Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 9, No. 04, April, 2023

Optimization of Integrated Reservoir for Supporting the Raw Water Supply

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Received 26 November 2022; Revised 08 March 2023; Accepted 11 March 2023; Published 01 April 2023

Abstract

This research intends to analyze the optimal operation pattern for fulfilling the raw water demand, and it is conducted in the integrated cascade reservoir of Duriangkang-Muka Kuning, Batam City, Indonesia. However, Batam City is the economic center of the Riau Islands and absolutely needs enough raw water supplies to support its development. The need for raw water in Batam City is predicted to reach about 6,630.29 l/s in 2025. Due to the population growth that is estimated to reach about 1.8 million people in 2025 and the plan of Batam City development as an industry and tourism center, Batam City is faced with the condition that reservoir management becomes a very important thing for supporting the continuity of water supply. The methodology consists of collecting the supporting data, such as inflow, reservoir capacity curve, and data on water needs; then building the optimization model by determining the objective function and constraints of the integrated reservoir; and carrying out the optimization model by using linear programming and simulation models for the integrated reservoir operation. The result presents optimal reservoir operation of the integrated Duriangkang-Muka Kuning reservoirs. The reservoir operation consists of the boundary curve of upper and lower normal operation, the outflow for fulfilling the water need, and the rule of supply pumping from Duriangkang reservoir to Muka Kuning reservoir. It is hoped that the result can be used as a reference in operating the two reservoirs to fulfill the water needs of the Batam City population.

Keywords: Optimization; Duriangkang; Muka Kuning; Reservoir Operation; Water Supply.

1. Introduction

The important tasks that are faced by the decision-makers and the water resource managers are to find and assess effective solutions for some water problems. The general systems approach to the problems has been to optimize [1], simulate [2], or choose an alternative solution based on the trade-offs among the conflicting objectives [3]. The population growth in income implies the growth of water and food demand [4], but it is also reflected in the contamination of water bodies. Water resources have a direct relationship with the system approach due to both the system and non-linear relations [5]. A system is mentioned as a set of elements with connections among each other. Any system is composed of many sub-systems, each of which is open and autonomous, directly integrated with and interrelated with its environment [6]. In drafting the multi-reservoir operation pattern, the water transfer from the spillway reservoir has to consider the available capacity from the acceptor reservoir. A set of new release rules in every reservoir has to be analytic by considering the optimum condition of water balance and reservoir capacity of each reservoir [7]. Therefore, the management of multi-reservoir systems needs comprehensive consideration because between the reservoirs there is a relationship like a separate reservoir [5].

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http://dx.doi.org/10.28991/CEJ-2023-09-04-07

There are some previous studies that have developed the multi-reservoir operation method. Guo et al. [7] developed the operation pattern of a multi-reservoir system with a graded model for minimizing run-off and maximizing water availability. However, Gu et al. [2] developed the operation model of multi-reservoir water transfer between watersheds to minimize the risk of a water deficit. Rani et al. [8] have developed the water transfer optimization model through three objective functions that are to maximize the benefit of agricultural yield, minimize the water transfer cost, and combine the two previous stages. Mao et al. [3] have carried out the optimization of several reservoirs upstream of a lake to review the maximum satisfactory value of water availability for the environment in normal and dry years. Optimization is intended to handle reservoirs that have many objectives [9-11]. To determine the availability of water, it is necessary to carry out monitoring of the surface water resource volume. It is intended to analyze the material load that comes out of the water catchment area, especially for carrying out the verification of the consumption norms like clean water, irrigation, etc. [12–14]. Therefore, it is much needed to make water use distribution as effective and efficient as possible.

The Duriangkang and Muka Kuning reservoirs play an important role in supplying clean water to Batam City. The Duriangkang reservoir was built in 1992–1995 as the first estuary dam in Indonesia and as the reservoir that has the biggest volume of storage in Batam City. The dam, with an effective storage volume of about 107 million m^3, functions to fulfill the water needs with a capacity of about 2,500 l/s. However, the Muka Kuning reservoir was finished being developed in 1990, but it was just operated in 1991. In the beginning, the IPA of Muka Kuning had a water production capacity of about 310 l/s, but the capacity is increasing to 600 l/s in 2015, as the water need in Batam is increasing. The result of the bathymetry survey from the special study of Duriangkang reservoir and dam indicates that the sedimentation in Duriangkang from the beginning of operation until 2018 was about 25.9 million m^3. To return the storage volume to its initial condition, it is necessary to carry out a volume of dredging of about 7 million m^3. However, the volume change does not show a significant change because there is only about 6.5% of normal storage volume.

The Duriangkang reservoir has a surplus for water availability throughout the year in the conditions of wet years, normal years, and dry years, and the water balance of Muka Kuning reservoir has a surplus for water availability throughout the year only in the wet year. However, in normal year conditions, the Muka Kuning reservoir has several deficits in February, March, and August. The pretty bad water deficit also happened in the Muka Kuning reservoir in the dry year condition, where the surplus water only happened in July, November, and December [15]. The conditions of a big enough water surplus in the Duriangkang reservoir and a water deficit in the Muka Kuning reservoir indicate that there is enough water potency to supply the Muka Kuning reservoir. The water supply from Duriangkang reservoir to Muka Kuning reservoir intends to minimize the water deficit in the Muka Kuning reservoir and increase the usage of water storage in the Duriangkang reservoir so that it does not overflow. However, remembering that the topography site of Muka Kuning reservoir is upstream of Duriangkang reservoir, the supply between the two reservoirs can only be carried out by using pumps [15].

The raw water need in the Muka Kuning reservoir is about 0.57 m^3/s, and there is a water deficit condition in the Muka Kuning reservoir, so the value of supply potency can be reliable for fulfilling the deficit in water balance that has occurred. The value of water supply potency from Duriangkang reservoir is big enough if it is compared with the water need in Muka Kuning; even in the wet and normal year conditions of inflow, the value of supply potency is greater than the water need in Muka Kuning. In the dry year condition of inflow, the reliability of water supply is relatively low, that is, in the range of 0-1.30 m^3/s. It is worried that it will not be able to fulfill the deficit water need in the Muka Kuning reservoir. Therefore, it is needed to regulate the reservoir operation that is integrated between Duriangkang and Muka Kuning reservoirs so the water needs can be fulfilled [16]. Therefore, further research is needed about the optimization of the two reservoirs operation patterns so that the fulfillment of water needs can be optimized [17, 18].

In the cascade system of Muka Kuning and Duriangkang reservoirs, there is taking from the downstream storage by using pumps to fulfill the inflow of the upstream storage. The historic data of water level depth that is recorded shows that the Duriangkang reservoir experienced a big enough run-off by the end of 2017 until the beginning of 2018. In addition, the happened run-off [9] in the Muka Kuning reservoir becomes the additional flow of the Duriangkang reservoir. Therefore, it is needed to carry out research about the optimization of Duriangkang-Muka Kuning integrated management for supporting the raw water supply in the continuity Batam city. This study focuses on the optimization [10] of pumping supply from Duriangkang to the Muka Kuning reservoir.

