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Dimension Analysis Of The Emergency Spillway Of Tirawan Dam With The Application Of The System Dynamic Model

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ABSTRACT

Tirawan Dam emergency spillway is planned to be able to drain the initial flood discharge when the gate above the main spillway is closed so that there will be sufficient time to open the gate to pass the peak flood discharge through the spillway safely. The emergency spillway elevation is designed to accommodate maximum water as a natural reserve during the dry season. This study aims to analyze the factors that play a role in emergency spillway design in meeting the availability of optimal raw water storage and increasing the safety factor against flooding using a simulation modeling method with the help of the Vensim PLE program. The modeling is made in three stages. The first is the analysis of the system model, the second is the creation of a caustic diagram, and the third stage is the simulation of the model and scenario model. The simulation results of this model scenario obtained an effective emergency spillway elevation of +69.50 m and a width of 20 m. The spillway can pass the Q_{1000} design flood without the control gate operation with a freeboard of 0.41 m with a raw water reserve of 240,649.69 m^3. From the simulation results, it is also known that the operation of the main spillway serves to add a safety factor to the discharge capacity of the flood discharge during an emergency condition and cannot be operated to optimize the reservoir.

1. Introduction

Tirawan Dam is located in Tirawan Village, Pulau Laut Utara District, Kotabaru Regency, South Kalimantan Province [1]. It was built in 2016 to meet the raw water needs of residents in Pulau Laut Utara District.

The construction of Tirawan Dam was initially in the form of a selected soil embankment with an overflow spillway of reinforced concrete construction equipped with a sluice gate, a raw water intake gate, and a flushing gate on the right side. The placement of the sluice gate above the spillway is intended to control the water level in the inundation area so

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that the storage volume can be utilized optimally, especially in the dry season when the intensity of rain decreases.

In early June 2019, there was a flood due to high rainfall where the sluice gate above the spillway was closed. This causes runoff above the dam crest (overtopping), leading to the Tirawan Dam's collapse [2]. Given the vital function of the Tirawan Dam as a source of raw water for residents in the Pulau Laut Utara District, it is necessary to rehabilitate it immediately. This study is planned to repair the Tirawan Dam by considering the disaster events that have occurred. The construction of the Tirawan Dam is planned to use a gravity type dam with cyclone concrete material. To increase the safety factor of the Tirawan Dam, an emergency spillway is planned by maintaining the existing spillway.

The emergency spillway is planned to be able to drain the initial flood discharge when the sluice gate above the main spillway is closed so that there will be sufficient time to open the sluice gate to pass the peak flood discharge through both spillways safely [3][4]. On the other hand, the elevation of the emergency spillway is designed to accommodate the maximum volume of water to increase raw water reserves during the dry season [5]. The design of an emergency spillway includes several factors that influence each other and are complex [6][7]. Thus, an effective and efficient approach is needed in emergency spillway planning, using dynamic system modeling [8].

In dynamic system modeling, the model represents all variables related to the research [9][10]. When the supporting data and objectives have been determined, the data can be processed and studied so that assumptions, constraints, causes, and effects of a variable with other variables can be formulated and other factors related to modeling. This research aims to plan an emergency spillway according to the procedure for determining the design flood and spillway capacity for a dam, SNI 3432-2020 and planning a combination of the emergency spillway and main gated spillway to obtain optimum reservoir storage by dynamic analysis.

2. Research Methodology

The identification of conditions in this research is modeling and simulation of emergency spillway planning combined with the main spillway to obtain optimal reservoir storage [11]. The problem faced is determining the variables that will be used in planning the dimensions of the emergency spillway and how the effects and consequences of changing the variable parameters in the planning scenario are made. The scenario design applied to conditions that are different from the existing conditions will impact other variables so that it can be known which variables are prioritized in deciding the emergency overflow design. Based

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on the analysis of several scenarios above, it can be concluded whether the reservoir body is safe against overtopping, the operating requirements for regulating gate openings[12][13], and the volume of raw water reserves obtained. Furthermore, the dimensions of the required emergency spillway are determined.

2.1 Spillway Design

The main function of the spillway is to remove excess reservoir water so that the water does not run over the top of the dam (overtopping), which can endanger the dam, especially the earth-fill type dam. According to [14], the spillway uses a flood design of Q_{1000} , with an overflow capacity of 1.25x Q_{100} . The emergency spillway building in this study was designed and combined with the control gate exit building on the main spillway.

