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Semi Cascade Dam Operation for Flood Control at Pacal Dam and Gongseng Dam

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Abstract

The existing condition of the Pacal Dam is experiencing swallowing due to sedimentation, resulting in a reduction in storage capacity.The construction of the Gongseng Dam is a solution to this problem.Pacal Dam and Gongseng Dam are semi-cascade dams whose management is an integration of different rivers. Hydrological analysis was carried out to obtain the Inflow hydrograph using the Nakayasu HSS Method using the discharge value at a 500-year return period (Q500). To determine the optimal capacity in flood control, a simulation of the operation of the Pacal Dam gate was carried out using the Level Pool Routing method on each dam. There are four scenarios simulated in the operation of the Pacal Dam spillway gate, namely the gate is completely closed (scenario 1), the gate is opened 50% (scenario 2), the gate is opened 75% (scenario 3), and the gate is fully opened (scenario 4). The simulation results show that in scenario 1 the Pacal dam is not safe, with a maximum outflow discharge value of 72.12 m3/dt with a water level above the spillway of 6.16. In scenarios 2, 3, and 4, the outflow discharge value is 80.39 m3/dt, 113,49 m3/dt, 143,62 m3/dt with water height above the spillway of 2.68 m, 2.37 m, 2.14 m. The results of the simulation of the operation of scenarios 1, 2, 3, and 4 of the Gongseng Dam routing are safe with a maximum outflow discharge value of 260.15 m3/dt, 280,89 m3/dt, 297,90 m3/dt, 319, 38 m3/dt and water height of 1.98 m, 2.08 m, 2.16 m, 2.27 mon spillway landmark. The best scenario is scenario 4 considering the height of the guard water on the spillway.

Introduction

Cascade dam operations are operations of several dams in the same river and managed in one integrated system (Minister of PUPR Regulation Number 27/PRT/M/2015 concerning Dams) (Umum, 2014). Semi-cascade dam operations are an integrated management system of several dams located on several rivers. A dam can be defined as a structure across a river that is built with the aim of creating a reservoir (Satrio, 2024; Wang et al., 2021; Wahlstrom, 2012). Dams function to store water or reservoirs, so the most important physical characteristic is the storage or reservoir capacity (Rahmanda & Dasanto, 2018; Şen, 2021). Another function of the dam is to control flooding by accommodating excess water volume that enters its reservoir (Li et al., 2010; Chakraborty et al., 2025).

The condition of the dam service at the beginning of construction reached 100%. However, with the progress of dam use, the performance has decreased (Wulansari et al., 2018). The dams studied in this study are the Pacal Dam and Gongseng Dam located in Bojonegoro Regency, East Java. The existing condition of the Pacal Dam has experienced swallowing due to sedimentation, resulting in a reduction in the storage capacity which was initially 43 million

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$m^3$to 23 million m^3. Pacal Dam has experienced a decrease in the service life of the reservoir due to sedimentation caused by damage to the water catchment area, the presence of roots and tree trunks that settle at the bottom of the reservoir, and the presence of mud that clogs the gates of the Pacal reservoir as well as changes in land use from forests to corn plantations (Nisa, 2023; Chakraborty, 2021). Therefore, Pacal Dam also has a function in reducing flood runoff (Firmansyah & Purwahono, 2023). The efforts made by the government are by constructing the Gongseng Dam. The Gongseng Dam is a semi-cascade dam because of integrated management of different rivers and functions to irrigate the Pacal Irrigation area and flood control.

Pacal Dam receives inflow from Pacal River. Gongseng Dam receives inflow from Soko River and Jono River. Jono River is a river from the Pacal Dam outflow spillway which leads to the Gongseng Dam reservoir. The spillway is a combination overflow type and has three gates. The operation of the spillway gate aims to regulate the structure so that overtopping does not occur which will cause flooding downstream (Xiang et al., 2024; Rajabzadeh et al., 2023). The gate operation pattern regulates the number and height of gate openings at certain water level elevations, so that the flood discharge flowing from the spillway gate can be regulated and does not exceed the capacity of the channel downstream of the dam (Zargar et al., 2016; Nematzadeh & Hassanzadeh, 2021; Serra-Llobet et al., 2022).