2. Material and Method

2.1. Study Location

The study location is in the Duriangkang and Muka Kuning reservoirs that are located in Batam City. The two reservoirs are in a cascade system with the Muka Kuning reservoir in the upstream and the Duriangkang reservoir in the downstream, which are estuaries to the sea, as presented in Figures 1 and 2 [7, 8]. The area of Duriangkang reservoir is about 75.18 km^2, and the reservoir volume capacity is 106.1 million m^3. However, the area of Muka Kuning reservoir is about 9.64 km^2, and the capacity volume is about 6.32 million m^3.

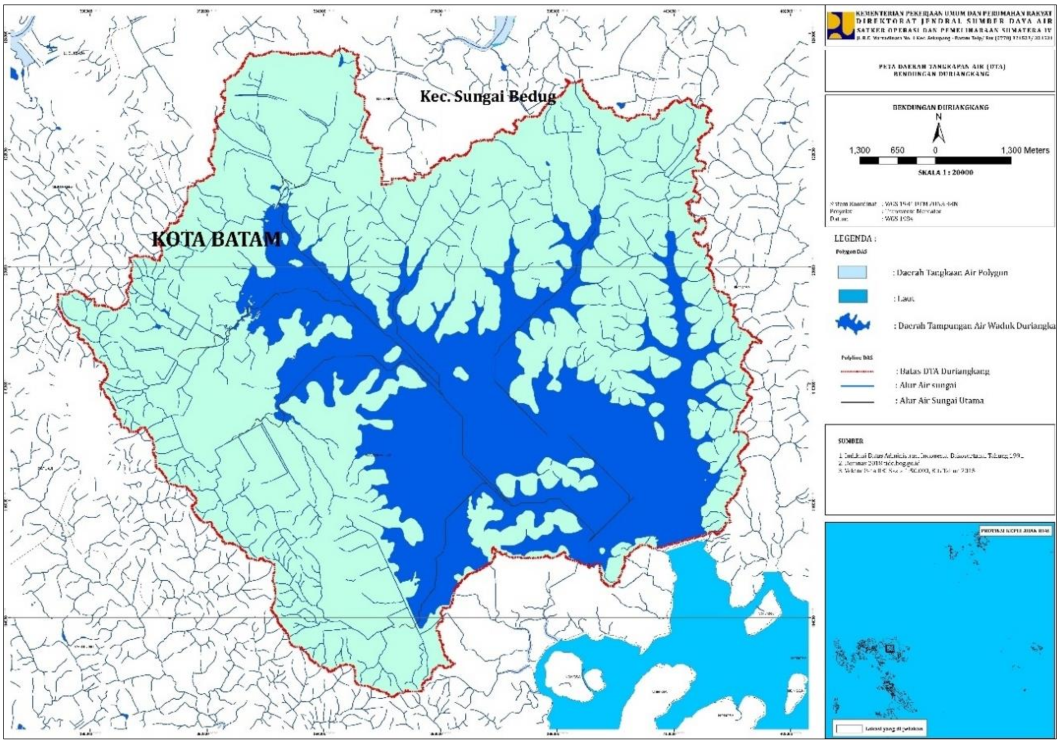


Figure 1. Catchment area map of Duriangkang reservoir, Batam city-Indonesia

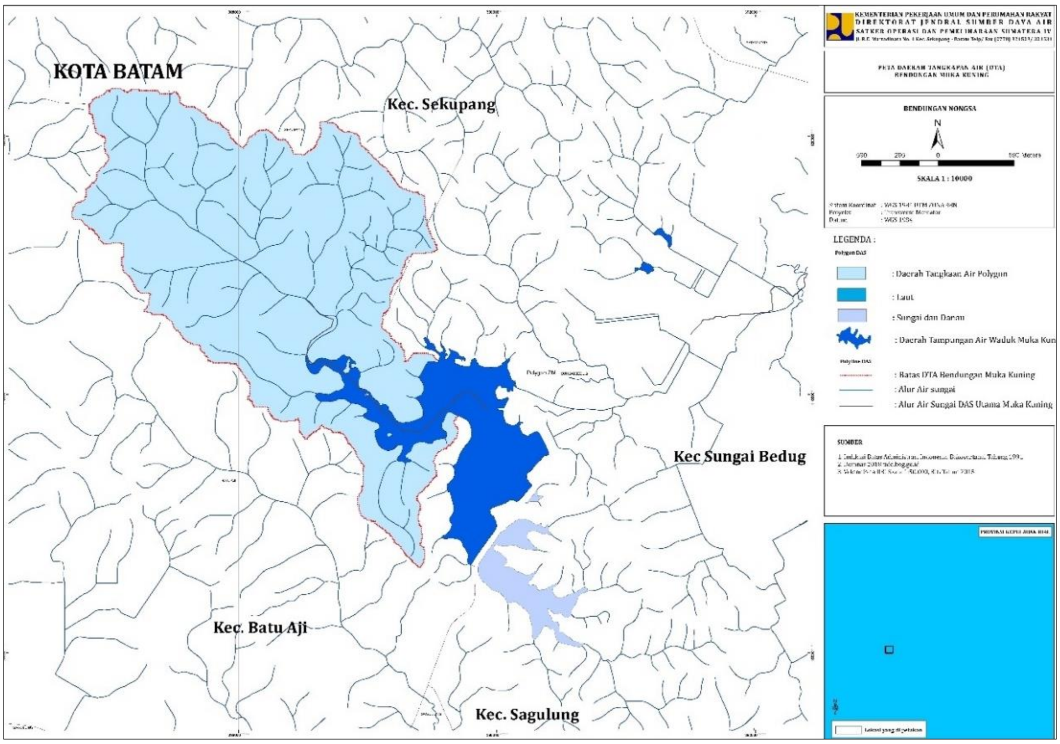


Figure 2. Catchment area map of Muka Kuning reservoir, Batam city-Indonesia

2.2. Optimization Model of Reservoir Management

There are several basic approaches that can be used in the planning of reservoir systems [9]:

- Simple method: it does not carry out the analysis but is based on the relationship curve between chance events and production yield.
- Simulation analysis that can be carried out for the multi-purpose reservoir by entering the stochastic and dynamic uncertainty of the reservoir system.
- Optimization analysis depends very much on the designer's ability to manipulate the design and operation policy variables efficiently.

Optimization is a process to select or find the values of variables in order to obtain the optimal value of an objective function while fulfilling the constraints of raw material as the input and something that is more useful as the output.

2.3. Reservoir Operation Pattern

Reservoir operation pattern (POW) is a rule of water regulation for operating the reservoirs that is agreed upon together by the water user and manager through the Committee of Water Regulation Setting (PTPA). The basic principle for setting the cascade POW is the same as that carried out on the single reservoir. The difference is that for the cascade reservoir, understanding is needed for carrying out equal sharing for each reservoir, so the benefit of the cascade POW can give the optimal result overall for each reservoir operation. In operation, the cascade reservoir is operated proportionally based on the effective volume from each reservoir every month, and each reservoir is always the same. To analyze the optimal reservoir operation pattern, it starts with data collection, testing, and analysis of reservoir availability, then determines the objective function and constraints, analyzes the potency of discharge, and then the next step is to optimize the reservoir operation. Figure 3 presents the flow chart of research, and Figure 4 presents the scheme of the Duriangkang-Muka Kuning reservoir.

