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Analysis of The Impounding Using The F.J. Mock Flow Discharge Model at The Pamukkulu Dam

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Abstract

Dam construction consists of several stages, namely, development preparation, development planning, construction implementation and initial filling of the reservoir. The purpose of this study is to determine the duration of the initial filling of Pamukkulu Reservoir in dry, normal and wet years using the F.J. Mock method of water availability approach. Water loss in this study is the release of reservoir water through the bottom outlet as a fulfillment of irrigation water of 0,3 m^3/sec and reservoir evaporation. The calculation the duration of the initial filling of the reservoir is the accumulation of volume each month to reach a storage volume of 82,57 million m^3 at a normal water level of +126,00. The results of the analysis the duration for the implementation of the initial filling of Pamukkulu reservoir were obtained in a dry year with a reliability of 31,81% inflow discharge for 11,16 months or 335 days, in a normal year with a reliability of 63,63% inflow discharge for 8,66 months or 260 days and in a wet year with a reliability of 77,27% inflow discharge obtained 7,63 months or 229 days. From the results of this study known that Pamukkulu Dam will reach normal water level storage volume in December period I with inflow discharge classification in wet years.

Keywords*:* *Engineering, F.J. Mock, Water Loss, Impounding, Pamukkulu Dam*

1. Introduction

The construction of a dam consists of several stages, namely, development preparation, development planning, construction implementation and impounding of the reservoir (Ministry of PUPR, 2015). The stages of activities for the implementation of the initial filling of the reservoir begin with the closure of the dodge door, plugging, monitoring, supervision and control of the filling implementation, evaluation of the filling implementation, and preparation for operation and maintenance (POP) (Ministry of PUPR, 2019). Pamukkulu Dam started its construction implementation in 2017, and a technical hearing on the reservoir's initial filling permit was conducted at the Dam Safety Commission. In April 2024, the implementation of the reservoir initial filling works will begin with the start of the closure works of the bypass tunnel. The stages of the implementation of the circumvention tunnel closure are the installation of the bottom outlet pipe, closure of the closure gate, concrete plugging, installation of the 1.400 mm diameter elbow pipe, installation of the 1.400 mm diameter penstok pipe, and outlet house work (BBWS Pompengan Jeneberang, 2016).

The implementation of the first filling of the reservoir has been delayed compared to the plan. The delay in the implementation of the initial filling of the reservoir has the potential for obstacles, considering that it is currently entering the dry season and the need for irrigation water that will enter the second planting period in the Pamukkulu irrigation area (D.I). Therefore, in the implementation of the initial filling (impoundment) of Pamukkulu Dam, the operation of the bottom outlet pipe is 0,3 m^3/sec as a fulfillment of irrigation water needs. This condition will certainly have an impact on the length of time for the implementation of the initial filling of the reservoir. There are several methods that can be used to calculate the implementation time of the initial filling of the reservoir, such as the F.J. Mock model and the Tank Model. Calculation of the initial filling of the reservoir with the Tank Model at Raknamo Dam with the results of the impoundment period is three and a half months (Krisnayanti et al., 2020).

Based on this description, the purpose of this study is to calculate the length of time for the implementation

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initial filling of the reservoir based on the amount of inflow discharge that enters the reservoir storage area for each classification of discharge pattern (wet year, normal year, and dry year) to reach the normal water level at +126,00 m elevation. Then find out what factors affect the initial fill level of the reservoir at Pamukkulu Dam. The water loss considered in this study is the evaporation from the reservoir and the release of water through the bottom outlet as the irrigation water supply is assumed to be constant at 0,3 m^3/sec.

2. Material and Method

The data used to analyze the impoundment time of Pamukkulu Reservoir are secondary data obtained from the Pompengan Jeneberang River Basin Agency. The data required are: technical data of the dam and hydrological data as input for the analysis of rainfall to discharge conversion. Data availability includes rainfall data for 21 years (2003-2023) at DAS Pamukkulu rainfall post, climatology data from Pamukkulu Climatology Station for 6 years (2018-2023), and observed discharge data from Pamukkulu Weir for 15 years (2008-2022). Figure 1 shows a flowchart of the analysis in this study.

