Study on Wonogiri Reservoir Operation Performance for Flood Control Purposes Using New Operation Rules

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Abstract. To overcome the Wonogiri Reservoir sedimentation problem, a closure dike and a new spillway have been built that separates the reservoir into the main reservoir (MR) and sediment storage reservoir (SSR). This study assesses the dam safety through reservoir flood routing simulation with the flood control water level (CWL) of +135.8 m. The new reservoir operation rules and the design flood of Q_{60}, Q_{500}, and PMF were used to estimate the maximum reservoir water level and the total outflow discharge. The results show that for the Q_{60} and Q_{500} the reservoir water level has not reached CWL until the end of the fourth day, so it is vulnerable to the risk of dam overtopping. Besides, the freeboard does not to comply with the dam safety requirements and the maximum outflow discharge for the PMF is much higher than the expected flood control capacity. It is necessary to update the reservoir operating regulations by changing the reservoir water level limit and the opening of the two spillway gates. The results showed that although the reservoir water level in the MR and SSR can be controlled not to exceed the EFWL, the total discharge from the PMF still exceeds the maximum limit.

Keywords: *closure dike; control water level; freeboard; overtopping; sedimentation*

1 Introduction

Wonogiri Reservoir is located in Central Java Province's Wonogiri Regency. This reservoir's primary purpose is to regulate floods on the Upper Solo River. Furthermore, the Wonogiri reservoir serves as an agricultural water source for the Regencies of Klaten, Karanganyar, Sukoharjo, and Sragen. The Wonogiri Reservoir also serves as a hydroelectric power plant (PLTA) in the Wonogiri region, with a maximum capacity of 12.4 MW, which is used for tourism purposes. Thus, the Wonogiri reservoir may be classed as a multifunctional dam based on its role. Nippon Koei Co., Ltd (2010) conducted research on the management of sedimentation in the Wonogiri Reservoir, which resulted in a Detailed Design of Structural Countermeasures for Sedimentation on the Wonogiri Reservoir to address sediment issues [4], specifically by constructing sediment storage buildings that accommodate sediment flow from the Keduang and Pondok rivers via the installation of a closure dike on the Wonogiri Reservoir. A closure dike is a structure constructed entirely of earthfill and located within a reservoir. The building's primary duty is to collect silt from the Keduang River, which is then pushed straight via the new spillway. Due to the closing dike's construction, the Wonogiri reservoir was divided into two storage, the Sediment Storage Reservoir (SSR) and the Main Reservoir (MR) [1]. Both storage get inflows from their respective watersheds, with MR receiving inflows from eight watersheds: Kepuh, Tirtomoyo, Temon, Solo Hulu, Alang Nguploadan, Kedunguling, Wuryantoro, and Durensewu [5]. It receives inflow from the Pondok Watershed and the Keduang Watershed in the SSR. In the SSR, a new spillway was constructed that flowed straight downstream of the dam for sediment flushing. Along with its sediment-flushing function, the new spillway is also used for flood management. There is an overflow dike (side of spillway dam) between the closing dikes that allows water to flow from SSR to MR when the new spillway is closed. A connecting canal with a door is located on the overflow dike. The objective is to predict when the flow from the Keduang River into the SSR will not surpass the overflow dike, at which point the overflow door may be opened [3]. This study aims to assess the safety of the Wonogiri Multipurpose Dam from the flood control point of view, which will use the new reservoir operation rules in accordance with current conditions (Nippon Koei Co. Ltd., 2016) with the flood control water level (CWL) of +135,8 m.

2 Materials and Methods

2.1 The New Operation Rules

The Operation and Maintenance Study of the Wonogiri Reservoir and Related Structures was completed in 2016, following the completion of the sediment management structures. The previous study's flood control operation was revised to incorporate the characteristics of the existing outflow spillway and the new spillway as a result of testing the hydraulic physical model, and to maximize the number of new spillways used to remove sediment from the Keduang River as it enters the sediment storage reservoir. The following is a flood control operation once the sediment control structure is completed, as well as a revision of the current operation and maintenance standards. **Figure 1** illustrates flood control activities at Wonogiri Reservoir during a Standard Highest Flood (SHF, typical flood water levels), whereas **Figure 2** illustrates flood control operations during an emergency (Report on Operation and Maintenance of Multipurpose Dam Wonogiri 2016).