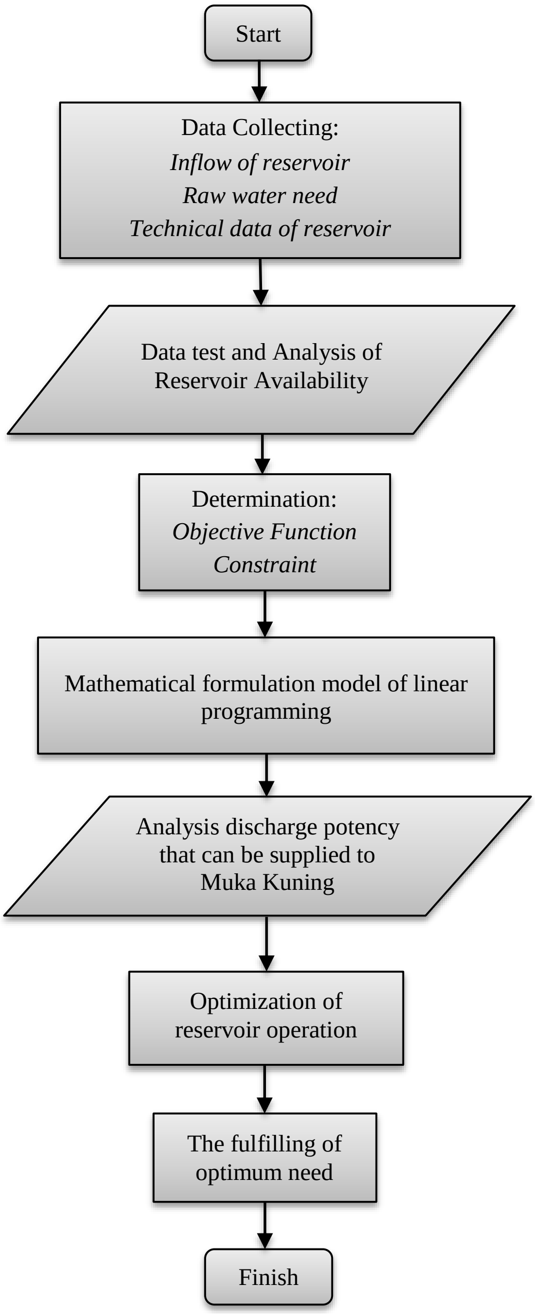


Figure 3. Flow chart of the research methodology

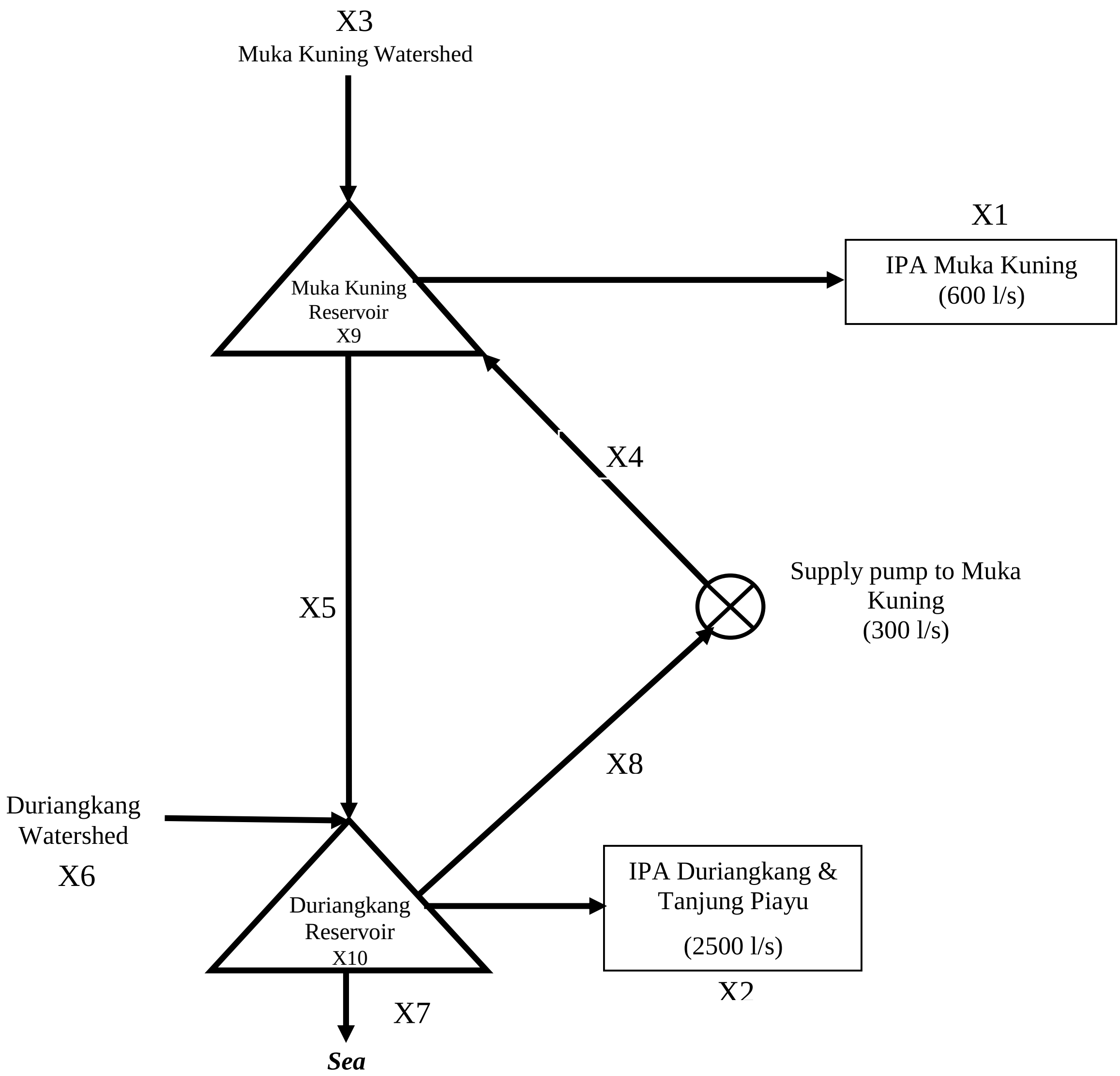


Figure 4. Scheme of Duriangkang-Muka Kuning Reservoir [7, 8]

C = optimal coefficient Constraint [9, 19, 20]:

1. Water balance:

   $X_9 = X_3 + X_4 – X_5 – X_1$

   $X_{10} = X_6 + X_5 – X_8 – X_7 – X_2$

2. Raw water need for the two reservoirs is not more than the pump capacity that is installed:

   $X_1 \leq 600$ l/s

   $X_2 \leq 2500$ l/s

3. The utilization of inflow due to the rainfall in each reservoir is not more than pump capacity that is installed:

   $X_3 + X_4 \leq 600$ l/s

   $X_3 + X_4 \leq X_5 + X_1$

4. Supply pump capacity from Duriangkang reservoir to the Muka Kuning reservoir:

   $X_4 \leq {}_{300}$ lt/dt

5. Discharge that is run over will be utilized by the accepted reservoir:

   $X_6 + X_5 \leq X_7 + X_8 + X_2$

6. Constraint of reservoir storage operation:

   Minimum operation boundary $\leq X_9 \leq$ Effective storage of Muka Kuning.