Design Flood is the flood flow that enters the reservoir within a limited period (a few hours or days) used in the dam's design. The design flood was obtained through hydrological analysis, while the design flood discharge analysis used the Nakayasu Synthetic Unit Hydrograph[15][16]. Flow-through the threshold (spillway) in the form of "ogee" can be expressed by the formula [17]:

$Q = C\ L\ H^{3/2}$

Where :

Q = flow rate (m^3/s)

C = spillover coefficient

L = spillway net width (m)

H = height of water pressure above the threshold (m).

The flow through the control gate on the main spillway can be expressed by the formula [18]:

$Q = K\ a\ B\ \sqrt{2gh}$

Where :

Q = discharge, m^3 / s

K = factor for sinking flow coefficient of discharge

a = gate opening, m

B = gate width, m

g = acceleration due to gravity, m/s^2 (9.8)

h_l = depth of water in front of the gate above the threshold, m

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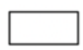
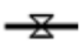
2.2 Variable Identification

Variable identification is made to determine the variables involved in modeling the system. Variable identification is based on the formula for flow through the spillway and flows through the gate. The main variables include flood discharge, type of spillway, the width of the spillway, elevation of the spillway, control gate operating system, flood catchment, and raw water reserves.

2.3 Dynamic System Modeling

System dynamics is an appropriate method used to build computer simulations of a complex system to produce more effective policies and organizations [19]. System dynamic modeling is used to analyze the relationship and behavior of a complex system consisting of variables and feedback loops and then depicted in a causal diagram (Causal Loop Diagram/CLD) [20][21]. CLD is useful and flexible for describing the interrelationships in a system and is expressed in stock and flow diagrams [22]. The application used is Vensim PLE (Ventana Simulation Personal Learning Edition) [23][24]. The diagram is used to examine the behavior and effects of changes in the system structure and policies that affect it. The symbols used in stock and flow diagrams are:

- Stock/level indicates the part of the system whose value depends on the behavior of the previous system. Stock/level shows accumulation. 
- Source/sink is stock that lies outside the system constraints. 
- Auxiliaries/converters represent parts of the system whose values can be derived from other parts through some computational procedure. 
- Flow/rate shows the rate or amount whose value depends on the current stock condition.
  
- Connectors/information flow shows how the inside of the system can influence each other. 

Model verification is carried out to test the suitability/accuracy of the model logic and ensure that there are no errors in the model. The process of checking units or unit variables is carried out. At the same time, the model validation is done to compare the behavior of the simulation model with the actual system behavior. If there is a significant difference in behavior in the test, then the system variables can be reviewed again or modified as necessary. However, if behavioral conformity is achieved, the model can be accepted as a valid representation of the system.

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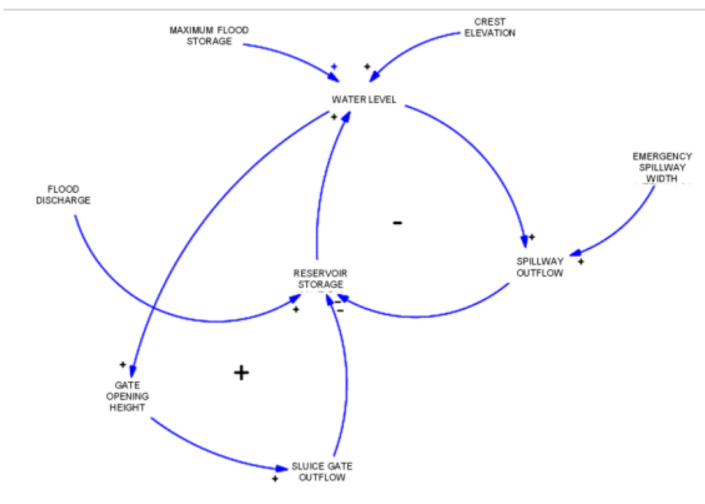
2.4 Scenario Preparation

Scenario design is carried out to determine the impact of each scenario if applied to the model. Scenarios are made to find out the ideal conditions for the system. In this study, a scenario of a combination of changes in the values of several main variables of flow planning through emergency spillways and gates was developed, and variations in the spillway crest elevation were arranged. Then a simulation of each model scenario was carried out using the Vensim PLE program to obtain graphs and values of reservoir storage volume, flood storage, reservoir water level elevation, discharge through spillway, and control gate [25].