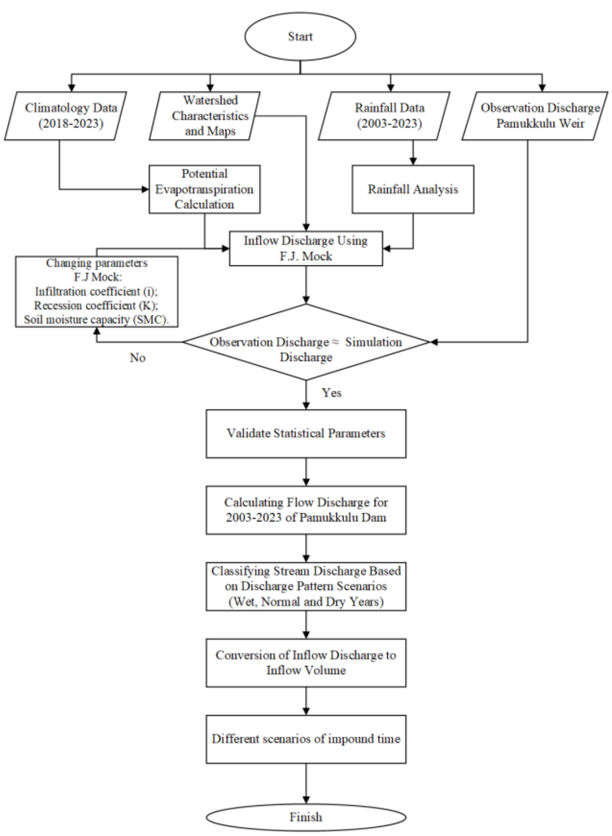

Figure 1. Flowchart of the initial reservoir fill.

Figure 1 shows the steps that are carried out, namely data collection, calculation of potential evapotranspiration, calculation of runoff, calibration of the runoff model up to the calculation of the duration of impoundment. Calibration of the simulated runoff is done by finding the correlation coefficient (R) and NSE values. The purpose of calibration to minimize the deviation that occurs, the calibration process is said to be successful when the parameters have reached the specified accuracy. The discharge evaluation that will be carried out is a simulated discharge and observation discharge in 2014-2017.

3. Result and Discussion

3.1 Regional Rainfall

Pamukkulu Dam is located in the upper Pappa Watershed with the availability of 5 (five) rainfall posts. The rainfall data of each rainfall post may not be the same, so it is necessary to perform a hydrological analysis to determine the regional rainfall, one of the methods is Thiessen Polygon (Suncaka, 2013). This method assumes that each Rainfall Post of a watershed has a certain area of influence, which becomes a correction factor in the calculation of regional rainfall (Maknun, 2024). ArcMap software is used to determine the area of influence of each gauging station. The results of the regional rainfall analysis of the Thissen Polygon method are shown in Table 1.

Table 1. Pappa Watershed rainfall posts impact area.

No	Rainfall Posts	Influence Area	
		km^2	%
1	PCH DAS Pamukkulu	161.798	40,505
2	PCH Malolo	88.051	22,043
3	PCH Cakura	66.791	16,220
4	PCH DAS Pappa	55.218	13,823
5	PCH Takalar	29.594	7,409

Table 1 describes the DAS Pamukkulu rainfall posts influence area as 161.798 km^2 or 40,505% of the total area of the Pappa Watershed. Malolo rainfall posts influence area as 88.051 km^2, Cakura rainfall posts as 66.791 km^2, DAS Pappa rainfall posts as 55.218 km^2 and Takalara rainfall posts as 29.594 km^2. From the 5 existing gauging stations, it can be seen that the Pamukkulu gauging station has the largest area of influence on the Pappa watershed. Figure 2 shows the map of the results Thiessen polygon analysis in the Pappa Watershed and the effect on the water catchment area of the Pamukkulu Reservoir.