   Minimum operation boundary $\leq X_{10} \leq$ Effective storage of Duriangkang.

where: X_1 = Water needs in the Muka Kuning reservoir on t-period;

X_2 = Water needs in the Duriangkang reservoir on t-period;

X_3 = Inflow of Muka Kuning reservoir on t-period;

X_6 = Inflow of Duriangkang reservoir on t-period;

X_5 = Outflow of Muka Kuning reservoir to the Duriangkang reservoir on t- period;

X_8 = Outflow of Duriangkang reservoir as the supply to the Muka Kuning reservoir on t-period;

X_4 = Supply pump Muka Kuning reservoir on t- period;

X_7 = Run-off from Duriangkang reservoir on t-period;

X_9 = Run-off from Muka Kuning reservoir on t-period;

X_{10} = Storage of Duriangkang on t-period.

3. Optimization Analysis of Reservoir Operation

3.1. Optimization Result in the Wet Year

The simulation in the wet year uses a dependable discharge of 35% for the inflow of Duriangkang as well as the Muka Kuning watershed. The operation rule curve of Duriangkang and Muka Kuning reservoirs as optimization results is presented in Figures 5 and 6.

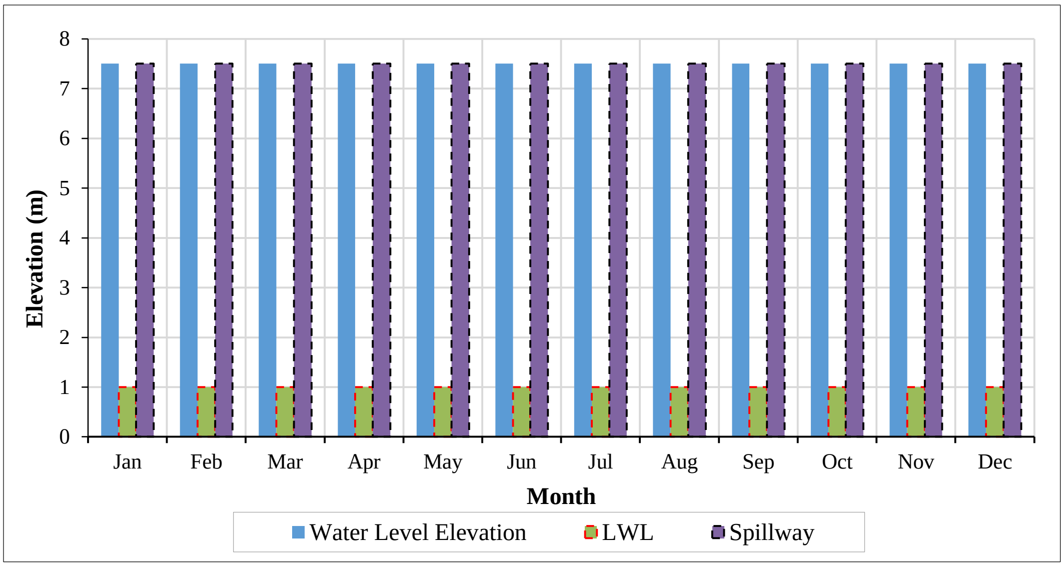


Figure 5. Reservoir operation of Duriangkang in the wet year

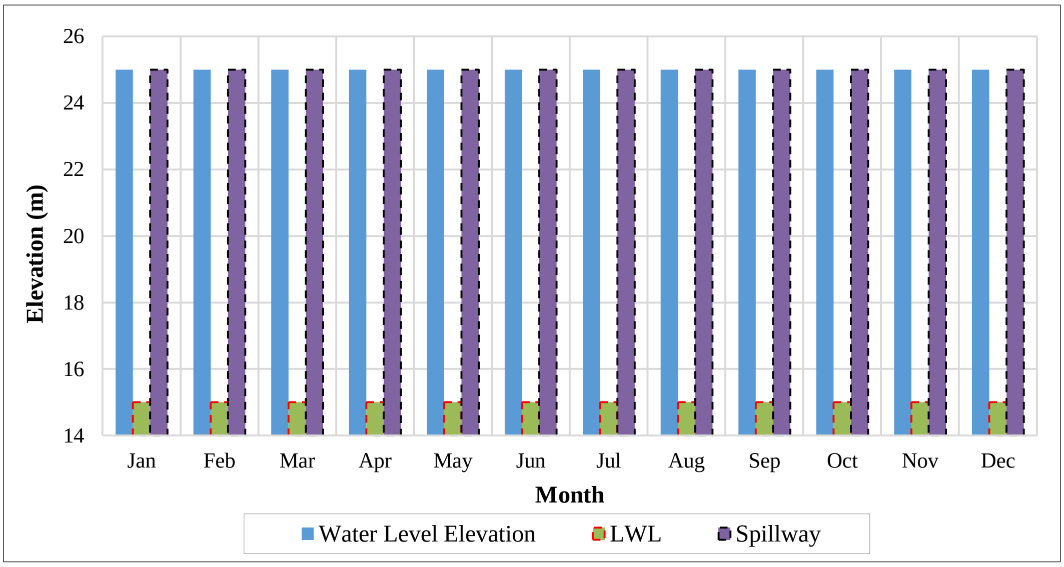


Figure 6. Reservoir operation of Muka Kuning in the wet year

Figures 7 and 8 show that Duriangkang and Muka Kuning reservoirs will experience runoff throughout the year. It is because water availability exceeds demand. Therefore, the water need can be fulfilled throughout the year, and there is no need for regulation or allocation of water taking as well as supply from Duriangkang reservoir to Muka Kuning reservoir.