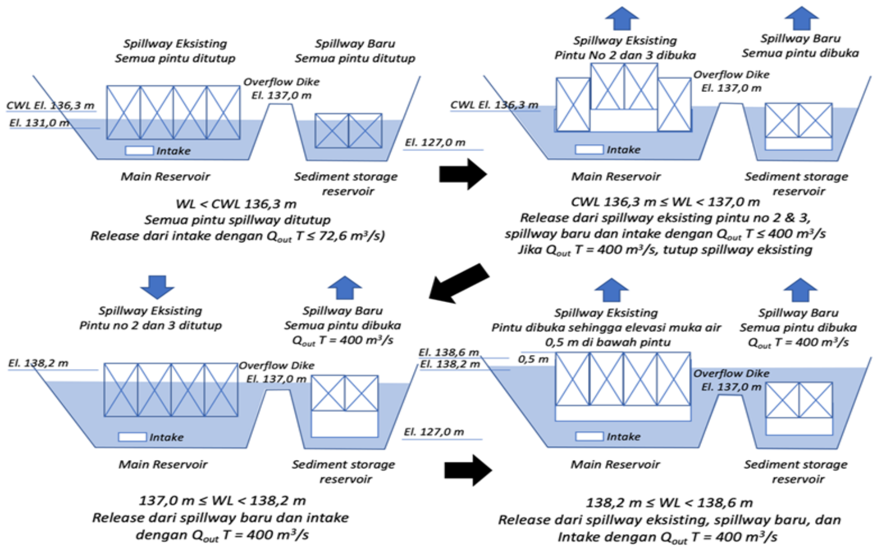

Figure 1 Operation rule of spillway gates for standard highest flood.

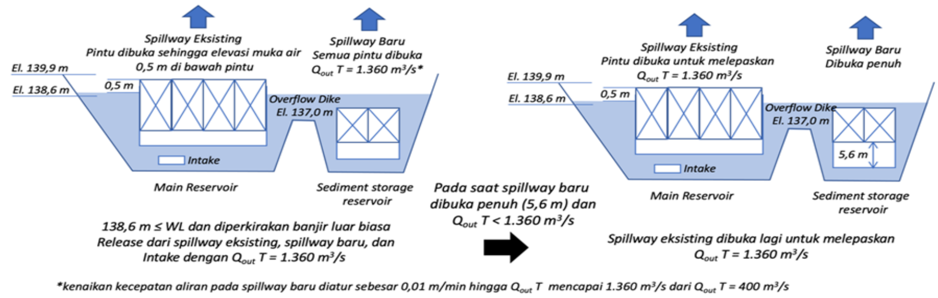

Figure 2 Operation rule of spillway gates for large scale flood.

Flood control operations are formulated with flood tracking taking into account the following principles:

a. Total outflow should not exceed 400 m³/s.

b. The gate on the new spillway in the sediment storage reservoir are operated to drain as much of the incoming sediment as possible from the Keduang River.

The gate on the existing spillway must be opened when the water level in the main reservoir reaches an elevation of +138,2 m to prevent overtopping.

2.2 Reservoir Flood Routing

The reservoir's flood routing simulation model is developed by taking into consideration the reservoir's features and the existence of new structures, specifically the closure dike, overflow dike, and new spillway. Setting the release of water for flood control purposes according to the new operating rule. **Figure 3** illustrates the fundamental principle of reservoir operation for flood control, where the release can be regulated by opening a new spillway gate, an old spillway gate, or both of spillway gate, depending on the reservoir's water level elevation and discharge amount. The predicted input flood is calculated in such a way that the reservoir water level does not exceed the maximum set limit and creates as minimal flooding downstream of the reservoir as feasible [3].