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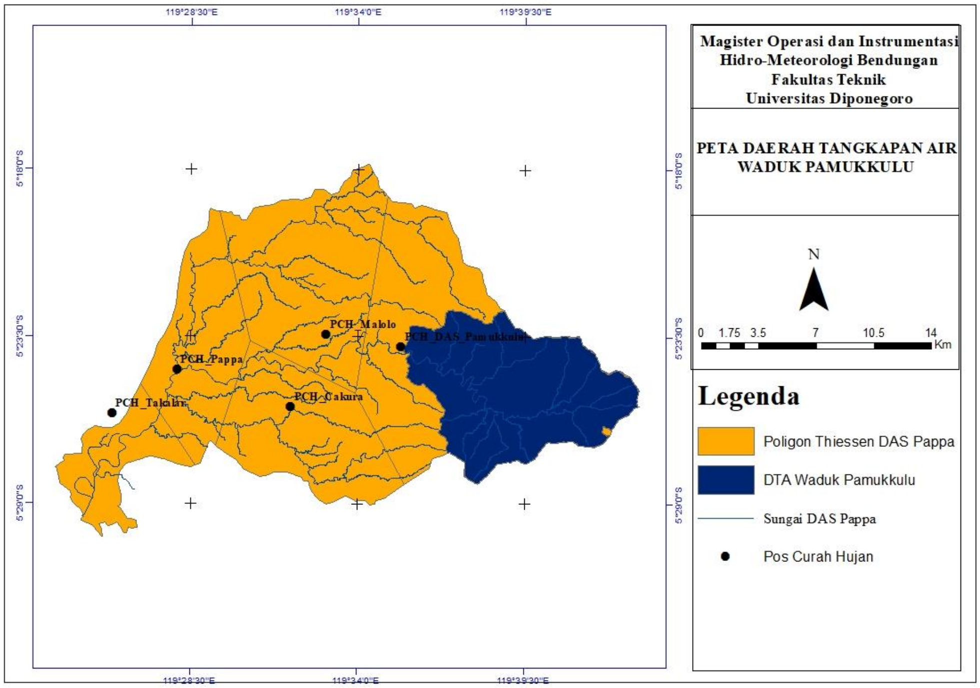

Figure 2. Polygon Thiessen Pamukkulu Watershed.

Figure 2 shows that the catchment area of Pamukkulu Reservoir is within the rainfall posts influence area of Pamukkulu watershed. The results of the regional rainfall analysis concluded that the catchment area of Pamukkulu Reservoir is influenced by 100% of the recorded rainfall data of DAS Pamukkulu rainfall posts.

3.2 Rainfall Data Quality Test

Before using rainfall data in hydrological analysis, availability and testing of rainfall data are the main requirements that must be met (Pambudi & Sriyana, 2024). Referring to (National Standardization Agency, 2016) on the procedure for calculating the planned discharge, testing the quality of rainfall data must meet at least three test criteria that is consistency test, trend absence test, and outlier test. The results of the rain data quality test for the Pamukkulu Watershed are as follows:

1. Consistency test
   The results of the RAPS method consistency test on the DAS Pamukkulu rainfall posts showed a calculated Q / ($n^{0,5}$) value of 0,943 less than the theoretical Q / ($n^{0,5}$) of 1,18 and a calculated R / ($n^{0,5}$) value of 0,621 less than the theoretical R / ($n^{0,5}$) of 1,41. Rainfall data from the DAS Pamukkulu rainfall post can be concluded to be consistent.
2. Test for absence of trend
   The absence of trend test of rainfall data is a test of the truth of field data that is not affected by errors and must truly describe the hydrological conditions as they really are (Suhartanto et al., 2019). The results of the absence of trend test using the Spearman method show that the t_c value of 1,729 is greater than the t_c value of -0,8867. The results of the absence of trend test concluded that the rainfall data recorded in the DAS Pamukkulu rainfall posts did not have a trend or came from the same population.
3. Outlier test
   The Outlier Test is a statistical procedure employed for the identification of outliers in data sets, defined as values that are disproportionately large relative to the data set as a whole. The outcomes of this test are illustrated in Figure 3.

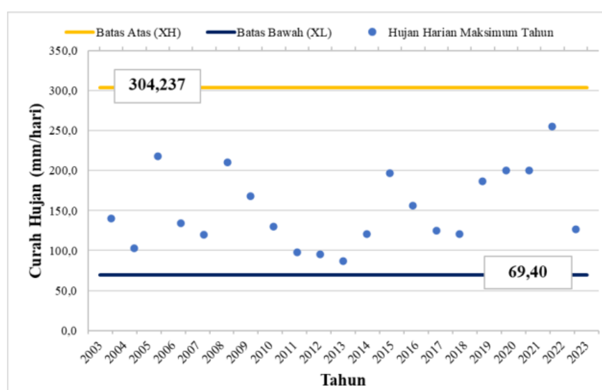

Figure 3. Outlier test results.

Figure 3 shows the results of the annual maximum rainfall data outlier test for 21 years (2003-2023) are

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between the lower outliers and upper outliers. The results of the outlier test concluded that recorded rainfall data of DAS Pamukkulu rainfall posts has no outliers and can be used for further analysis.