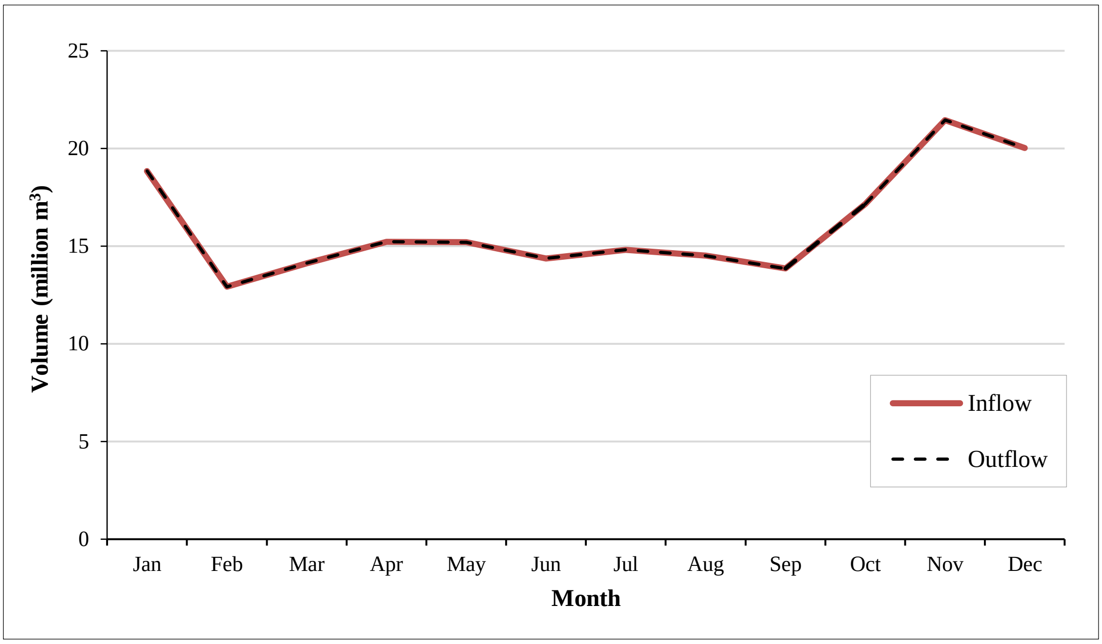


Figure 7. Optimization result of inflow-outflow in Duriangkang reservoir in the wet year

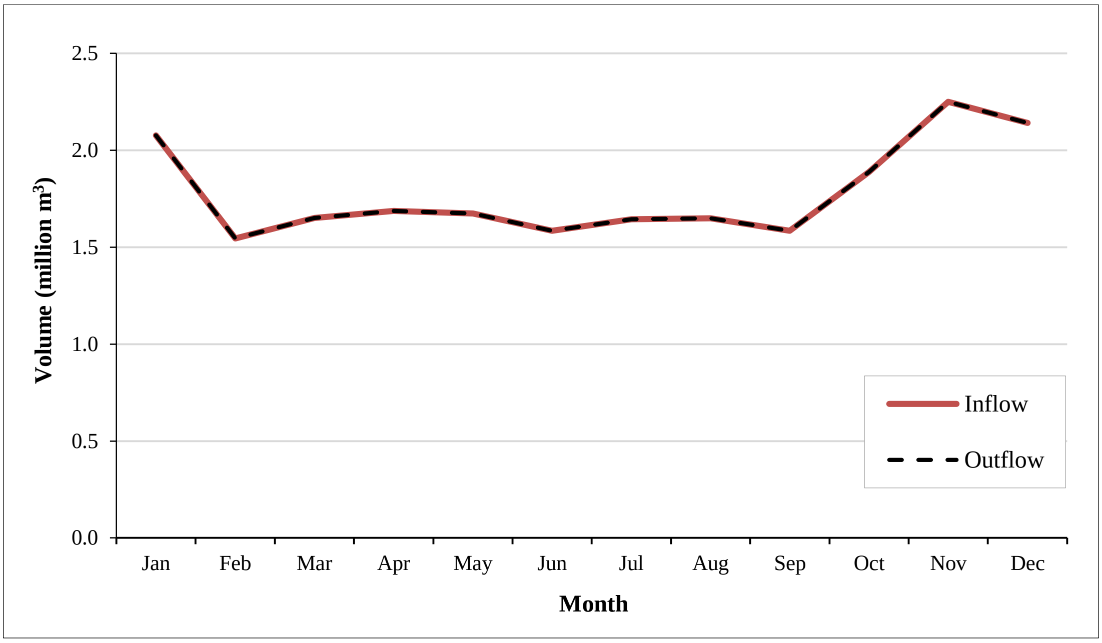


Figure 8. Optimization result of inflow-outflow in Muka Kuning reservoir in the wet year

The optimization result in the wet year is shown in Figures 7 and 8 by comparing the inflow and outflow volumes in each reservoir. The curve shows that the inflow and outflow volumes of Muka Kuning and Duriangkang reservoirs intersect along a period. Therefore, the result of the optimization model can be said to have reached the optimal value.

3.2. Optimization Result in the Normal Year

The simulation in the normal year is carried out by using the dependable discharge of 50% for the inflow in each Duriangkang and Muka Kuning watershed. The operation rule of Duriangkang and Muka Kuning reservoirs as the optimization result is presented in Figures 9 and 10.

