Optimization of Gunungrowo Reservoir operation

by Dyah Ari Wulandari

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1 Introduction

1.1 Back ground

Water resource projects are large-scale projects and typically require substantial cost and long construction times [1]. In the management of water resources, reservoirs have an important role, especially with the global issues of climate change and rapid population growth [2]. Much effort has been made in planning and designing as well operation of reservoirs [3]. The reservoir must be optimally operated with a high level of performance [4,5]. Due to the large amount of funding required and the risks of uncertainty, it is also important to solve problems related to water resources often used optimization techniques [5]. One of the most commonly used optimization techniques is the dynamic program. Dynamic program optimization technique is very suitable to get optimal result on operation of reservoir. In the dynamic program, the steps are done step by step and interpreted according to space and time. Therefore, optimal results can be obtained as a sequence of steps, and each stage involves decisions that affect the characteristics of the problem [6,7]. Many researchers use dynamic modeling to optimize the operation of the reservoir with different objective functions [4,8,9,6,10,11,12,5,13].

The problem of reservoirs in Indonesia is sedimentation, which causes a decrease in reservoir storage capacity and reduced inflow during the dry season, thereby reducing the reliability of the reservoir in meeting its needs [9,14]. The similar problem happens in Gunungrowo Reservoir. Gunungrowo reservoir is used to store water during the wet season, and the stored water is used to meet water demand in the dry season. According to its function, Gunungrowo Reservoir is used to irrigate in the planting season II and III, so the water from the reservoir is released in planting season II and III from February to the end of August. Based on the evaluation of the Gunungrowo Reservoir monthly data report for the period of operation of 2004–2014, water from the reservoir is released in the second half of April to December. In May–June, there is excess release of reservoir water, while in the period from July to August there is a shortage of water release, or inaccurate release of reservoir water can be said to occur. After more than 90 years of operation, the Gunungrowo Reservoir operation needs to be evaluated to determine its performance and update existing operating patterns in accordance with changes in water demand patterns, hydrological conditions and reservoir storage capacity [15,16]. According to [17,18,19,20,21,22,23] indicators to assess the performance of reservoir operations in meeting needs are reliability, resiliency, and vulnerability.

1.2 Description of Gunungrowo Reservoir

Gunungrowo Reservoir was built in 1918. Gunungrowo Reservoir is located in Sitiluhur village in Gembong subdistrict, Pati District, Central Java Province at

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precisely 6° 39' 21.67" S and 110° 57' 55.77"E. A map of the location of Gunungrowo reservoir can be seen in Figure 1.

A schematic of the reservoir system can be seen in Figure 2. The inflow of Gunungrowo Reservoir is from Brambang irrigation channels, Bendoroto/Kedawung irrigation channels, and the catchment area around the reservoir. Water from the reservoir enters the intake conduit through a five-doors intake located on the intake tower. The function of door 1 is to flush the sediment, so the door is always closed during operation. Doors 2, 3, 4, and 5 of the water gates are opened based on the elevation of the water in the reservoir and the water is stored in the tower until the elevation of the water in the reservoir and the tower is the same. Door 6 is a gate for regulating the outflow discharge, and the door is located right at the mouth of the conduit. The operation of the door is based on the water needs in accordance with the agreed pattern of operation.

In 2015, the conduit channel was repaired and the sediment in the reservoir was dredged so that the maximum reservoir storage capacity increased to 6.53 million m^3.

Fig. 1. Map of Gunungrowo Reservoir (Google map, 2018)

The cropping pattern in irrigation area (DI) Gunungrowo follows the customs of the local community, with *paddy-paddy-palawija* and cane grown throughout the season. The planting season begins in October and drying takes place in the month of September. The function of Gunungrowo Reservoir is to help provide irrigation during the planting season II and III, so the water from the reservoir is released in the growing seasons II and III from February to the end of August. The planting period of Gunungrowo Reservoir is divided into three periods [24], namely:

- Planting Season I (MT I): 1 October – 15 January, paddy plants
- Planting Season II (MT II): 1 February – 15 May, paddy plants
- Planting Season III (MT III): June–August, *palawija* plants

2 Methods

The purpose of this study was to evaluate the operation of existing reservoir and to carry out an optimization of the reservoir operation. The objective is to conduct a hydrological analysis, to evaluate the operation of reservoir, to formulate a model of reservoir operation, to optimize the operation of the reservoir, and to analyse the results of the reservoir operation optimization.