3. Result and Discussion

3.1 Causal Loop Diagram

Causal Loop Diagram (CLD) described the relationship between previously identified spillway planning variables. The arrowhead indicates the cause variable, while the arrowhead indicates the effect variable.



Sources: Vensim PLE program data input

Figure 1. Causal Loop Diagram of Emergency Spillway Design

The CLD diagram of the emergency spillway design above shows that the reservoir capacity increases with the flow of flood discharge, which causes an increase in water level. The water level is also influenced by the elevation of the spillway and the volume of the flood storage. The spillway outflow is influenced by the water level and the width of the spillway. The water level and the gate's opening affect the outflow of the gate. The spillway outflow and the gate outflow together affect the reservoir storage.

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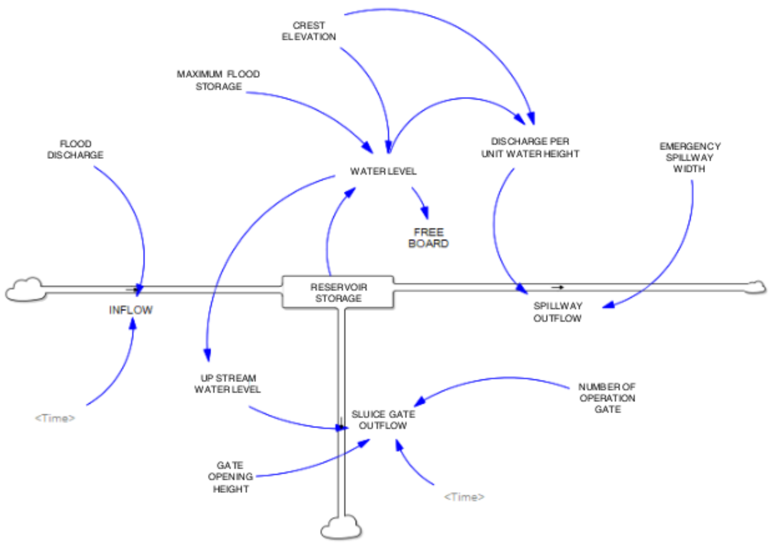
3.2 Stock And Flow Diagrams

Stock and flow diagrams are described by causal loop diagrams to detail the relationship between variables and to determine the effect of time on the decision to plan the dimensions and elevation of the emergency spillway. Stock shows the accumulation of variable values, while the rate shows the rate of change of the system every time.



Sources: Vensim PLE program data input

Figure 2. Stock And Flow Diagram of Emergency Spillway Design

The stock and flow diagram of the emergency spillway design above depicts the reservoir as a stock that increases over time with the flow of flood discharge and decreases with outflow from the spillway outflow and gate outflow. The outflow of the spillway is affected by the width of the spillway and the height of the water table. The outflow of the gate is influenced by the water level upstream of the gate, the operation of the gate opening, and the number of gates operated.

3.3 Model Verification and Validation

Verification and Validation are carried out to ensure that the simulation model created can represent the actual conditions. Verification is done by comparing the characteristics of changes in the value of each variable in the subsystem generated through simulation with the actual value in the actual situation. Validation is carried out to assess whether a model can be considered to provide a true picture of a system and its results. This dynamic system simulation model was created with the help of the Vensim PLE application, which demands consistency

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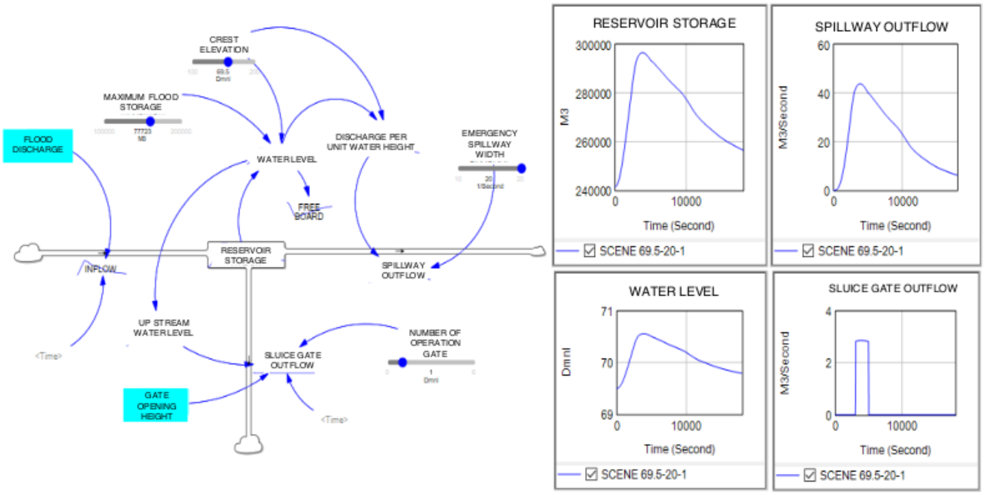
in the dimensions used so that the simulation can run. Because this simulation model can run automatically the consistency of its dimensions has been tested.