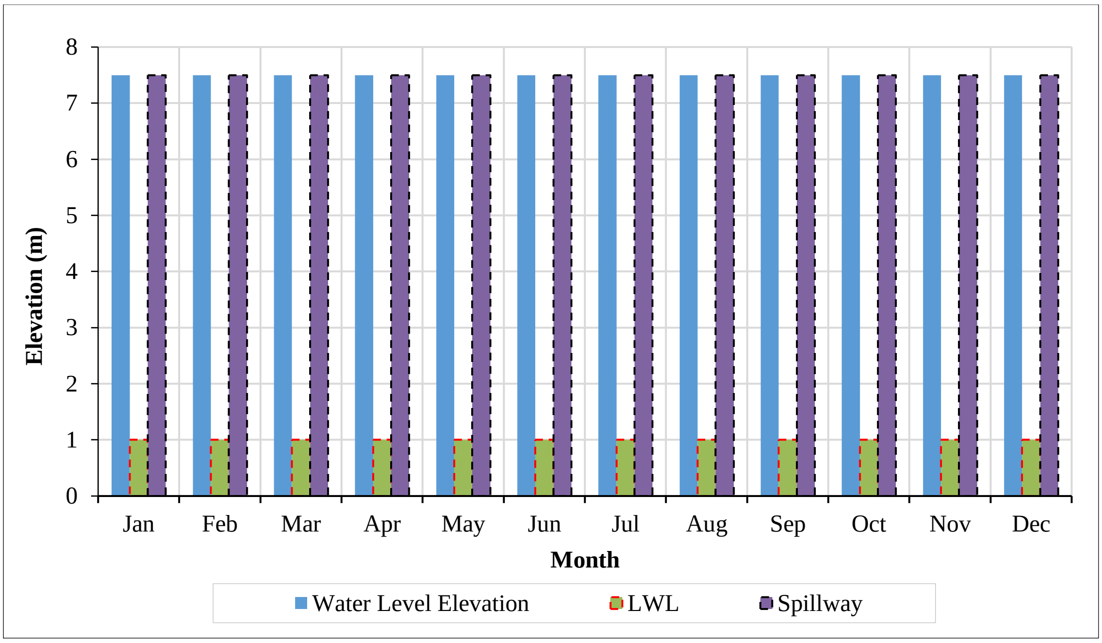


Figure 9. Reservoir operation of Duriangkang reservoir in the normal year

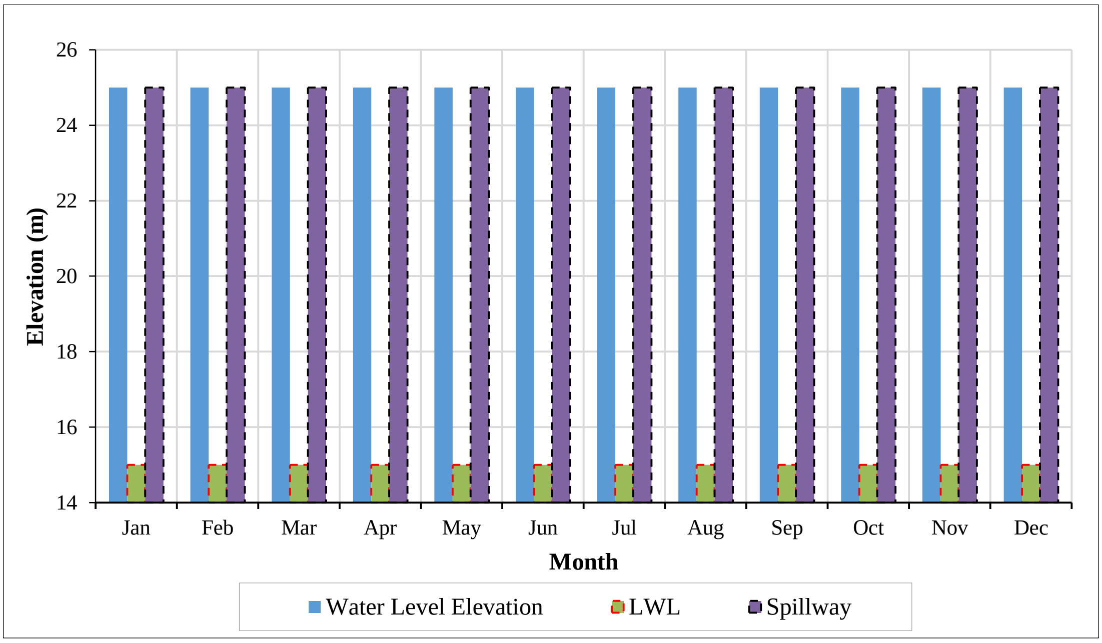


Figure 10. Reservoir operation of Muka Kuning in the normal year

In the simulation, in a normal year, the water availability in the Muka Kuning reservoir cannot fulfill the water needs throughout the year. In other words, the value of the water need is greater than the water availability for a certain month. Therefore, the water supply from Duriangkang reservoir is needed, so the water need remains fulfilled. Table 1 presents the variation of supply pumping discharge that is needed so the reservoir operation becomes optimal.

Table 1. Supply pumping discharge of Muka Kuning reservoir in the normal year

	Month					
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**
Pumping discharge (l/s)	1.15	0.00	0.00	0.00	0.00	0.00
	Month					
	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Pumping discharge (l/s)	3.24	0.00	0.00	0.00	0.00	0.00

The optimization result in the normal year is presented in Figures 11 and 12 by comparing the inflow and outflow volumes in each reservoir. The curve shows that the inflow-outflow volume is intersecting along the period. However, in the Muka Kuning reservoir, the inflow and outflow volumes intersect at more than one point.

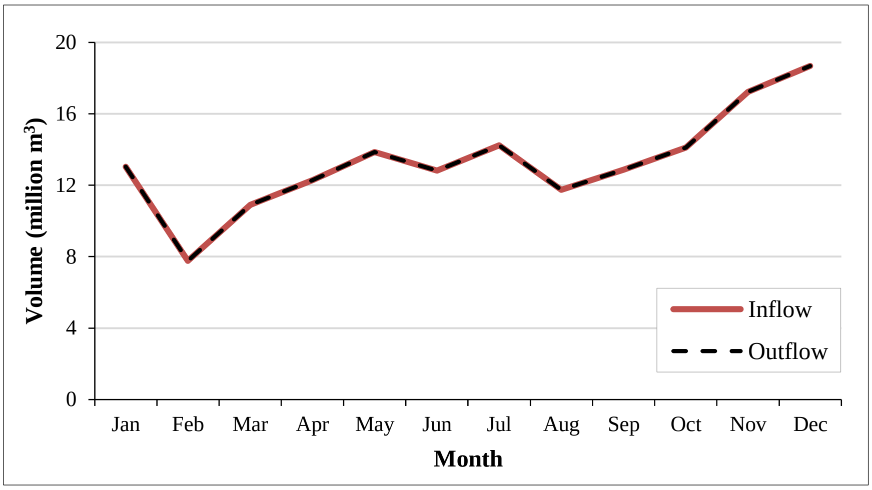


Figure 11. Optimization result inflow-outflow of Duriangkang reservoir in the normal year

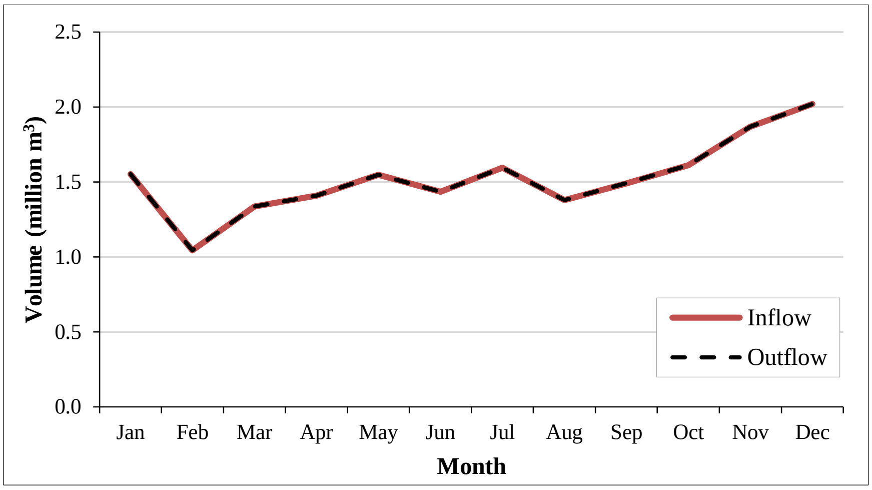


Figure 12. Optimization result of inflow-outflow in Muka Kuning reservoir in the normal year

3.3. Optimization Result in the Dry Year

The simulation in the dry year uses a dependable discharge of 65% for the inflow in the Duriangkang and Muka Kuning watersheds. The operation rule curve of the Duriangkang and Muka Kuning watersheds as the optimization result can be seen in Figures 13 and 14.

