes and cassava as leading crops in the area around the Mrica Reservoir would cause soil and water conservation, thereby increasing the rate of erosion. In addition, there are still many people who farm with a dry land system on steep slopes, which further increases the rate of erosion. It is presumed that existing land use patterns do not support erosion prevention. The main rivers that play a role in the entry of sediment into the Mrica Reservoir are the Serayu and Merawu rivers, whose watersheds are volcanic areas (Mt. Sumbing, Mt. Sindoro, and the Dieng mountainous area). The morphology of the Serayu River Basin has cliffs and steep valleys. Vegetation is often found in the form of field crops and shrubs, with plants being very rare. Thus, rocks on the riverbanks are easily eroded. The morphology of the Merawu watershed has rock cliffs that are soft and easily destroyed, making it very easy for erosion to occur.

1.1. Sedimentation in Mrica Reservoir
The main problem in the management of the Mrica Reservoir is the significant sedimentation originating from the Merawu River. Over the last few decades the sedimentation countermeasure has been carried out by flushing, but the level of efficiency still needs to be improved. The Mrica Reservoir is managed by PT. Indonesia Power and began to function (first impounding) in April 1988. This reservoir captures water from the Serayu River, then releases water to drive 3 units of power plant turbines with a capacity of 61.5 MW each with a production target of 580,000 MWh per year. Intensive sedimentation has caused the performance of the power generation to decrease significantly from time to time [2].
Land erosion in the catchment area of the Mrica reservoir occurs due to the reduction of forest areas in the upper reaches of the catchment. The reduction in forest area occurred because of changes in land use from forests to agriculture. On one hand, this agricultural land provides benefits to the community, but on the other hand, it also raises the risk of erosion. The erosion rate of the Mrica Reservoir in recent years has increased. At the end of 2004, the volume was only 55.26% or 78.05 million cubic meters from the initial condition (in 1988) of 141.274 million cubic meters (PT. Indonesia Power, 2005). This will result in changes in reservoir storage capacity, both dead storage capacity and the total storage capacity. The comparison of the land use condition between 2007 and 2013 indicate that the areas of forests, bodies of water (reservoir, ponds, and so on), wetlands, and bushes remained the same or unchanged. However, the area of yards and paddy fields decreased by approximately 0.45% and 0.99% respectively, whereas bare land increased by approximately 0.37% (Table 1). It is also obvious that the settlement area increased by approximately 1.99%.

### Table 1. Land use conditions in 2007 and 2013

| No. | Land use        | Area (ha) 2007 | Area (ha) 2013 | Change in land use (%) |
|-----|-----------------|----------------|----------------|-----------------------|
| 1   | Body of water   | 1,061          | 1,061          | 0.00                  |
| 2   | Bushes          | 9,164          | 9,164          | 0.00                  |
| 3   | Buildings       | 34             | 34             | 0.00                  |
| 4   | Forests         | 1,431          | 1,431          | 0.00                  |
| 5   | Yards           | 30,293         | 30,156         | -0.45                 |
| 6   | Settlements     | 6,880          | 7,017          | 1.99                  |
| 7   | Wetlands        | 6              | 6              | 0.00                  |
| 8   | Grasses         | 482            | 474            | -1.64                 |
| 9   | Paddy fields (a)| 6,164          | 6,138          | -0.42                 |
| 10  | Paddy fields (b)| 13,039         | 12,964         | -0.57                 |
| 11  | Bare land       | 29,500         | 29,607         | 0.37                  |
|     | TOTAL           | 98,053         | 98,053         | 0.00                  |

The sedimentation of Mrica Reservoir from 1998 to 2014 has decreased the storage capacity significantly (Figure 2).

![Figure 2](image)

**Figure 2.** The storage capacity of Mrica Reservoir from 1998 to 2014

Further evaluation is required to identify the efficiency of sediment flushing. Such evaluation has the aim of improving efficiency and hence cost-effectiveness.
2. Materials and Methods
The required data for the study of the flushing efficiency are average daily and annual water inflow, annual sediment inflow, and sediment properties such as grain size distribution and mass density of sediments. The catchment area of the Mrica Reservoir, which covers an area of 957 km², is shown in Figure 3, whereas the summary of the technical data of the Mrica Reservoir is shown in Table 2.