Data required in this study are primary and secondary data obtained from the relevant authorities, namely the reservoir technical data, storage capacity of the reservoirs, evaporation, bathymetry of reservoirs, hydrological data, climatology, topography and land use in the catchment area of the reservoirs, river data and facilities in the upstream of the reservoirs, water demand, reservoir operation manual guidelines (existing reservoir operation pattern), data records of reservoir operation, and reports of relevant prior studies.

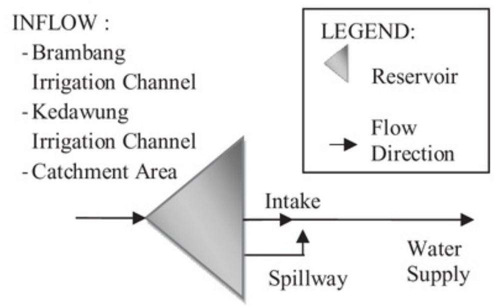

Fig. 2. Gunungrowo Reservoir system schematic

Modelling of reservoir operation begins with identifying the objective function and constraint functions, followed by the formulation of a model of the objective function and constraint functions in the form of mathematical equations as input from a dynamic program. The dynamic program used for the mathematical equations is solved using the software package CSUDP to obtain the optimum results of the objective function. Then the performance of the reservoir operation optimization results, including the reliability, resilience, and vulnerability, can be viewed. An overview of the research stages can be seen in the flow chart in Figure 3.

A model was developed to regulate the release of water to meet the needs of irrigation (target) and maintenance of the river. The water released is carried through the spillway and the intake. Release through the spillway is carried out in the case of flooding. The release to meet the water demand (target) takes place through the intake conduit. Water storage for irrigation and maintenance of the river is carried out between elevations of +307.7 masl and +320.0 masl. The functions of flood control are carried out between the elevation of +320.0 masl and +321.0 masl. Optimization of reservoir operation is carried out under three scenarios as follows:

- Release of water to meet the water demand in MT II and MT III
- Release of water to meet the water demand in the month of October, MT II, and MT III
- Release of water to meet the water demand in MT I, MT II, and MT III

The formulation of the reservoir operation model can be seen in Table 1. There are two kinds of definitions of reliability, the first reservoir is considered to fail if the reservoir cannot meet the total requirement, the second reservoir is considered only able to supply some of its needs if the reservoir cannot meet the needs in total (Mahon and Russel (1978) in [17,20]. This study used the first definition.