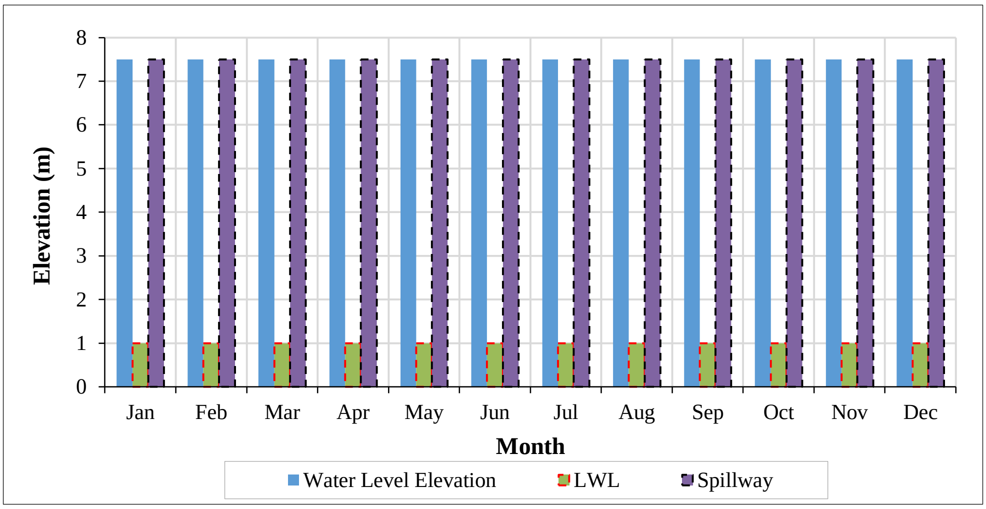


Figure 13. Reservoir operation of Duriangkang reservoir in the dry year

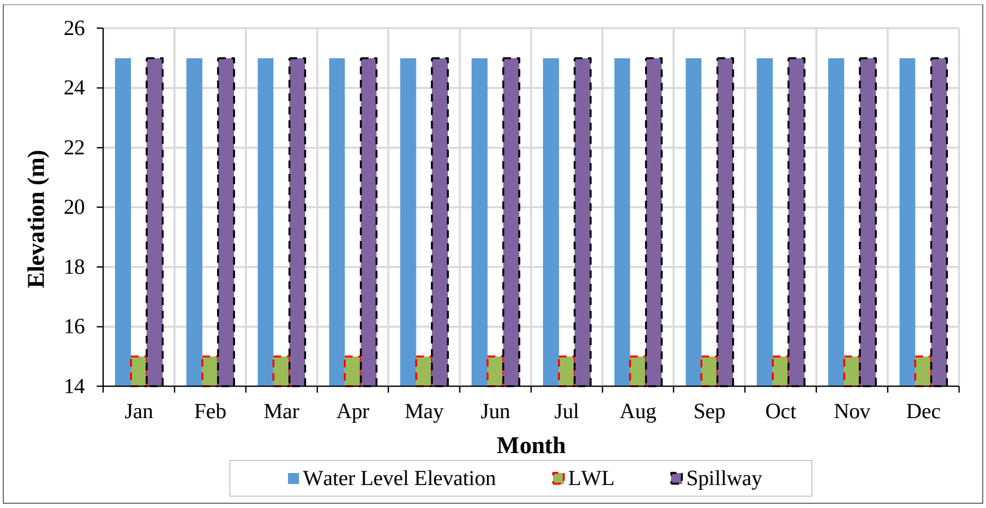


Figure 14. Reservoir operation of Muka Kuning reservoir in the dry year

Figure 15 shows that the condition of Duriangkang reservoir is relatively the same as the inflow condition in the wet and normal years; it is just that in February and March there is no run-off and the elevation of reservoir water level is decreasing. In the simulation of Muka Kuning reservoir as presented in Figure 16, the elevation of the reservoir water level is low because the water availability is lower than the water need. Therefore, it is needed the additional water supply from Duriangkang reservoir for maintaining the water level elevation. For the fulfillment of water needs in the Muka Kuning reservoir in the dry year, there is a need for water supply from Duriangkang reservoir. The optimization result shows that supply pumping is needed from January until October, with a pumping value every month as shown in Table 2.

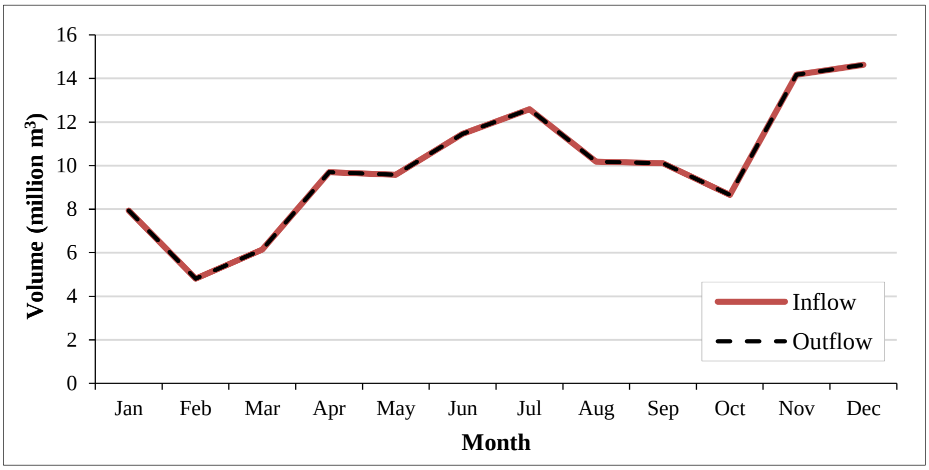


Figure 15. Optimization result of inflow-outflow in Duriangkang reservoir in the dry year

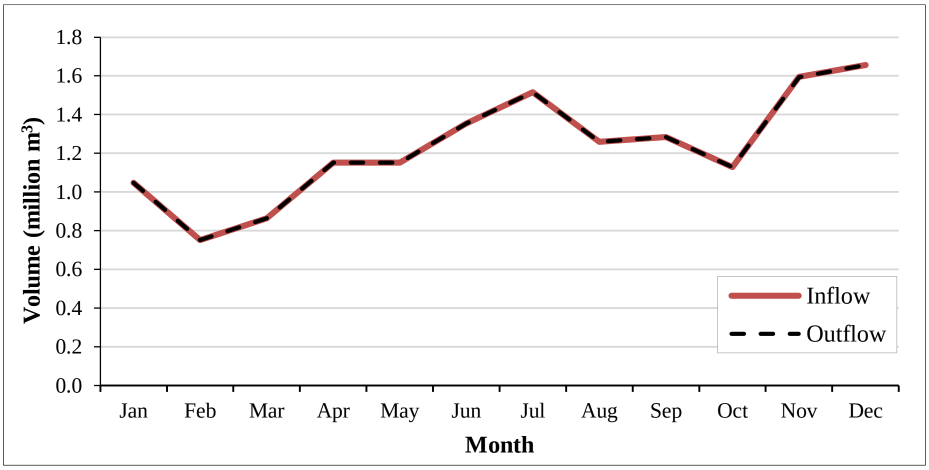


Figure 16. Optimization result of inflow-outflow in Muka Kuning reservoir in the dry year

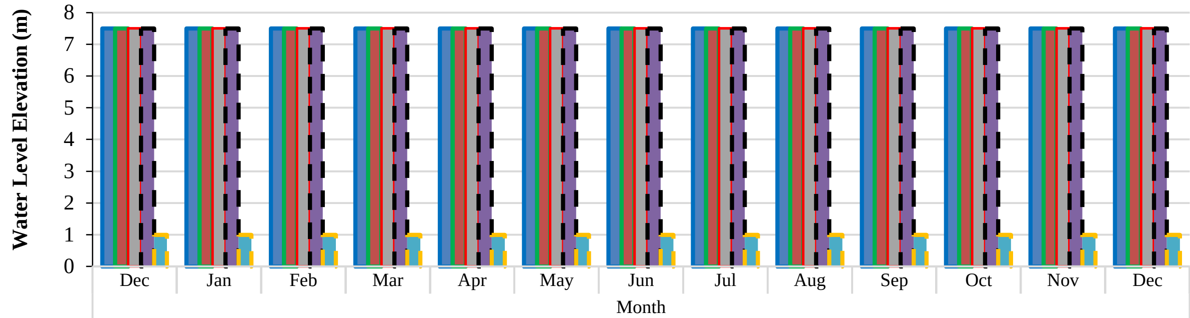
Table 2. Supply pumping discharge of Muka Kuning reservoir in the dry year

	Month					
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**
Pumping discharge (l/s)	1.97	0.00	0.00	0.65	10.18	20.35
	Month					
	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Pumping discharge (l/s)	33.23	13.40	25.68	20.15	0.00	0.00

The validation of the model in the dry year is done by comparing the inflow-outflow total volume as presented in Figures 15 and 16. In the dry year, the inflow-outflow volume in the Muka Kuning reservoir intersects at more than one point.