(a) (b)

Sources : Vensim PLE program operating results

Figure 3. Emergency Spillway Design Model Simulation

The image above shows the simulation screen display on the Vensim PLE application based on the specified scenario. **Figure 5a.** Shows the determinant variables on stock and flow diagrams. **Figure 5b.** showing the effect of changes in the determinant variable on the system will be shown in the output graph of the selected variable. This makes it easier to determine which variables have a dominant influence and vice versa.

3.4 Model Simulation Scenario

Scenario design is carried out to determine the impact of each scenario if applied to the model. Scenarios are made to find out the ideal conditions of the system.

The scenarios carried out in this research are:

Table 1. Emergency Spillway Design Model Scenario

NO.	VARIABLE	SCENARIO I	SCENARIO II	SCENARIO III
1	Flood Discharge	0	0	0
2	Spillway Width (m)	10 - 15 - 20	10 - 15 - 20	10 - 15 - 20
3	Spillway Crest Elevation (+….dpl)	69.00	69.50	70.00
4	Gate of Main Spillway Operational System	-/+	-/+	-/+

Sources: Research Analysis

Description : 0 constant
-/+ closed/open

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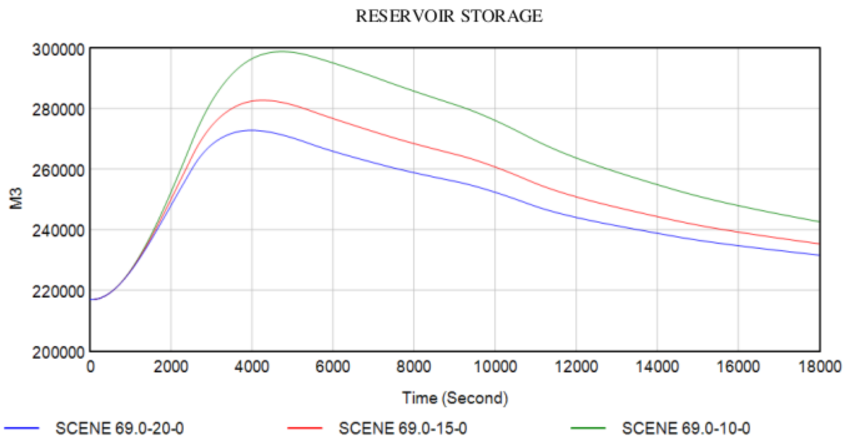
3.5 Simulation And Result Analysis

The simulation and analysis of the simulation results in each scenario are presented in the following graphs and tables :

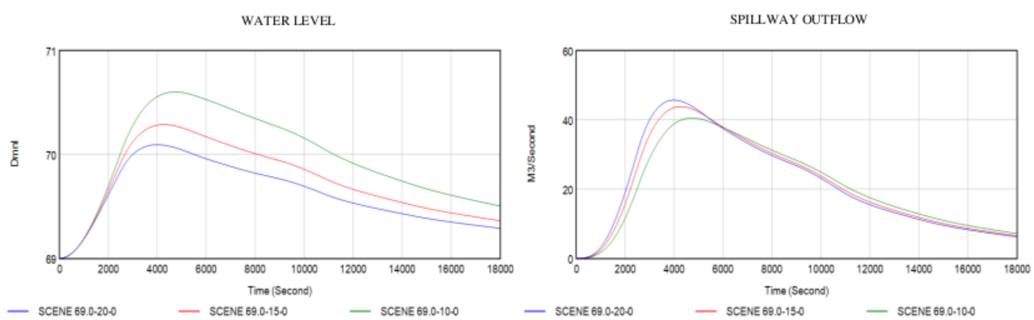
1) Scenario I



Sources: Vensim PLE program operating results

Figure 4. Reservoir Storage Variable Output Graph

Scenario I Simulation (spillway width 10 m, 15 m, and 20 m, spillway elevation +69.00) without operating the control gate on the main spillway. In the output graph of the simulation results, the reservoir storage volume on the reservoir storage variable is below the maximum limit.