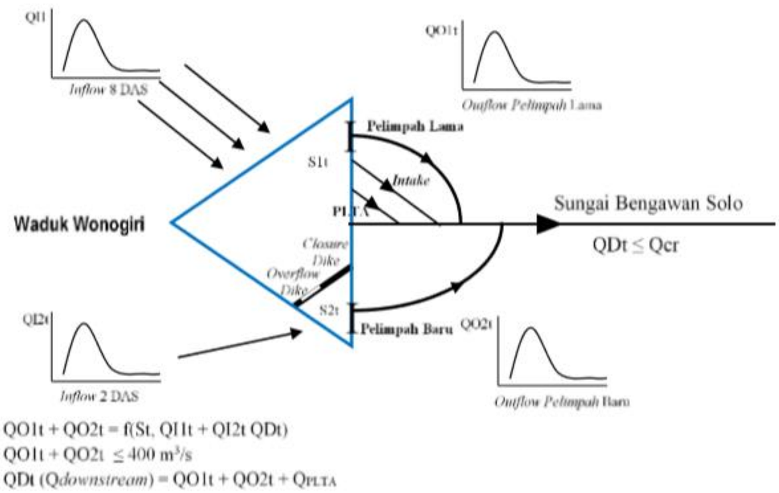

Figure 3 Schematic of flood routing model in reservoir for flood control.

Simulation analysis of reservoir flood routing in new conditions, after construction of a dike closure with a CWL of +135,8 m and a count time of 96 hours with 15 minute for time step intervals, utilizing reservoir operating principles from the Nippon Koei Co.Ltd.(2016) research. The inflow hydrographs of ten watersheds in the Wonogiri reservoir were derived from the findings of data analysis for Perum Jasa Tirta I. (2020). This simulation is a hydraulic model for predicting the outflow discharge and the estimated water level, which will impact the spillway gate's operating pattern. For this purpose, a simulation model of reservoir flood routing has been developed and applied using the new operation rules with inflow hydrograph of 60 years (Q_{60}) and 500 years (Q_{500}) return period as well as the PMF. **Figure 4** illustrates the stages of reservoir routing simulation.

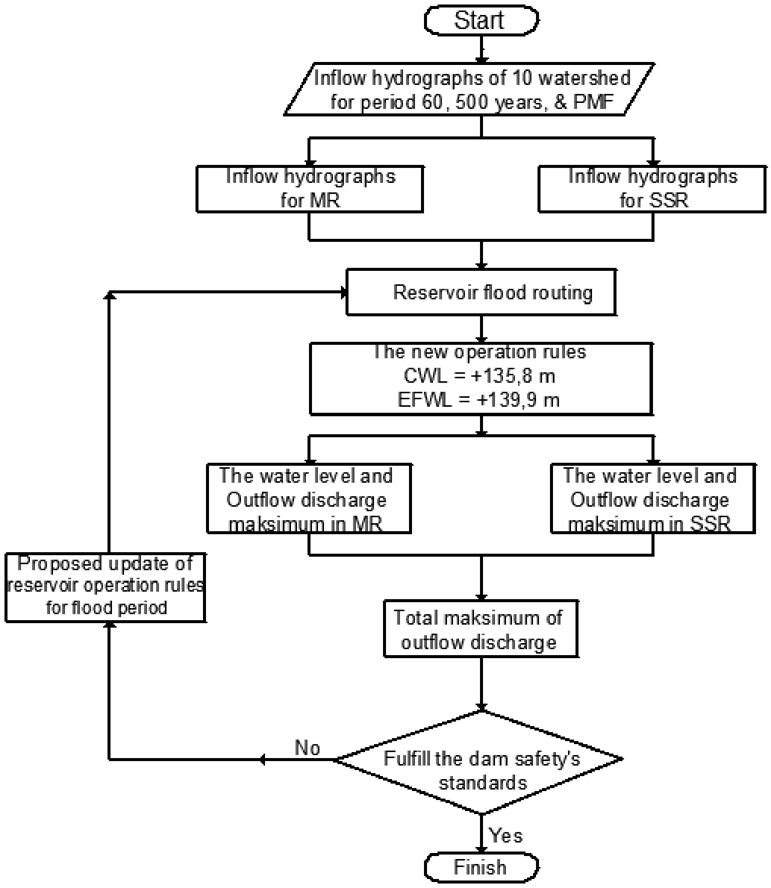

Figure 4 Flow chart of reservoir flood routing.