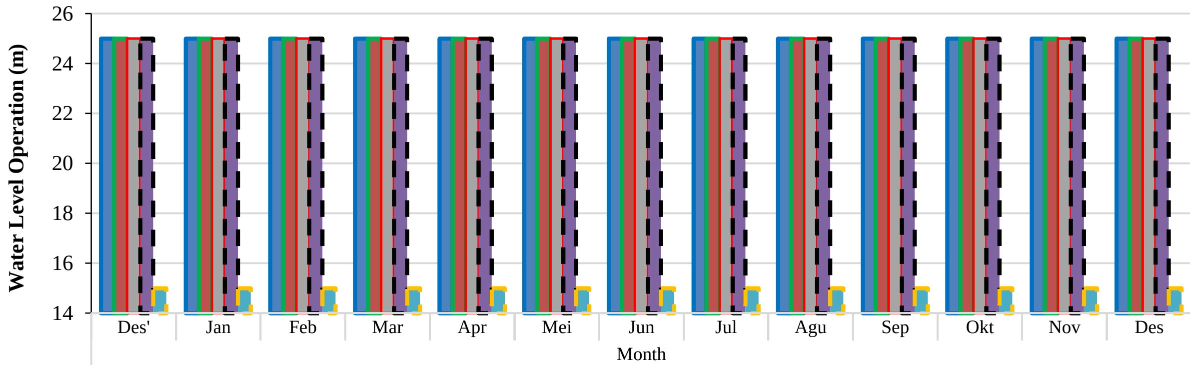
3.4. Optimal Reservoir Operation Pattern

Based on the optimization results of reservoir operation in the wet, normal, and dry years, there can be an optimal reservoir operation pattern between the Duriangkang and Muka Kuning integrated reservoirs. The reservoir operation pattern consists of an operation boundary curve of upper and lower normal, outflow for fulfilling the water need, and the rule of supply pumping from Duriangkang reservoir to Muka Kuning reservoir. The operation pattern of Duriangkang and Muka Kuning integrated reservoirs is shown in Figures 17 and 18. However, the operation pattern of the supply pump can be seen in Figure 19.



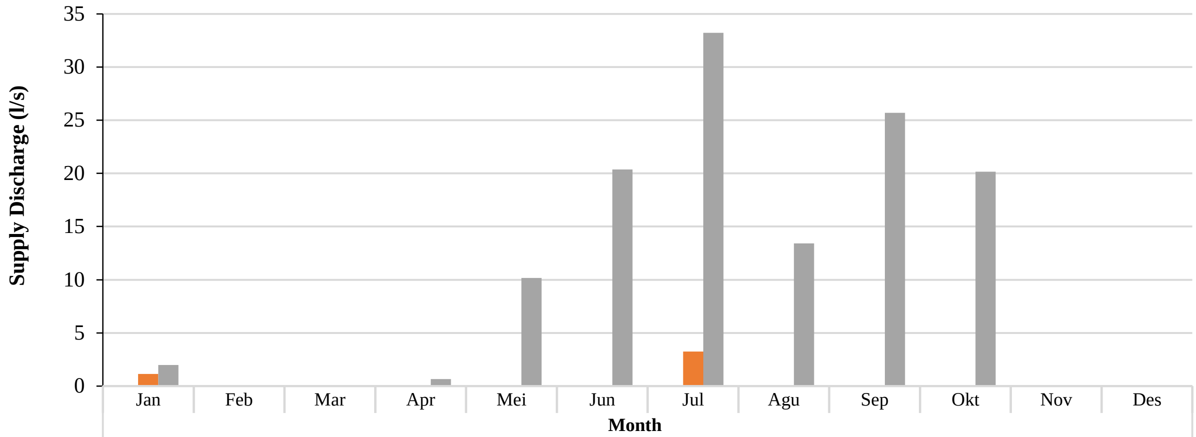
	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet Year	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
Normal Year	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
Dry Year	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
Spillway	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
LWL	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Figure 17. Reservoir operation pattern of Duriangkang



	Des'	Jan	Feb	Mar	Apr	Mei	Jun	Jul	Agu	Sep	Okt	Nov	Des
Wet Year	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00
Normal Year	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00
Dry Year	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00
Spillway	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00
LWL	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00

Figure 18. Reservoir operation pattern of Muka Kuning



	Jan	Feb	Mar	Apr	Mei	Jun	Jul	Agu	Sep	Okt	Nov	Des
Wet Year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Normal Year	1.15	0.00	0.00	0.00	0.00	0.00	3.24	0.00	0.00	0.00	0.00	0.00
Dry Year	1.97	0.00	0.00	0.65	10.18	20.35	33.23	13.40	25.68	20.15	0.00	0.00

Figure 19. Supply pumping operation pattern of Duriangkang reservoir to Muka Kuning reservoir

4. Conclusions

Based on the analysis and discussion above, it can be concluded as follows:

- The water availability in the Duriangkang reservoir is big enough that it can fulfill the water needs throughout the year in wet, normal, and dry years. However, the water availability in the Muka Kuning reservoir is relatively low, mainly in the dry years, so it frequently experiences a water deficit.
- The surplus water availability in the Duriangkang reservoir causes the water storage to overflow through the spillway to the sea, so the utilization of water resources becomes maximal and decreases. The run-off volume of Duriangkang reservoir is the potential water supply and additional inflow for Muka Kuning reservoir. The potency of supply discharge from Duriangkang reservoir is variable between 0-3.53 m^3/s and depends on the condition of the inflow and initial storage of the reservoir.
- The optimal reservoir operation pattern between Duriangkang and Muka Kuning integrated reservoirs has been obtained, so it can be used as a reference in operating the two reservoirs to fulfill the population's water needs in Batam City.

5. Declarations

5.1. Author Contributions

Conceptualization, S.B. and L.M.L.; methodology, S.B.; validation, S.B.; formal analysis, S.B.; investigation, S.B.; resources, S.B. and L.M.L.; data curation, S.B.; writing—original draft preparation, S.B. and M.S.; writing— review and editing, M.S. and W.S.; visualization, M.S. and W.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

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