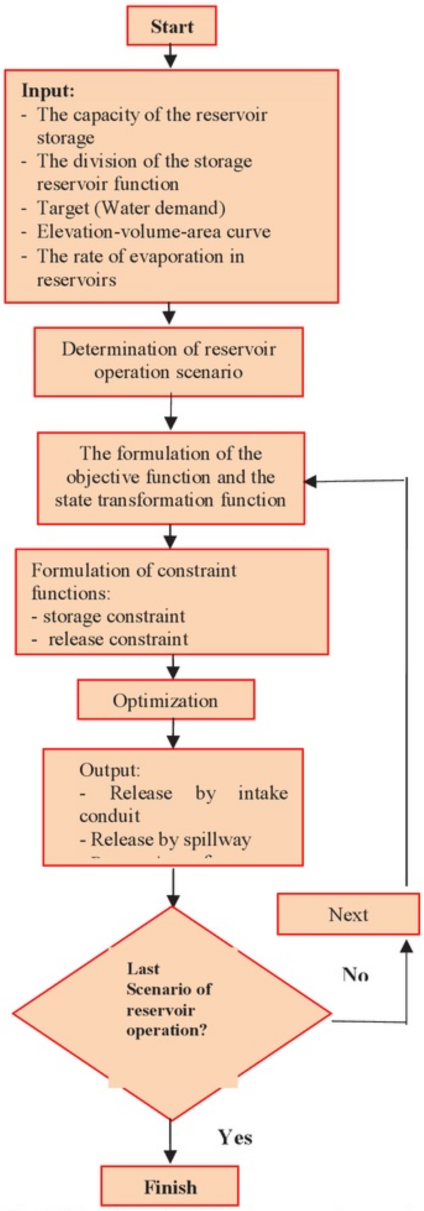

Fig. 3. Flowchart of optimization reservoir operation

3 Results and discussion

Based on Figure 4, Gunungrowo Reservoir stores water during the period of the rainy season and releases water in the dry season. In each period of reservation operation, the water decrease is exceeding the minimum water level (< +307.7 masl). In the operation of the reservoir during the year 2010/2011, there was excess water, so there was no decrease in the water level of the reservoir. Figure 5 shows that water from the reservoir is released in April second half until December. In the period from May to June, water excess is released, it can be said to occur inaccurate water release. In the period from July to August, there is a shortage, this may because of reservoir capacity decrease by sedimentation and error in regulating the release water.

Optimization of reservoir operation by using a dynamic program, the CSUDP package, generates patterns that indicate the operating water level of reservoirs and release of water in each period as well as the objective function value in each scenario of the reservoir operation. The minimum objective function value for each reservoir operation scenario was selected based on the minimum objective function value with the initial capacity of the reservoirs was near to the minimum limit of capacity or equal to 1.1365456×10^6 m^3. A summary of the optimization of reservoir operation can be seen in Table 2.

Based on Table 2, the total release in scenarios I and II approaches the same value, whereas in scenario III it is smaller. The total removal of water in scenarios I and II is greater than the water demand, while in the third scenario the total release is smaller than the water demand. In all operating scenarios, the amount of water released through the intake is greater than the amount of water released through the spillway. In scenario III, the reservoir operation gave the smallest value of the objective function, which means reservoir operation in scenario III generates the smallest difference between the water demand target and release.

Based on Figures 6 and 7, it can be seen that in scenarios I and II the reservoir water level is always at a high elevation, except in 2011, when the reservoir water level drops sharply in scenario II. In scenario III, the reservoir water level always decreases to the minimum operating limit (+307.7 masl) and then rises again. In the existing reservoir operation, reservoirs are always discharged to the elevation below the minimum operating limit (+307.7 masl) and in the rainy season of 2006 the reservoir water level never exceeds the maximum elevation (+ 320.0 masl).

Based on Figures 8 to 10, it can be seen that in some reservoir operation periods the reservoirs cannot meet the target in scenarios I, II, or III. The reservoir performance can be determined by analysing the reservoir performance to the results of reservoir operation optimization under a variety of scenarios. The reservoir performance optimization results under various scenarios can be seen in Table 3.

Based on three scenarios of reservoir operation, the reliability value ranges from 55 % to 75 % (Table 3). This indicates that in certain months, especially in the dry season, failure will occurs, as shown in Figure 8 to Figure 10, there is no release at any period. Scenario I has the highest reliability of 75%, meaning the reservoir can fulfill its function of 75%. According to [17,18,19,20,21,22,23] reliability measures the ability of the reservoir to meet the needs that are targeted during its lifetime, reliability does not measure the magnitude of failures that occur. The possible severity of failures is described by other criteria that are resiliency and vulnerability.