The computation of flood routing in reservoirs is based on many fundamental equations of the level pool routing method's principle of mass conservation [6].

$$\frac{dS}{dt} = I - O \quad t = 0, \Delta t, 2\Delta t, \ldots, j\,\Delta t, (j+i)\,\Delta t, \ldots \tag{1}$$

$$\int_{S_i}^{S_{i+1}} dS = \int_{j\Delta t}^{(j+1)\Delta t} I(t)dt - \int_{j\Delta t}^{(j+1)\Delta t} Q(t)dt \tag{2}$$

Because changes in input discharge (I) and outflow discharge (O) are considered linear across the computation time interval t (1 hour), the equation for reservoir change (S) may be stated as follows.

$$\left(\frac{2S_{j+1}}{\Delta t} + Q_{j+1}\right) = \left(I_j + I_{j+1}\right) + \frac{2S_j}{\Delta t} - Q_j \tag{3}$$

Sj is the reservoir storage volume on hour j, Ij and Oj are the inflow and outflow discharge of the reservoir on hour j, and Δt is the time step calculation which calculated hourly.

The outflow discharge flowing through the ogee type of spillway with half-opened gate can be calculated using the equation below [4].

$$Q = \frac{2}{3}\sqrt{2g}CL\,(H_1^{\frac{3}{2}} - H_2^{\frac{3}{2}}) \quad (4)$$

The overflow discharge calculation from SSR to MR or vice versa during free overflow condition are based on the overflow dike characteristics as shown in **Figure 5** and **Figure 6** [1].

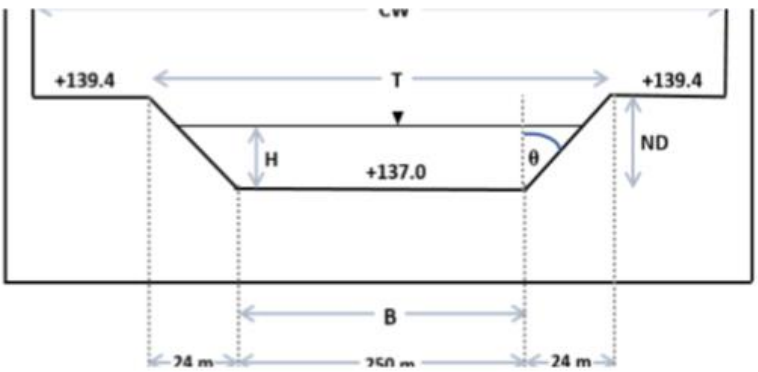

Figure 5 The dimensional sketch of the overflow dike.

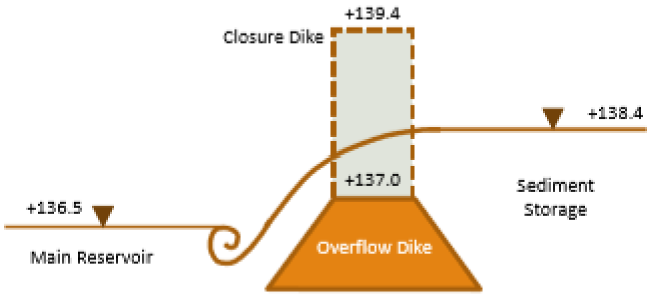

Figure 6 Sketch of free flow from SSR to MR.