3.3 Potential Evapotranspiration

Some empirical formulas for calculating potential evapotranspiration are: Thornthwaite, Blaney-Criddle, Penman, and Turc-Langbein-Wundt (Nurhayati, 2015). Evapotranspiration is an important component in calculating water availability because the process of water loss through evaporation and transpiration can reduce water storage in water bodies, soils and plants. Potential evapotranspiration represents a large portion of streamflow (Adiningrum, 2015). Potential evapotranspiration can be calculated using the mathematical equation of the Penman method, which can be seen in Equation 1.

$$ET_0 = c(W\text{x } R_n + (1 - W) \text{ x } f(U) \text{ x } (ea - ed)) \quad (1)$$

where ET_0 = potential evapotranspiration (mm/day), c = weather condition adjustment factor, W = solar irradiance factor, Rn = net radiation (mm/day), f(U) = wind speed factor, ea = saturated vapor pressure (mbar), ed = actual vapor pressure (mbar).

Based on Equation 1, the potential evapotranspiration value is shown in Figure 4.

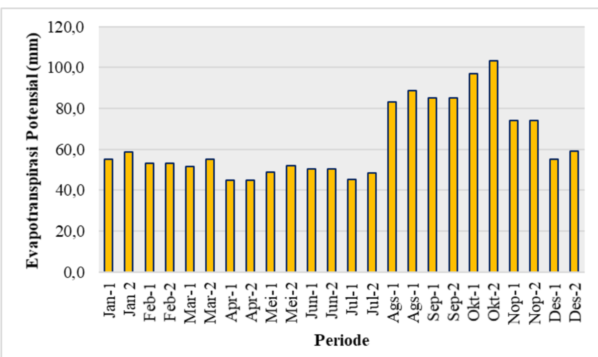

Figure 4. Potential evapotranspiration Pamukkulu Reservoir

Figure 4 shows that the highest potential evapotranspiration value occurred in the October-2 period at 103,47 mm and the lowest in the April-1 period at 44,71 mm. The semi-monthly potential evapotranspiration value is used in the calculation of the F.J. Mock method streamflow.

3.4 Flow Discharge Analysis

The F.J. Mock method basically considers the volume of incoming water, the volume of outgoing water and the volume of water stored in the soil. The volume of incoming water is rain while the outgoing water is infiltration, percolation and the dominant one is due to evapotranspiration (Taufik, 2019). The flow discharge analysis is carried out to determine the inflow discharge that will enter the reservoir. The calculation of streamflow discharge is obtained from equation 2.

$$Q = \frac{R_0}{1000} \text{ x A x } 10^6 \text{ / (n x 24 x 3600)} \quad (2)$$

Where Q = flow discharge (m^3/sec), R0 = river runoff (mm/month), A = catchment area (km^2), n = number of rainy days.

The steps to calculate discharge using the F.J. Mock method are (Limantara, 2016):

1) Prepare the necessary data, including the regional rainfall rate (P), potential evapotranspiration (ETo), number of rainy days, groundwater flow recession factor (k), and infiltration coefficient number (i);
2) Determine limited evapotranspiration;
3) Determine the amount of rain on the ground (Ds);
   A positive Ds value (P > Et) means that water will infiltrate the soil if the soil moisture capacity has not been reached and, conversely, that it will overflow if the soil is saturated. A negative Ds value (P < Et) means that some of the soil water will escape and there will be a deficit. Where P is percipation and Et is limited evapotranspiration.
4) Detemine soil moisture capacity value (SMC);
   An estimate of the initial soil moisture capacity is required at the beginning of the simulation. The initial soil moisture value depends on the porosity of the topsoil of the drainage area. The initial soil moisture value is assumed to be 50 to 250 mm.
5) Determine infiltration (i), with coefficient 0 –1,0;
   The infiltration coefficient is estimated based on the porosity of the soil and the slope of the drainage area. Areas with porosity, such as fine sand, have higher infiltration values than clay soils.
6) Determine groundwater overflow coefficient;
7) Determine groundwater content (Vn);
   At the beginning of the simulation, the initial storage must be determined, the amount of which depends on the local geological conditions and the time of the simulation.
8) Determine changes in groundwater content (DVn);
9) Determine baseflow and direct flow;
10) Determine available discharge in the river.

The calculation of runoff refers to the water balance where part of the rain evaporates and part falls on the ground surface (Nur et al., 2023). The runoff to be simulated is from 2003 to 2023 or 21 years to determine the classification of the inflow-discharge patterns. The results of the calculation of the discharge monthly average runoff for 2003-2023 are shown in Figure 5.