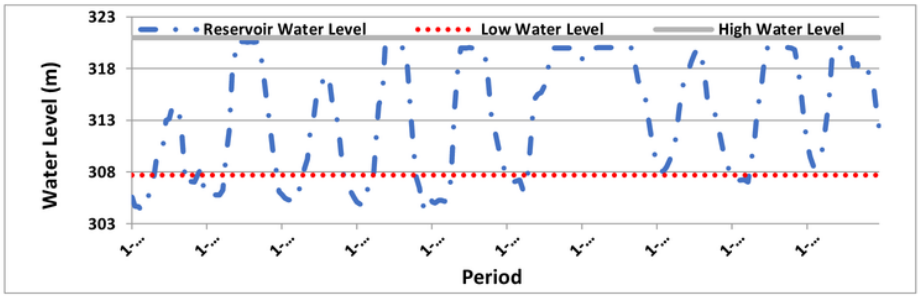

Fig. 4. Storage in Gunungrowo Reservoir, period October 2004 – November 2014

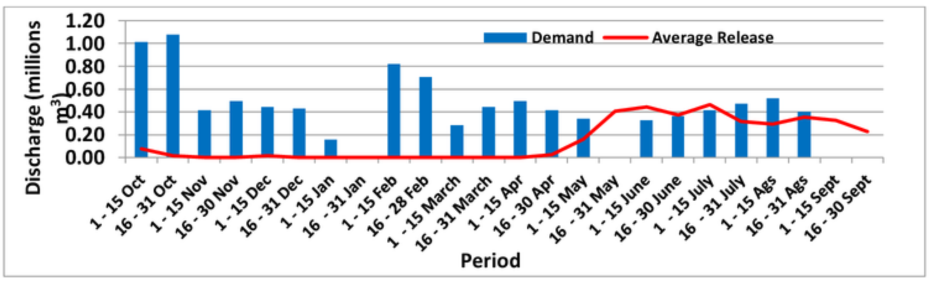

Fig. 5. Average release and demand for the period of 2004–2014

Table 1. Model formulation

No.	Description	Formulation
1	Objective function	$\text{Min } Z = \sum_{i=1}^{N} \frac{\lvert T_i - X_i \rvert}{T_i}$
2	State transformation function	$S_{i+1} = S_i - X_i + I_i - E_i - SO_i$
3	Recursive equation	$\left(\min \frac{\lvert T_i - X_i \rvert}{T_i}\right)_N + \left(\min \frac{\lvert T_i - X_i \rvert}{T_i}\right)_{N-1}$
4	Constraint	
	Storage	$1{,}000 \leq S_i \leq 5{,}506 \times 10^3\ m^3$ Using H-V-A curve in 2015 after dredging
	Release	$0 \leq X_i \leq$ Target
5	Demand/ Target	In accordance with the water needs of [3] and adapted to the changing reservoir operation scenario
6	Inflow	The inflow calculation results used were based on the reservoir operations record for 2004–2014 by Gunungrowo Reservoir Management
7	Evaporation	$E_i = e_i x \left[11.52x \left(\frac{S_i + S_{i+1}}{2}\right)^{0.434}\right]$
8	Discretization	
	Decision variable (thousand m^3)	$\Delta S = 45.5152 \times 10^3\ m^3$ Discrete Number = 99 The final value of decision variables does not follow the discretization value
	State variable (thousand m^3)	$\Delta X = 1 \times 10^3\ m^3$ Maximum discrete number = 1011 The final value of the state variable using the discretization value

Table 2. The Release from Gunungrowo Reservoir under different scenarios

Description	Release (× 10^3 m^3)			Objective function	Demand (× 10^3 m^3)
	Intake	Spillway	Total		
Existing	34,999.57	0.00	34,999.57	–	60,030.00
Scenario I: MT II and MT III	65,731.01	44,714.08	110,445.09	1,426.70	60,030.00
Scenario II: October, MT II, and MT III	71,351.54	39,122.58	110,474.12	1,081.75	80,910.00
Scenario III: MT I, MT II, and MT III	91,368.24	1,136.69	92,504.93	431.78	100,200.00