3 Results and Discussion

3.1 Results of Reservoir Flood Routing

The SSR reached a maximum water level of +138,29 m at the 14,25 th hour. The water level in the SSR can return to CWL at 38,25 hours. The SSR's maximum outflow discharge is 309,38 m^3/s, while the MR's maximum water level is +137,31 m at the 63,5th hour. Until the 96th hour of the count, the water level on the MR was unable to return to the CWL of +137,30 m. The maximum discharge rate from MR is 90,54 m^3/s, while the maximum total discharge rate is 399,55 m^3/s. **Figure 7** and **Figure 8** illustrate the results of reservoir flood routing on SSR and MR for inflow Q60.

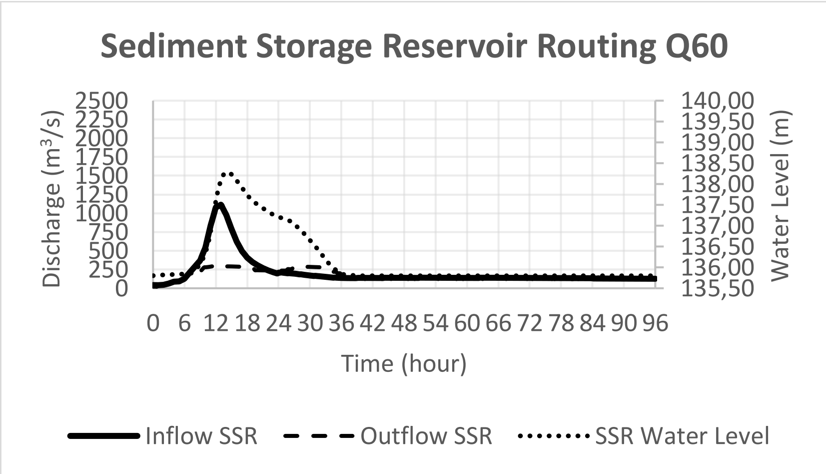

Figure 7 Hydrograph of inflow-outflow in SSR water level for inflow Q_{60} .

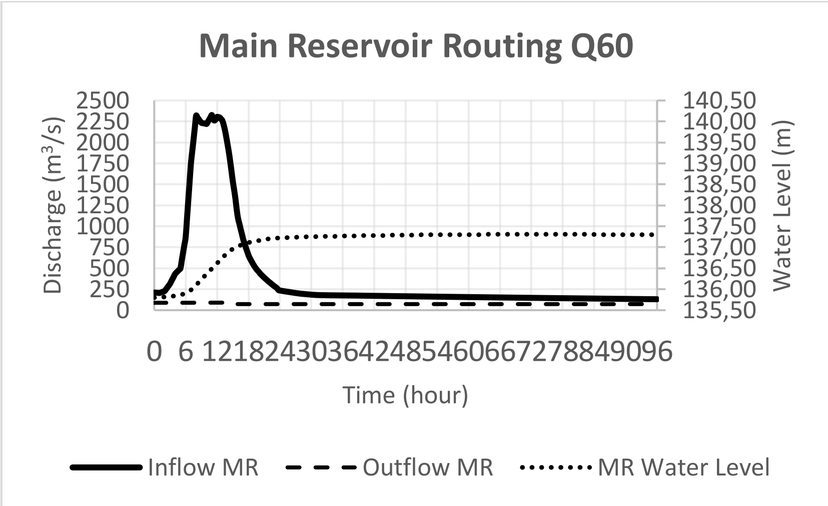

Figure 8 Hydrograph of inflow-outflow in MR water level for inflow Q_{60}.

The SSR's greatest water level is +139,06 m at the 11,75th hour. The water level in the SSR can return to CWL at 89,50 hours. The SSR's maximum outflow discharge is 324,64 m^3/s while the MR's highest water level elevation is +137,90 m at the 24,25 hour. MR's water level has been unable to return to CWL, which is +137,48 m till the conclusion of the count (96th hour). The highest discharge rate from MR is 90,48 m^3/s, while the maximum total discharge rate is 397,23 m^3/s. **Figure 9** and **Figure 10** illustrate the impacts of reservoir flood routing on SSR and MR for inflow Q_{500}.