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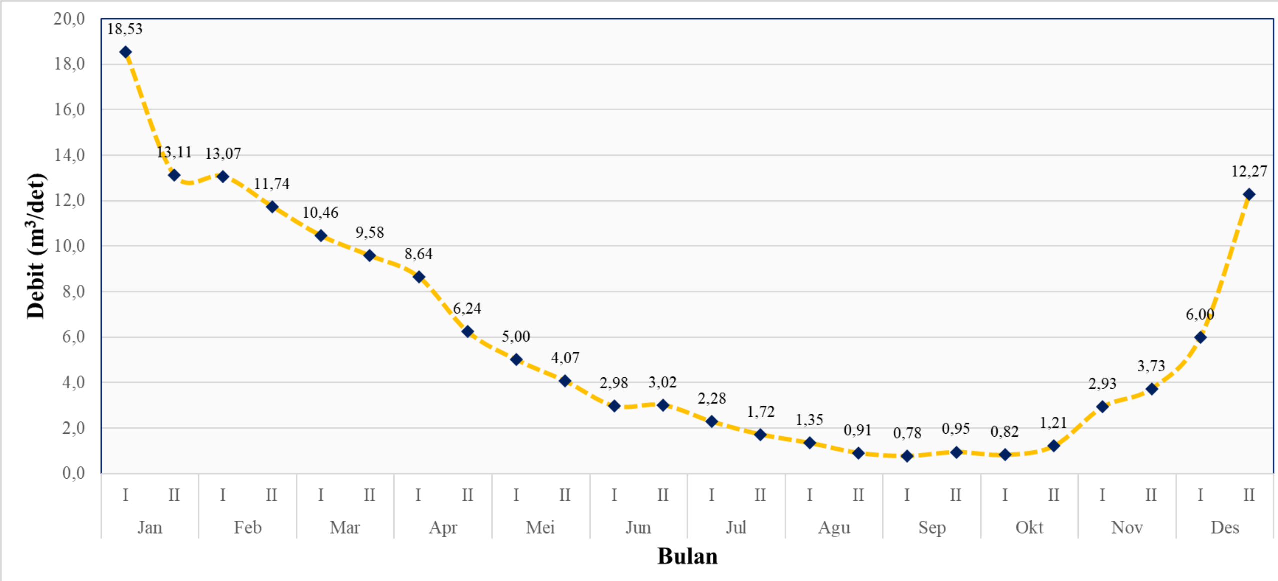

Figure 5. Pamukkulu reservoir half-month average discharge.

Figure 5 showed that the maximum discharge was 18,53 m^3/sec during the period January-1 and the minimum discharge was 0,78 m^3/sec during the period September-1. The flow discharge model is then evaluated based on the observed discharge data (recorded discharge at Pamukkulu Weir) before being used in further analysis. The result of the discharge calculation in this study is the reservoir inflow discharge. The inflow discharge that occurs greatly affects the length of time the reservoir is impounded.

3.5 Flow Discharge Evaluation

The results of the simulated flow discharge calculation must be tested to determine the level of accuracy. The evaluation of the simulated flow discharge to be performed is calibration and validation. Calibration is defined as the process of adjusting simulation parameters that affect flow events. Calibration aims to find a combination of parameters in the modeling to produce a model that resembles the actual situation. The evaluation of the flow discharge was done by correlating the simulated discharge with the observed discharge in 2014-2017 (for 4 years). Validation is done by running simulations using parameters determined in the calibration process. Validation is performed using data outside the data period used for calibration. The correlation coefficient is a value that indicates whether or not the linear relationship between two variables is strong. The calibration of the simulated data is classified into different states, namely: very good, good, satisfactory and unsatisfactory, based on each criterion (Moriasi et al., 2015), which can be seen in Table 2.

Table 2. Calibration model evaluation criteria.