Sources: Vensim PLE program operating results

Figure 5. Output Graph of Variable Water Level and Spillway Outflow

In the output graph of the simulation results, the water level elevation on the Water Level variable is below the maximum limit. In contrast, the maximum discharge outflow on the Spillway Outflow variable is smaller than the maximum inflow discharge. The graph output data is presented in the following table:

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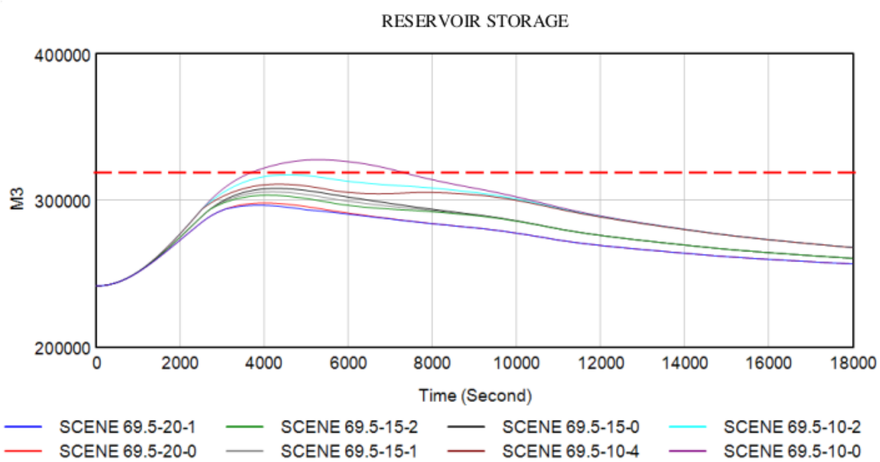
Table 2. Simulation Results of Scenario I Emergency Spillway Design Model

Scenario	Crest Elevation	Spillway Width (M)	Number of Operation Gate (Unit)	Reservoir Storage (M^3)	Water Level (M)	Spillway Outflow (M^3/S)	Raw Water Storage (M^3)
		10	0	298,738.06	70.60	40.50	
I	+69.00	15	0	282,658.38	70.29	43.76	216,844.44
		20	0	272,757.97	70.09	45.69	

Sources: Vensim PLE program operating results data recapitulation

Table 2. shows the output data from the simulation graph with the spillway crest elevation at +69.00. On the planned spillway width of 10 m, 15 m, and 20 m, the reservoir water level elevation is below the dam crest elevation, which is +71.00, so that the dam body is safe against the risk of overtopping. With the spillway crest elevation at +69.00, a reservoir capacity of 216,884.44 m^3 is obtained.

2) Scenario II



Sources: Vensim PLE program operating results

Figure 6. Reservoir Storage Variable Output Graph

Scenario II Simulation (spillway width 10 m, 15 m, and 20 m, spillway elevation +69.50) by operating a control gate on the main spillway where the simulation of the number of open gates 0 and 1 unit at a spillway width of 20 m, 0, 1 and 2 units in the width spillway of 15 m and 0, 2 and 4 units on a spillway width of 10 m.In the output graph of the simulation results, the reservoir storage volume on the reservoir storage variable with the number of open gate 0 units and the spillway width of 10 m is above the maximum limit. This indicates that the reservoir capacity has been exceeded, and runoff occurs above the dam body.