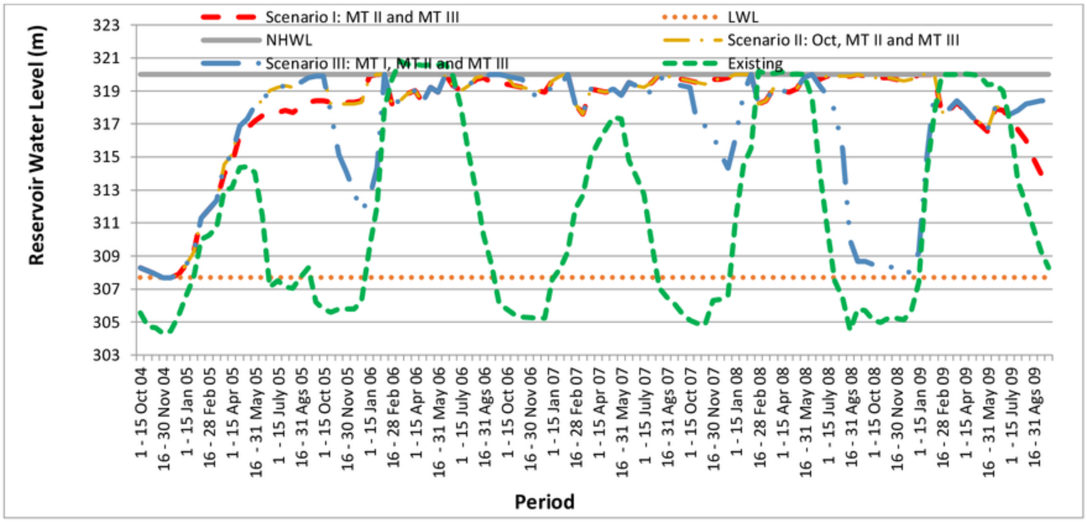

Fig. 6. Hydrograph of Reservoir Water Level of Gunungrowo Reservoir for the years 2004–2009 under different scenarios

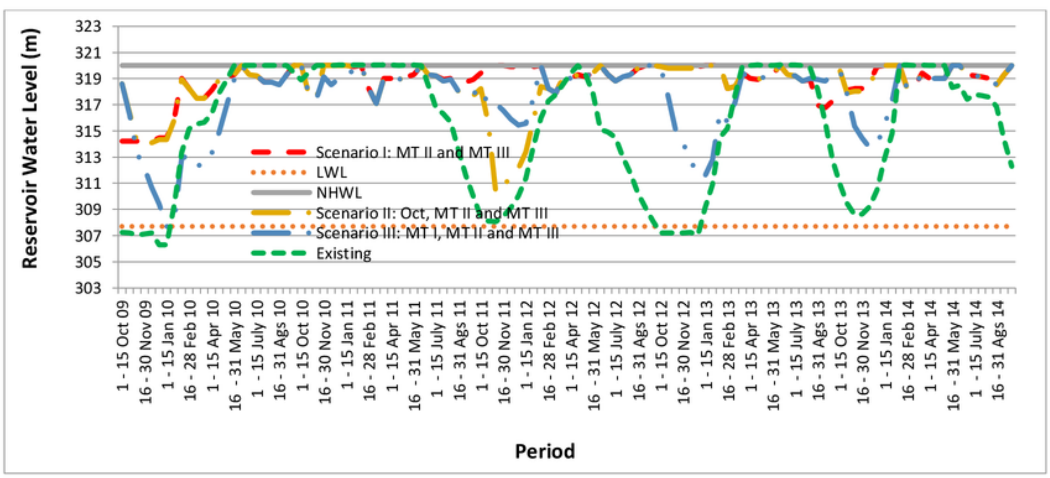

Fig. 7. Hydrograph of Reservoir water Level of Gunungrowo Reservoir for the years 2009–2014 for different scenarios

Resiliency measures the reservoir's ability to return to a satisfactory state of a failed state. If the failure occurs prolonged then the system recovery will be slow, this will seriously affect the system. The system is designed to be able to quickly recover into a satisfactory state [17,18,19,20,21,22,23]. Based on three scenarios of reservoir operation, the resilience value ranges from 0.34 to 0.37 with T_{fail} ranges from 2.73 to 2.9 (Table 3). Scenario II has the highest resiliency of 0.37 with T_{failed}

2.73, which means it takes 2.73 periods to return to a satisfactory state.

The magnitude of the failure occurring is measured on the vulnerability, including the average deficit ratio and average deficit [17,18,19,20,21,22,23]. Based on three scenarios of reservoir operation, average deficit ratio ranges from 1.35 % to 1.64 % with an average deficit amounting from 57.23 to 119.79 (Table 3). Scenario III has the lowest average deficit ratio, 1,35 %, meaning that 1.35% of water demand is not met from a failure with an average deficit amounting to 113,460 m^3 each period of failure.