Parameter	Ctiteria: **Very Good**	**Good**	**Satisfactory**	**Unsatisfactory**
NSE	>80	0,70 – 0,80	0,50 – 0,70	≤0.50
PBias (%)	< ±5	±5 - ±10	±10 - ± 15	> ±15
R^2	>0,85	0,75 – 0,85	0,65 – 0,75	< 0,60

The mathematical equations of the correlation coefficient and the Nash-Sutcliffe coefficient are shown in Equation 3 as follows.

$$R = \frac{\Sigma(Q_{sim} - Q_{sim\ average})(Q_{obs} - Q_{obs\ average})}{\sqrt{\Sigma(Q_{sim} - Q_{sim\ average})^2 \times (Q_{obs} - Q_{obs\ average})^2}}$$

$$NS = 1 - \frac{\Sigma(Q_{obs} - Q_{sim})^2}{\Sigma(Q_{obs} - Q_{obs\ average})^2} \quad (3)$$

Where Q_{obs} = observation discharge (m^3/sec), Q_{sim} = simulation discharge (m^3/sec). The Nash-Sutcliffe efficiency coefficient is used to evaluate the simulation model of hydrologic prediction data. Table 3 shows the parameters used to evaluate the flow discharge.

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Table 3. Simulated flow discharge calculation parameters.

No	Parameters Calculation	Initial Value	Calibration Value
1	Infiltration (I)	0,6	0,4
2	Recession coeffiecient (K)	0,6	0,6
3	Exposed Surface (m)	30 – 50 %	30 – 50 %
4	Initial volume (V)	100 mm	100 mm
5	Soil measure capacity (SMC)	200 mm	250 mm
6	Catchment area (DTA)	85,55 km^2	85,55 km^2

The results of the initial evaluation of the simulated discharge with the observed discharge with respect to the parameters of Table 1 obtained a correlation coefficient (R) value of 0,610, the value is included in the interpretation of "moderate" and the NSE value of 0,133 with the interpretation of "unsatisfactory". Calibration is needed to increase the value of R and NSE to approach the optimal value of 1 (Mufrodi & Sriyana, 2024). The calibration results obtained a correlation coefficient (R) value of 0,604, which falls within the interpretation of "moderate", and the NSE value increased to a value of 0,686, which is interpreted as "good". Graphically, the evaluation of the observed flow discharge with the simulated discharge is shown in Figure 6.

3.6 Year Inflow-Discharge Patterns Classification

The annual average monthly inflow (m3/d) for 21 years was sorted from the smallest to the largest inflow using the Weibull method. By using the reservoir inflow discharge in different classifications such as "dry year", "normal year" and "wet year", the reliable discharge pattern can be used to calculate the amount of water entering the reservoir (Maknun, 2024). The classification of discharge reliability in the dry year is 0-33,33%, the normal year is 33,34-66,66%, and the wet year is 66,67-100% (Kementerian PUPR, 2017). The results of the flow pattern calculation are shown in Figure 7.

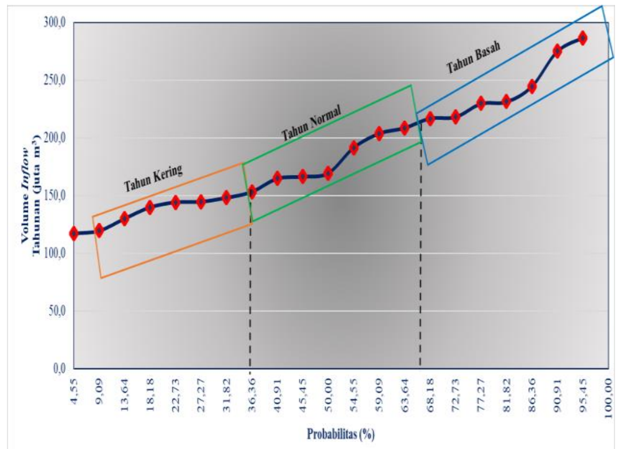

Figure 7. Inflow discharge pattern classification chart.