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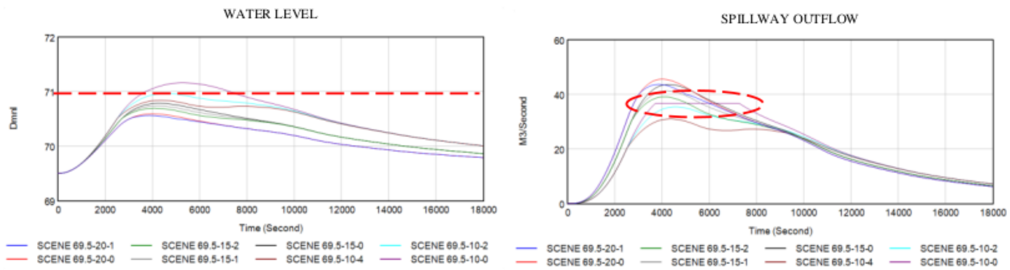

Sources: Vensim PLE program operating results

Figure 7. Output Graph of Variable Water Level and Spillway Outflow

In the output graph of the simulation results, the water level elevation on the Water Level variable with the number of open gates 0 units and the spillway width of 10 m is above the maximum limit. In contrast, the graph of the maximum discharge outflow on the Spillway Outflow variable has a truncated peak shape indicating that the flow has overflowed above the crest Dam. The graph output data is presented in the following table:

Table 3. Simulation Results of Scenario II Emergency Spillway Design Model

Scenario	Crest Elevation	Spillway Width (M)	Number of Operation Gate (Unit)	Reservoir Storage (M^3)	Water Level (M)	Spillway Outflow (M^3/S)	Raw Water Storage (M^3)
II	+69.50	10	0	327,506.75	71.16	36.76	240,649.69
			2	317,284.94	70.96	35.41	
			4	310,835.84	70.84	30.99	
		15	0	307,959.84	70.78	43.62	240,649.69
			1	305,565.72	70.74	41.29	
			2	303,252.69	70.69	39.08	
		20	0	297,982.16	70.59	45.58	240,649.69
			1	296,403.50	70.56	43.68	

Sources: Vensim PLE program operating results data recapitulation

Table 3. shows the output data from the simulation graph with the spillway crest at +69.50 elevation. In the simulation of the 10 m spillway width plan, the reservoir water level is obtained at +71.16 so that it is above the dam crest elevation, which is +71.00. Thus overtopping occurs. Meanwhile, by operating 2 and 4 control gates, there is a decrease in the water level so that no runoff occurs. In the simulation of the design of the spillway width of 15 m and 20 m without operating the control gate, the reservoir water level elevation is +70.78 and +70.59 so that it is below the dam crest elevation and no runoff occurs. Operating the

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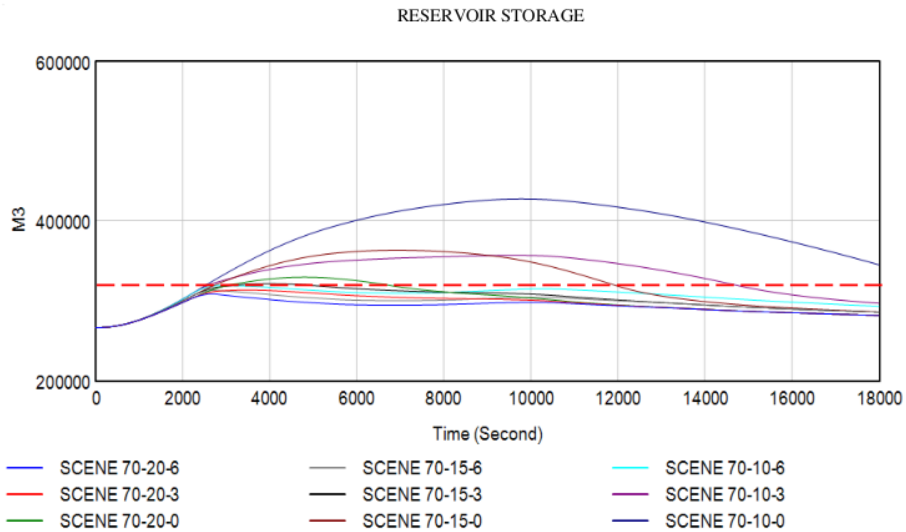
control gate will reduce the water level so that a safer freeboard is obtained. With the spillway crest elevation at +69.50, the reservoir capacity of 240,649.69 m^3 is obtained.