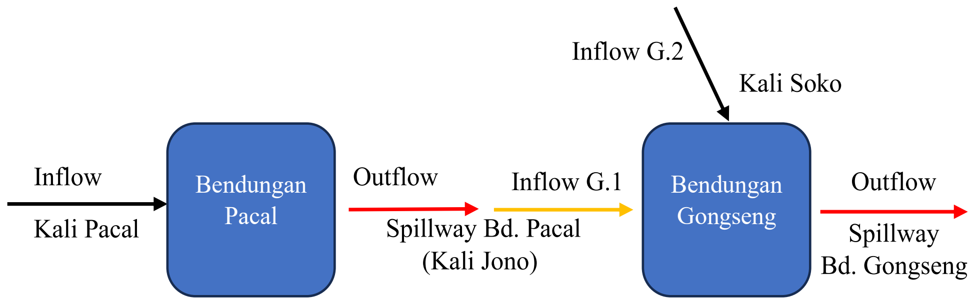

Figure 1. Pacal Dam and Gongseng Dam Flow Scheme

The operational performance of the dam during floods depends on the prediction of the inflow hydrograph and the regulation of the water level elevation (Ding et al., 2015; Zhang et al., 2021). Hydrological analysis using the Synthetic Unit Hydrograph (HSS) method is an appropriate method for planning flood discharge compared to empirical methods (Abdaa & Darfia, 2021). The Nakayasu HSS method is one of the most popular methods in Indonesia. The calculation of the design flood discharge value using the Nakayasu HSS method is the value that is closest to the watershed conditions (Damayanti et al., 2022; Rahmadani et al., 2024; Jenny et al., 2024).

Flood tracking is an estimate of the hydrograph at a point on a stream or river section based on observations of the hydrograph at another point. The purpose of flood tracking is to estimate short-term floods by calculating unit hydrographs at points along the river from the unit hydrograph at a point in the river to determine the characteristics of the outflow hydrograph which is very necessary in flood control (Soemarto, 1987; Rodda, 2021; Adeyi et al., 2020; Guo, 2022; Goswami, 2022). One method of flood tracking on dams is the Level Pool Routing method which presents a simple linear concept between the inflow and outflow relationships. The Level Pool Routing method produces the maximum discharge and determines the effectiveness of a reservoir (Amalia & Wesli, 2021; Nematollahi et al., 2022). Then, in flood tracking on rivers there is the Muskingum-Cunge method. The Muskingum linear method is a simple and popular procedure for river flood tracking (Gelegenis & Serrano, 2000).

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In this study, it is necessary to analyze the inflow hydrograph, outflow hydrograph, dam flood tracing, river flood tracing and simulation of the Pacal Dam Spillway gate operation pattern during the rainy season to determine the sufficient capacity of the Gongseng Dam and maintain the dam water level at a safe elevation. This study was conducted to analyze the simulation of the semi-cascade Dam gate operation at the Pacal Dam and Gongseng Dam so that the capacity of both dams can be optimal.

Methods

Research Location

The locations in this study are Pacal Dam and Gongseng Dam. Pacal Dam receives flow from Pacal River. Gongseng Dam receives flow from Soko River and overflow from Pacal Building spillway. Administratively, Pacal Dam and Gongseng Dam are located in Kedung Sumber Village, Temayang District, Bojonegoro Regency, East Java Province. Pacal Dam is located at coordinates7º21’44,75” LS and111º52’ 14.75” E. Gongseng Dam is located at coordinates7º21’43,54” and111º 54’ 7,43” BT.