Based on Table 3, scenario I produces reservoir operation a highly reliable but less resilience with a moderate average deficit ratio. Scenario II produces reservoir operation a very resilient, fairly reliable but highly vulnerable. Scenario II produces reservoir operation a less reliability, adequate resilience and a small average deficit ratio. Overall performance of these three scenarios is better than the existing condition. The scenario which has highest reliability also has lowest resilience, the scenario which has highest resilience also has highest vulnerability and the scenario which has lowest reliability also has lowest vulnerability. Those performance criteria cannot be used together, depending on their needs. [23] stated that to assess the performance of a water resources system can be used only reliability or resilience and vulnerability are used together, to avoid overlap. Resilience and vulnerability are required in analyzes related to sustainability.

In this case we decided to use the criteria of reliability, because the fulfillment of the needs during the planting season is important to ensure the plant continues to grow. The existing reservoir operation is not optimal as its reliability is only 24%. Scenario I has the highest reliability of 75%. Attempts to maximize system reliability are attempts to make a system's operation failure-free. Few systems can be made so large or so redundant that failures are imposible to occurs, this is often not economical to do so [22]. Therefore scenario I is the selected scenario.

If the water level reservoir optimization results taken its average value over the 10 years of operation, then will get the rule curve as shown in Figure 11, which can be used as a guidelines in the operation of Gunungrowo Reservoir. In the existing reservoir operation, the reservoir storage has always empty. Under reservoir operation scenarios I, II, and III, the reservoir storage is not always emptied, this is beneficial for maintaining the availability of water in the next service period.