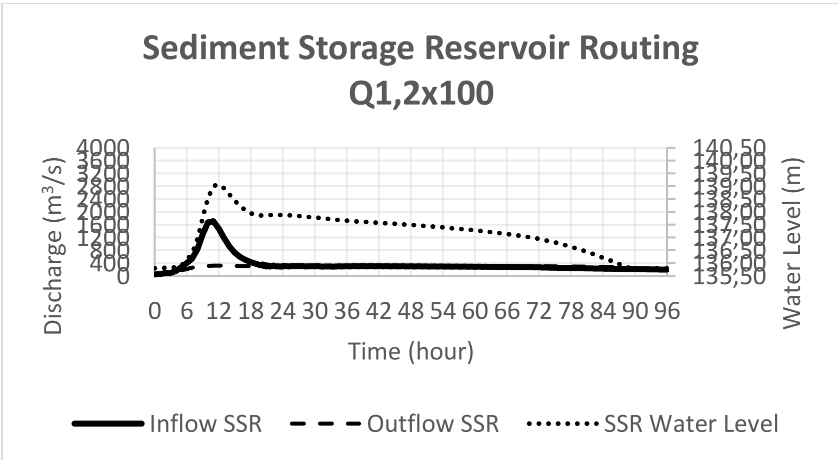

Figure 9 Hydrograph of inflow-outflow in SSR water level for inflow Q_{500} .

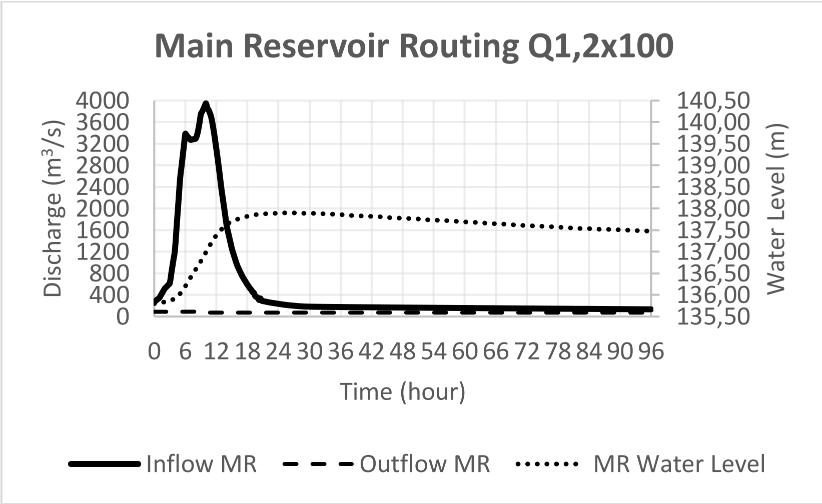

Figure 10 Hydrograph of inflow-outflow in MR water level for inflow Q_{500} .

The SSR's greatest water level height was +140,86 m at the 28,50 hour. At the 63,5th hour, the water level in the SSR can return to the CWL. The greatest discharge rate from SSR is 834,90 m^3/s while the maximum water level at MR is +140,86 m at 28,50 hours. At 96th hours, the water level can return to the CWL. The highest discharge rate from MR is 1870,81 m^3/s, whereas the maximum total discharge rate is 2.702,47 m^3/s. **Figure 11** and **Figure 12** illustrate the effects of reservoir flood routing on SSR and MR for PMF.

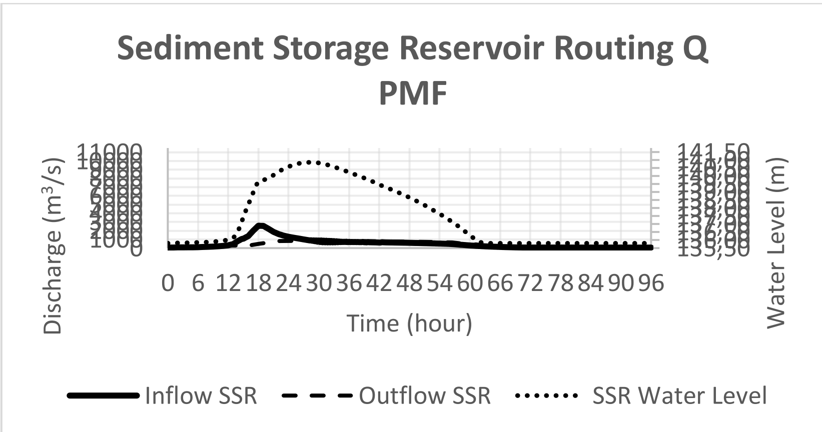

Figure 11 Hydrograph of inflow-outflow in SSR water level for inflow PMF.