![Figure 3. Catchment area and river system of Mrica Reservoir.](image)

### Table 2. Technical data of Mrica Reservoir

| No. | Parameter (unit)                          | Magnitude (remarks)                                      |
|-----|------------------------------------------|---------------------------------------------------------|
| 1   | Name of Dam (Reservoir)                  | Panglima Besar Sudirman (Mrica)                         |
| 2   | City/District                            | Banjarnegara                                             |
| 3   | Province                                 | Central Java                                            |
| 4   | Position/Coordinate                      | 7°7’S – 7°30’12” S and 106°47’28” E – 110°3’ E         |
| 5   | Type of Dam                              | Rockfill with Vertical Core (from Soil)                 |
| 6   | Length of Dam (m)                         | 832.00                                                  |
| 7   | Height of Dam (m)                         | 100.00                                                  |
| 8   | Dam Crest Elevation (m)                   | +235.00                                                 |
| 9   | Spillway Crest Elevation (m)              | +231.00                                                 |
| 10  | Width of Spillway Crest (m)               | 30                                                      |
| 11  | Inundation Area at Dam Crest (km²)        | 8.258                                                   |
| 12  | Inundation Area at PMF (km²)              | -                                                       |
| 13  | Catchment Area (km²)                      | 957.010                                                  |
| 14  | Reservoir Volume at Dam Crest (m³)        | 141,250,000                                             |
| 15  | Reservoir Volume at Dead Storage (m³)     | 30,000,000                                              |
| 16  | Elevation of Inlet (m)                    | +141.00                                                 |
| 17  | Type of Inlet Gate                        | Drawdown Culvert                                         |
| 18  | Type of Spillway Crest                    | Ogee without Gates                                        |
2.1. Flushing Efficiency

There are several ways to describe the degree of efficiency in flushing sediment from a reservoir. The general requirements to meet a high efficiency of flushing consist of the following [3]:

a) The amount of sediment transported through the bottom outlet during flushing has to achieve a balance between the incoming and the outgoing sediment.

b) The volume of sediment deposition left in the reservoir after equilibrium is reached has to be small enough to obtain or form a desired certain storage.

c) The costs of flushing do not exceed the obtained benefits. These costs are in principle the value of water that has been used to flush the sediment plus the damage that occurred due to flushing, while the benefits are the amount of water that is accommodated from the new storage after the flushing.

Some experts differ in expressing flushing efficiency in the implementation of sediment flushing for a reservoir. The flushing efficiency is the ratio of the volume of sediment deposits that dissolve in the volume of water used during flushing at a certain time interval [4]. The following are some methods that have been widely used to determine the level of flushing efficiency (Table 3).

| Method                      | Formula                  | Descriptions/Remarks                |
|-----------------------------|--------------------------|-------------------------------------|
| Qian (1982)                 | $F_e = \frac{V_d}{V_0}$  | $V_d = \frac{V_o C_o - V_i C_i}{\rho}$ |
|                            |                          | $F_e$ = flushing efficiency          |
|                            |                          | $V_o$ = outflowing water volume during flushing (m$^3$) |
|                            |                          | $V_d$ = volume of deposits flushed out (m$^3$), |
|                            |                          | $C_o$ = total sediment concentration of outflow (kg/m$^3$) |
|                            |                          | $C_i$ = total sediment concentration of inflow (kg/m$^3$), |
|                            |                          | $\rho$ = mass density of sediment (kg/m$^3$) |
| a Mahmood (1987)            | $F_e = \frac{V_2 - V_1}{V_0}$ | $F_e$ = flushing efficiency          |
|                            |                          | $V_2$ = storage capacity of the reservoir after flushing (m$^3$) |
|                            |                          | $V_1$ = storage capacity of the reservoir before flushing (m$^3$) |
|                            |                          | $V_0$ = volume of water released during flushing (m$^3$) |
| b Mahmood (1987)            | $F_e = \frac{V_2 - V_1}{V_{ori}}$ | $F_e$ = flushing efficiency          |
|                            |                          | $V_2$ = storage capacity of the reservoir after flushing (m$^3$) |
|                            |                          | $V_1$ = storage capacity of the reservoir before flushing (m$^3$) |
|                            |                          | $V_{ori}$ = original live capacity of the reservoir (m$^3$) |
| Ackers & Thompson (1987)    | $F_e = \frac{L_0}{L_1}$ | $F_e$ = flushing efficiency          |
|                            |                          | $L_0$ = annual quantity of sediment that has been flushed out (kg) |
|                            |                          | $L_1$ = annual quantity of sediment inflow (kg) |
| Atkinson (1996)             | $F_e = \frac{L_0}{L_1}$ | $F_e$ = flushing efficiency          |
|                            |                          | $L_0$ = annual quantity of sediment that has been flushed out (kg) |
2.2. Time-Dependence of Flushing

Flushing can be done through two processes: drawdown or emptying. The drawdown process is the process of flushing by reducing the reservoir water level to a certain reservoir water level elevation, whereas the emptying process is the process in which the reservoir is emptied first and then all river inflow is made to flow out through the bottom outlet. The emptying process is a complete drawdown process. In general, flushing with complete drawdown is much more effective compared to partial drawdown [5].