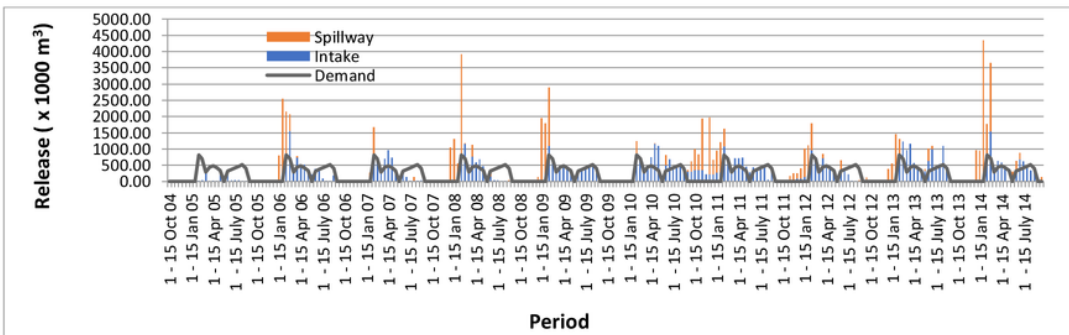

Fig. 8. Comparison of water release and demand in Scenario I

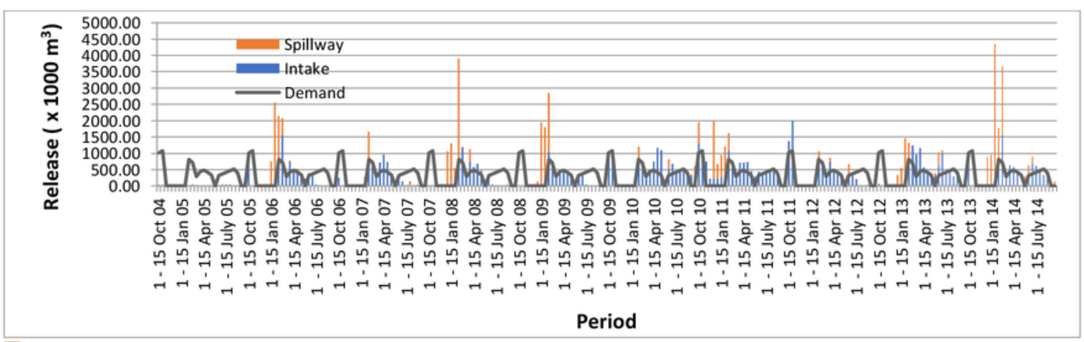

Fig. 9. Comparison of water release and demand in Scenario II

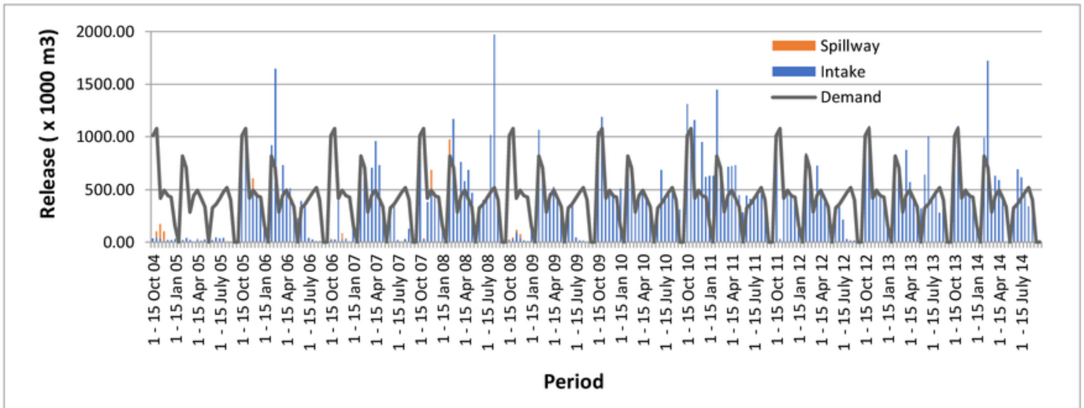

Fig. 10. Comparison of water release and demand in Scenario III

Table 3. Reservoir Performance under different scenarios

Description	Scenario I	Scenario II	Scenario III	Existing
Demand	MT II, MT III	October, MT I, MT II	MT I, MT II, MT III	MT II, MT III
Reliability	0.75	0.66	0.55	0.24
T failed	2.90	2.73	2.87	7.96
Resilience	0.34	0.37	0.35	0.13
Average deficit ratio	1.49	1.64	1.35	7.46
Maximum deficit ratio	1.00	1.00	1.00	1.00
Maximum deficit (× 1,000 m^3)	798.53	1073.82	1052.26	817.00
Average deficit (× 1,000 m^3)	57.23	119.79	113.46	190.12

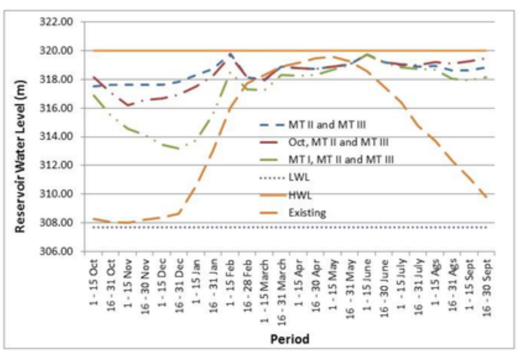

Fig. 11. Rule Curve of Gunungrowo Reservoir

4 Conclusion

The research carried out to optimize the operation of Gunungrowo Reservoir using a dynamic program can be summed up as follows:

- The operation of the existing reservoirs is not optimal and has a reliability of only 24%, this is due to errors in regulating water release and reduced reservoir capacity due to sedimentation.
-
- The optimal reservoir operation is achieved under the scenario I, which has a reliability of 75%. This operation can be used for future reservoir operation.

Suggestions relating to this study are as follows:

- The reservoir storage should not always be emptied. Excess water can be stored to meet the water needs in the next period, unless it is needed for a specific purpose such as flushing.
- If flushing is carried out, it is necessary to optimize the reservoir operation for flushing.
- If there is a change in water demand in the future, it should be optimized again.

The authors are grateful to UNDIP, who funded this research through the Riset Pengembangan dan Penerapan (RPP) scheme in 2016. Thanks are also offered to Balai Besar Wilayah Sungai Pemali Juana, who provided the data used in this study.

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