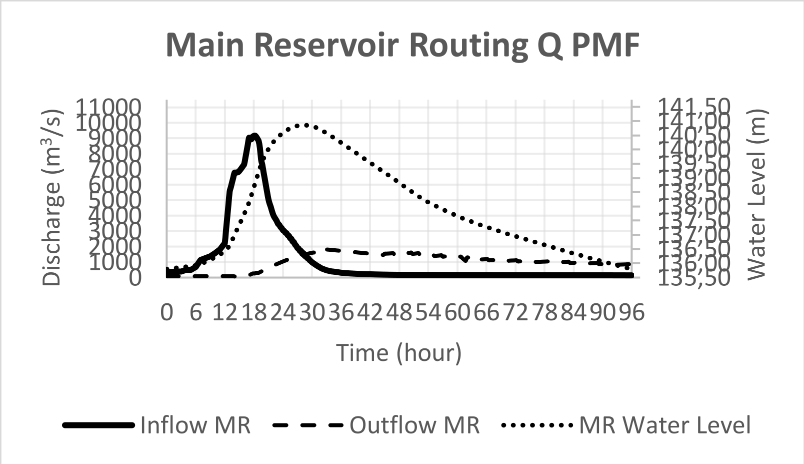

Figure 12 Hydrograph of inflow-outflow in MR water level for inflow PMF .

3.2 Recapitulation of Reservoir Flood Routing Results

Table 1 summarizes reservoir flood routing simulations for 60-year, 500-year, and PMF returns. The following are the outcomes:

a. Until the end of the calculation period, the water level elevation on the MR for flood discharge at 60 years and 500 years cannot return to CWL. This can make the Wonogiri Reservoir dangerous due to the possibility of overtopping.

b. While the water level on MR and SSR for flood discharge during PMF return can return to CWL, it has surpassed the maximum water level elevation (EFWL), which is greater than +139,9 m, and the dam's safety factor (free board) does not fulfill the standards, less than 1,25 m.

Table 1 Recapitulation of reservoir flood routing results.

Flood period	**Outflow maksimum (m^3/s)**			**The maksimum elevation (m)**		**Free board (m)**
	SSR	MR	Total	SSR	MR	SSR
Q_{60}	309,38	90,40	399,55	+138,29	+137,30	3,71
Q_{500}	324,63	90,48	397,23	+139,06	+137,90	2,94
PMF	834,90	1870,81	2702,47	+140,86	+140,86	1,14

3.3 Proposed Update to the Rules for Flood Period Reservoir Operation

Taking into consideration the findings of the evaluation of reservoir operation performance during the flood period conducted in accordance with the rules advised by Nippon Koei Co. Ltd. (2016), many revisions or updates to the reservoir operating rules might be offered as follows.

a. For flood design Q_{60} and Q_{500}

The old spillway door is shortened and closed when the MR water level reaches +137,00 m to +137,50 m (it was formerly +138,20 m). This is done to expedite the process of reducing the water level in MR so that it can return to CWL promptly. The ancient spillway features four doors with apertures that allow for a maximum total outflow of 400 m^3/s and 1.100 m^3/s for Q_{60} and Q_{500}, respectively.

b. For PMF design flood

For PMF or emergency flood inflows, the spillway door will be fully opened only when the SSR water level reaches +137,50 m; there is no need to wait until the SSR water level reaches +138,60 m and the total outflow discharge begins to grow. This is intended to lower the TMA in the SSR at peak input discharge. The total outflow discharge is not limited to the maximum of 1.360 m^3/s as in the original arrangement, but is designed so that the maximum reservoir water level in both SSR and MR offers a safe freeboard, therefore avoiding the possibility of dam overtopping.