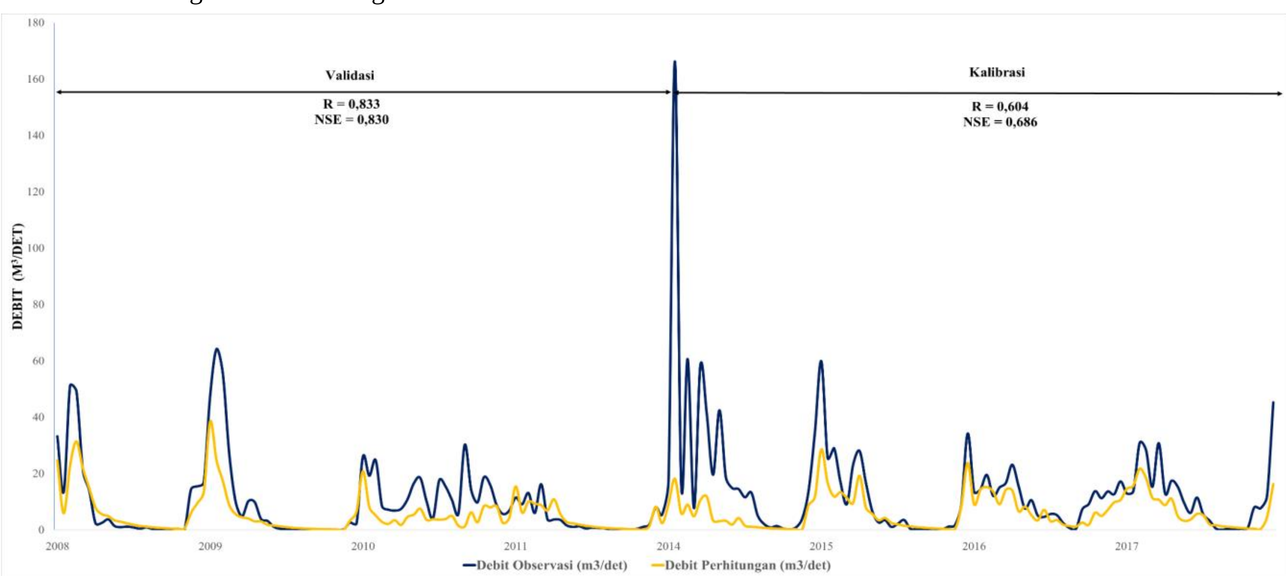

Figure 6. Graph of the calibrated discharge pattern versus the observed discharge.

Figure 6 shows graphically that the calibrated simulation flow pattern has the same pattern as the observed flow. It can be concluded that the results of the calibrated flow-discharge analysis are close to the real situation.

Figure 7 explains the classification of flow discharge patterns in the Pamukkulu catchment in the dry year classification, namely the probability of discharge control (0,00 – 31,82%), normal year (36,36 – 63,64%)

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and wet year (68,18 - 100%). A summary of the reservoir inflows is presented in Table 4.

Table 4. Pamukkulu Reservoir inflow volume.

Month	Period	Year Criteria		
		Dry Year	**Normal Year**	**Wet Year**
		Volume (million m^3)	**Volume (million m^3)**	**Volume (million m^3)**
Jan	I	21,958	26,772	30,591
	II	14,920	23,106	28,940
Feb	I	12,748	19,045	24,334
	II	11,298	16,917	20,495
Mar	I	10,377	15,939	20,016
	II	9,890	15,638	19,891
Apr	I	8,166	12,315	16,527
	II	5,474	8,459	10,428
May	I	3,695	6,533	6,927
	II	2,166	3,211	6,170
Jun	I	1,240	2,643	3,733
	II	0,857	2,940	4,899
Jul	I	0,514	1,460	2,982
	II	0,308	0,839	1,750
Aug	I	0,185	0,503	1,050
	II	0,111	0,302	0,630
Sep	I	0,067	0,181	0,378
	II	0,040	0,109	0,227
Oct	I	0,024	0,065	0,166
	II	0,014	0,039	0,099
Nov	I	0,015	0,417	8,071
	II	0,012	6,059	9,857
Dec	I	4,535	11,408	13,111
	II	6,446	21,831	28,377
Jumlah		**115,061**	**196,731**	**259,647**

Table 4 explains the total inflow in the "dry year" of 115,061 million m^3, the "normal year" of 197,731 million m^3, and the "wet year" of 259,647 million m^3. The largest discharge occurred in the period January-1 with 30,591 million m^3 in the wet year classification and the smallest discharge occurred in November-2 with 0,012 million m^3 in the dry year classification. The volume of reservoir inflow in each classification of the discharge year pattern is simulated to determine the length of time for the initial filling of the reservoir. It can be concluded that the implementation of the initial filling of the reservoir is strongly influenced by the inflow volume in each classification of the discharge pattern.

3.7 Water Losses

Reservoir water loss is calculated as a result of evaporation and meeting irrigation water needs of 0,3 m^3/sec for 1 week in each month, or equivalent to 0,181 million m^3, while ignoring percolation and seepage in the dam body. The calculation to obtain the evaporation volume is to convert the evaporation height into meters/day with the regression equation obtained from the graph of the relationship between the reservoir area and the reservoir volume (Zefri, 2022) is shown in Figure 8.