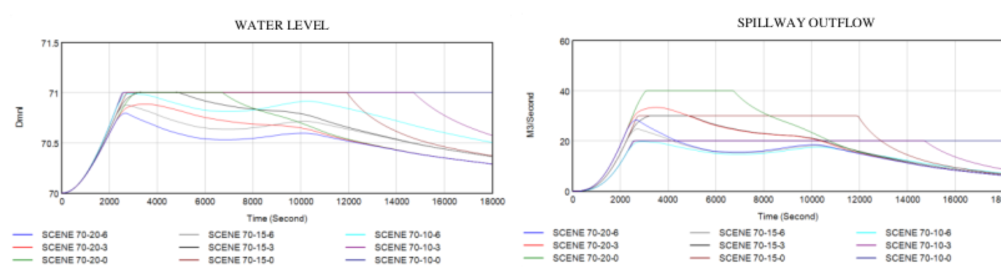
3) Scenario III



Sources: Vensim PLE program operating results

Figure 8. Reservoir Storage Variable Output Graph

Scenario III simulation (spillway width 10 m, 15 m, and 20 m, spillway elevation +70.00) by operating a control gate on the main spillway where the simulation of the number of open gates is 0, 3, and 6 units on each spillway width. In the output graph of the simulation results, the reservoir storage volume on the reservoir storage variable with the number of open gates 0, 3, and 6 units and the spillway width of 10 m is above the maximum limit. The reservoir volume with the number of open gates of 0 and 3 units and a spillway width of 15 m is above the maximum limit. The reservoir volume with the number of open gates of 0 units and the width of the spillway of 20 m is above the maximum limit.



Sources: Vensim PLE program operating results

Figure 9. Output Graph of Variable Water Level and Spillway Outflow

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The output graph of the simulation results, the water level elevation on the Water Level variable and the maximum discharge outflow on the Spillway Outflow variable with the number of open gates 0, 3, and 6 units, and the spillway width of 10 m has a truncated peak shape. The output graph of the simulation results with the number of open gates 0 and 3 units, and the spillway width of 15 m has a truncated peak shape. The output graph of the simulation results with the number of open gates 0 units, and a spillway width of 20 m has the shape of a truncated curve peak. The shape of the peak of the truncated curve indicates that the water level and the flow of the discharge have overflowed over the crest Dam. The graph output data is presented in the following table:

Table 4. Simulation Results of Scenario III Emergency Spillway Design Model

Scenario	Crest Elevation	Spillway Width (M)	Number of Operation Gate (Unit)	Reservoir Storage (M^3)	Water Level (M)	Spillway Outflow (M^3/S)	Raw Water Storage (M^3)
II	+70.00	10	0	427,402.66	71.00	20.00	266,064.07
			3	356,778.25	71.00	20.00	
			6	318,637.28	70.99	19.70	
		15	0	363,195.13	71.00	30.00	266,064.07
			3	321,023.69	71.00	30.00	
			6	312,729.84	70.88	24.71	
		20	0	329,269.47	71.00	40.04	266,064.07
			3	313,094.81	70.89	33.33	
			6	308,255.69	70.79	28.29	

Sources: Vensim PLE program operating results data recapitulation

Table 4 shows the output data from the simulation graph with the spillway crest at +70.00 elevation. In the simulation of the design for the spillway widths of 10 m, 15 m, and 20 m without operating the control gate, the reservoir water level elevation is above +71.00 so that it is above the dam crest elevation, and thus overflow occurs over the dam body (overtopping).

Meanwhile, by operating all the control gates in the simulation of the 10 m spillway width plan, the water level is obtained in +71.00, so there is a high risk of overtopping. In the simulation of the 15 m and 20 m spillway width plans to obtain the water level below the dam crest elevation, 6 control gates must be operated on the 15 m spillway width plan and 3 control gates on the 20 m spillway width plan. With the spillway crest elevation at +70.00, the reservoir capacity is 266.064.07 m^3 is obtained.

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4. Conclusion

The Tirawan Dam emergency spillway dimensions were chosen with a width of 20 m and a crest elevation of +69.50 m. In these dimensions, without the operation of the control gate, the freeboard is 0.41 m, and the raw water reserve is 240,649.69 m^3. The flood control provides a sufficient level of security against flood runoff where if there is an inaccuracy in determining the design flood discharge, it can be overcome by operating a control gate. On the dimensions of the emergency spillway width of 15 m and 10 m at the elevation of the crest +69.50 m, it is obtained that the flood control is smaller so that there is a high risk of overtopping. It is very necessary to operate the control gate. Under these conditions, the safety factor against flood runoff is very minimal, whereas if there is an inaccuracy in determining the design of flood discharge, the selection of the dimensions of the Tirawan Embung emergency spillway with a width of 20 m and a crest elevation of +69.50 m is adequate and an optimum raw water reservoir is obtained.

5. Acknowledgment

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