3.4 Recapitulation of simulation findings for reservoir flood routing using updated reservoir operation rules.

Recapitulation of calculation findings for reservoir flood routing simulations in **Tabel 2** using updated reservoir operating rules for CWL +135,8 m. Several significant findings can be summarized as follows.

a. Except for the MR during Q_{60} flood inflow, the SSR and MR water levels can recover to CWL prior to the conclusion of the simulation duration (96 hours).

b. The maximum TMA at SSR and MR for PMF flood inflow is greater than the EFWL (+139,90 m), which is +140,62 m, and the free board is somewhat greater than the minimum requirement of 1,25 m, which is 2,94 m for flood influx Q500 and 1,38 m for PMF flood inflow.

Table 2 Recapitulation of reservoir flood routing results with the new reservoir operating rules.

Flood period	Outflow maksimum (m^3/s)			The maksimum elevation (m)		Free board (m)
	SSR	MR	Total	SSR	MR	SSR
Q_{60}	309,38	90,40	399,55	+138,29	+137,30	3,71
Q_{500}	559,23	1028,58	1099,23	+139,06	+137,72	2,94
PMF	825,20	1867,81	2729,57	+140,62	+140,62	1,38

4 Conclusion

The results of the flood routing simulation using Nippon Koei Co. Ltd.'s (2016) proposed flood period reservoir operation rules should be revised because:

a. The TMA at MR in the Q_{60} and Q_{500} floods has not been able to return to CWL until the end of the simulation time (end of day 4), the risk of overtopping occurs in the event of heavy extreme rains consecutively with a gap of less than 4 days.

b. Freeboard on PMF flood inflow does not meet the dam safety requirements (less than 1,25 m), the maximum TMA of SSR and MR for CWL +135,80 m exceeds EFWL very risk of overtopping and endangering the stability of Wonogiri dam.

c. The maximum reservoir outflow discharge for PMF flood inflow in both CWL options exceeds the planned, which is greater than 1.360 m^3/s.

5 References

[1] Ansita G. Pradipta, 2014, Studi Pengaruh Pembangunan *Closure Dike* Waduk Wonogiri terhadap Pola Operasi Waduk Perioda Banjir, Tesis, Program Studi Magister Teknik Sipil, Fakultas Teknik Universitas Gadjah Mada, Yogyakarta. [In Bahasa Indonesia]

[2] Nippon Koei Co. Ltd., 2016, Countermeasures for Sedimentation on Wonogiri Reservoir under Lower Solo River Improvement Project Phase-2 (JICA Loan No. IP-522) Study Report on Operation and Maintenance of Wonogiri Multipurpose DAM and Related Structures, The Republic of Indonesia.

[3] Paska Wijayanti, 2020, Pola Operasi Waduk Wonogiri Setelah Pembangunan Pintu Pelimpah Baru untuk Pengendalian Banjir dan Sedimen di Wilayah Bengawan Solo Hulu, Tesis, Program Studi Magister

Teknik Sipil, Fakultas Teknik Universitas Gadjah Mada, Yogyakarta. [In Bahasa Indonesia]

[4] Rachmad Jayadi, Istiarto & Ansita Gukitapingin Pradipta, Impact of Sedimentation Counter Measure on the Performance of Flood Control: A Case Study of Wonogiri Reservoir, Applied Mechanics and Materials, ISSN:1662-7482, Vol 881, pp. 78-85, Mei. 2018.

[5] Siti Rahmi Oktavia, 2013, Pengembangan Model Hidrologi untuk Estimasi Hidrograf Banjir *Inflow* Waduk Wonogiri, Tesis, Program Studi Magister Teknik Sipil, Fakultas Teknik Universitas Gadjah Mada, Yogyakarta. [In Bahasa Indonesia]

[6] V.T. Chow, *Applied Hydrology*, Mc.Graw Hill, New York, 1988.