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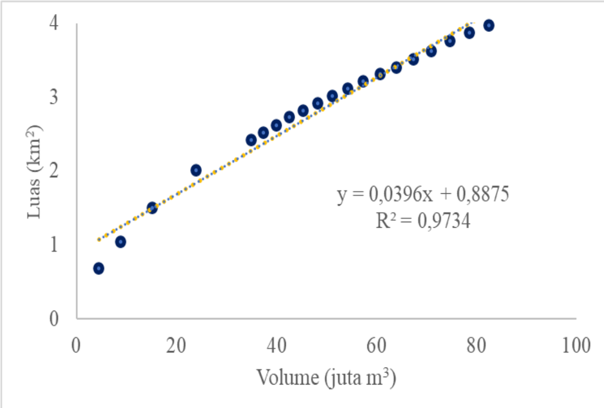

Figure 8. Regression equation for the relationship between reservoir area and volume

Using the regression equation in Figure 8, the evaporation value can be calculated based on Equation 4.

$$E_t = ET_0 \text{ x } \left[0{,}0395\left(\frac{S_t + S_{t+1}}{2}\right) + 0{,}8939\right] \quad (4)$$

Where ET_0 = actual Evapotranspiration (mm), St = reservoir storage period t (million m^3), St+1 = reservoir storage period t+1 (million m^3).

3.8 Calculation of Reservoir Initial Filling Time

Analysis of the calculation of the length of the initial implementation of Pamukkulu Dam is obtained from the inflow volume that has been calculated and then reduced by reservoir water loss (Rahmawati & Juwono, 2024). The duration of the Pamukkulu dam impoundment can be seen graphically in Figure 8.

Figure 9 explains that in the dry year classification, the reservoir will be full (reach normal water level) in the April-1 period, normal year in the January-1 period, and wet year in the December-1 period.

4. Conclusion

The duration of impoundment based on the discharge pattern year scenario to reach the planned storage volume in dry year is 11,1 months, normal year is 8,6 months and wet year is 7,63 months. Pamukkulu Dam will reach the normal water level elevation based on the analysis carried out as early as December of the first period. The factors that affect the implementation of early filling are weather, rain, river discharge and bottom outlet operation. The factor that can be controlled in the implementation of the first filling of the Pamukkulu reservoir is the release of reservoir water through the bottom outlet as a supply of irrigation water needs. The operation of the bottom outlet must always follow the weather downstream of the dam so that if there is rain downstream, the release of reservoir water through the bottom outlet can be stopped.

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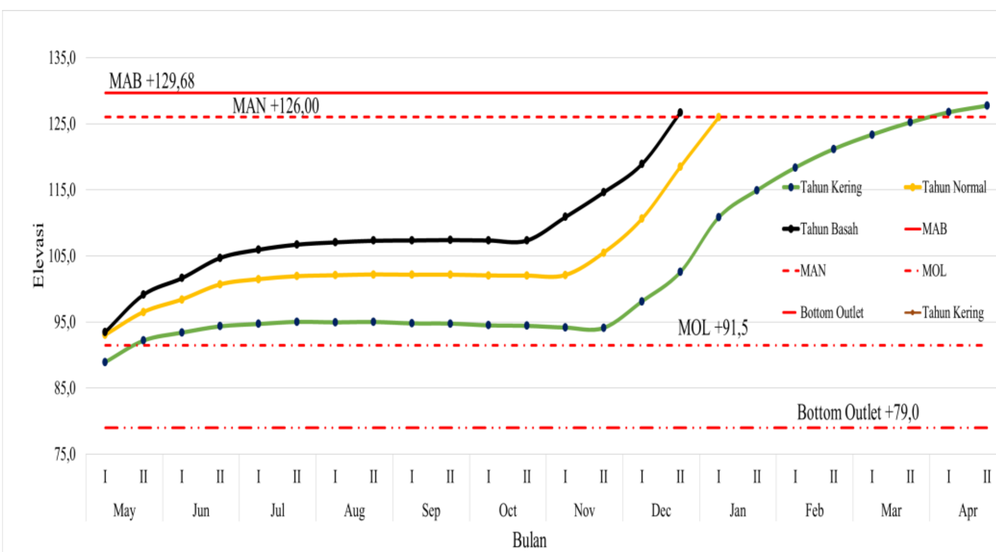

Figure 9. Time chart of Pamukkulu Dam impounding implementation

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