The amount of sediment that has been flushed during the flushing depends on various factors, including the deposit characteristics, the flow velocity through the gate, and the timing of the flushing itself. The most important factor related to sediment characteristics is the erosion rate of the deposit. For deposit where consolidation is relatively high, the erosion rate would be very low and therefore, a low amount of sediment would be flushed out. In some cases, the resuspension of the deposit should be introduced before and during flushing. The flow velocity may vary during the flushing, generally very fast at the beginning and gradually becoming slower, depending upon the inflow condition during the flushing. The timing of the flushing includes the initiation time of the flushing and the duration of the flushing. The following is the general equation of the sediment balance in the flushing process [3]:

\[ Q_s T_f = N M_{in} T E \]  

(1)

Where:

- \( Q_s \) is the sediment transporting capacity of the flow in the drawdown reservoir (which is a function of the discharge, the channel width and slope, and the sediment deposition properties);
- \( T_f \) is the duration of flushing;
- \( N \) is the interval between flushing processes in years;
- \( M_{in} \) is the sediment inflow rate; and
- \( T E \) is the trapping efficiency, the proportion of the sediment inflow which is deposited in the reservoir.

The transporting capacity \( (Q_s) \) of flushing flows can be estimated using an empirical method. The method (known as the Tsinghua University Method) is based on observations of flushing at reservoirs in China, where the predominant practice is annual flushing; thus, relatively little consolidation occurs between flushing operations. The governing equation is written below:

\[ Q_s = \Psi \frac{Q_{i}^{1.6-S_{i}^{1.2}}}{W^{0.6}} \]  

(2)
Where:

\( Q_s \) is the sediment transporting capacity (t/s);
\( Q_f \) is the flushing discharge (m³/s);
\( S \) is the bed slope;
\( W \) is the channel width (m); and

\( \psi \) is a constant according to the sediment type:
- 1600 for loose sediments
- 650 for other sediments with median size finer than 0.1 mm
- 300 for sediments with median size larger than 0.1 mm
- 180 for flushing with a low discharge

3. Results and Discussion

3.1. Storage Characteristics of Mrica Reservoir Sedimentation Management

Evaluation of the Mrica Reservoir flushing efficiency was carried out by utilizing the results of data from measurements or observations carried out by PT. Indonesia Power and data from previous studies [2, 6]. The aforementioned data included daily inflow data, the original reservoir storage characteristics (in this case from 1988), the annual sediment inflow, and the deposit characteristics. The calculation of sediment volume was determined based on the percentage of sediment content to the flow of water that flows out from the culvert drawdown for a certain period, while the volume of water that comes out was calculated based on the area of the graph which is limited by 2 occurrences of sediment retrieval to the time of opening of the drawdown culvert. The relationship between the elevation and the volume of the water in the reservoir for three different years is presented in Table 3, where \( S(\text{m}^3) \) is the volume of storage at the corresponding water surface elevation \( E (\text{m}) \).

### Table 4. Storage characteristics of Mrica Reservoir

| Year                  | Storage characteristics                      |
|-----------------------|---------------------------------------------|
| 1988 (at the beginning)| \( S = 24.362 \times (E - 160)^{3.1091} \)   |
| 2004                  | \( S = 12.472 \times (E - 190.72)^{2.3869} \) |
| 2014                  | \( S = 30.998 \times (E - 200)^{4.1298} \)   |

**Figure 4.** Outflow through bottom outlet at 15 hours flushing duration
3.2. **Flushed Sediments at Various Time of Initiations and Durations**

Under a chosen daily inflow, the impact of the timing (initiation and duration) to the amount of sediment that is flushed out through the bottom outlet was examined. Conservation of mass was used to carry out the reservoir routing during flushing, and the sediment was calculated according to the Tsing Hua University method. The results showed that under an inflow hydrograph and duration conditions, the initiation of the flushing at the rising hydrograph inflow produced a higher amount of flushed sediments. The discrepancy is considerably significant, at approximately 15% higher rather than what was initiated from the peak hydrograph (see Figure 4). This suggests carrying out the initiation of the flushing at the beginning of the inflow hydrograph, no matter what the water surface elevation condition is.

4. **Conclusion**

Flushing efficiency could be determined by applying several methods supported by parallel observations of inflow and outflow of water and sediment concentration during flushing. The timing of the flushing (that is, the initiation and the duration of the flushing), seem to be the dominant factors affecting the efficiency of the flushing. In the case of Mirca Reservoir the partial drawdown flushing from the full supply level, with a 2-year return period of the inflow hydrograph and a 15-hour flushing duration, shows that the maximum amount of flushed sediment takes place at the initiation of flushing at eight hours after the inflow hydrograph starts.

A proper prediction on the inflow hydrograph may present the best results; however, it might be very complex. To avoid this complexity, the development of scenarios of timings utilizing reservoir routing supported by data obtained from the hydraulics-hydrology monitoring system is considered essential.

**Acknowledgments**

The authors express their profound gratitude to PT. Indonesia Power that has provided data regarding the flushing practice in Mirca Reservoir, to Jasa Tirta I Public Corporation for their continuous collaboration in reservoir sedimentation-related studies, and to all colleagues in the Multimodal Sediment Disaster (MSD) Network for their cooperation and discussion related to reservoir management.

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