Figure 2. Pacal Dam and Gongseng Dam Location Map

Source: Google Earth

Research Steps

The research steps can be seen in the following diagram:

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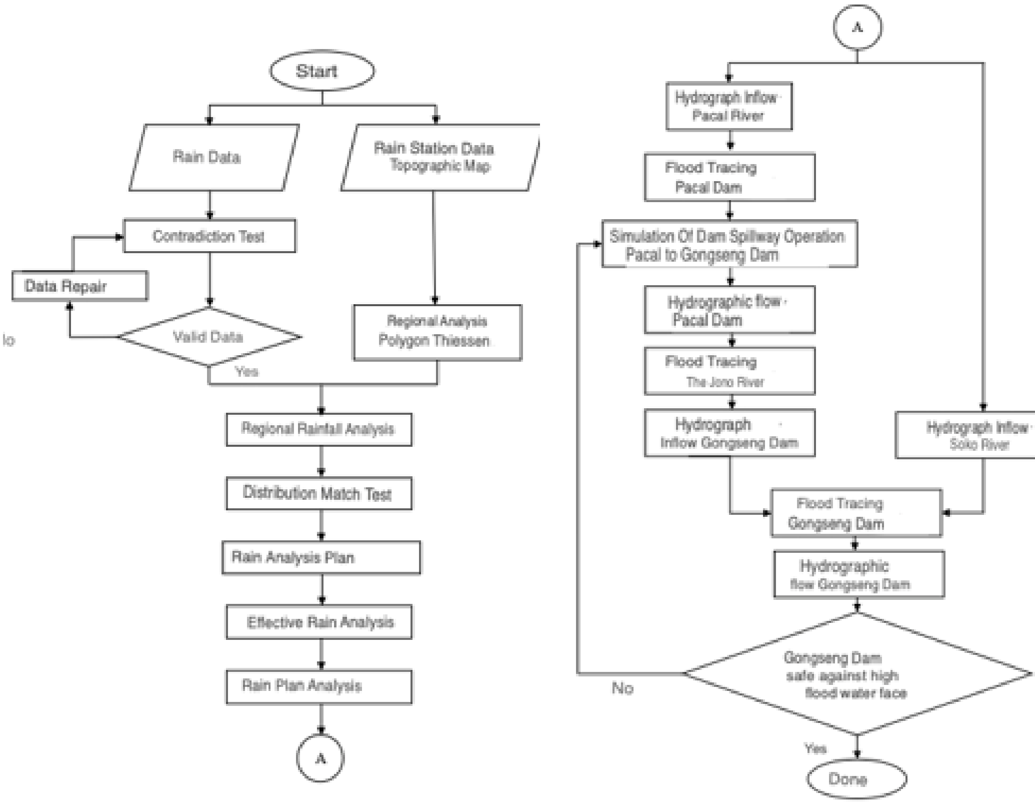

Figure 3. Research Flow Diagram

Library Review

Hydrological analysis in this study uses Synthetic Unit Hydrograph which is used to estimate flood discharge that occurs in the River Basin. The method used is HSS Nakayasu with the following equations:

Delay Time (t_g)

L > 15 km, then use the equation:

$t_g = 0,4 + 0,058\ L$ (1)

L < 15 km, then use the equation:

$t_g = 0.21\ L0.7$ (2)

Duration of Rain (T_r)

$T_r = 0,5\ t_g - t_g$ (3)

Peak Time (T_p)

$T_p = t_g + 0.8\ T_r$ (4)

Parameter Alfa (a)

$a = \frac{0.47(A.L)^{0.25}}{t_g}$ (5)

The time when the discharge is equal to 0.3 peak discharge ($t_{0,3}$)

$t_{0.3} = a \times t_g$ (6)

Peak Discharge (Q_p)

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$$Q_p = \frac{A \times R}{3.6(0.3T_p + t_{0.3})} \quad (7)$$

After knowing the hydrological analysis, a hydraulic analysis is carried out by conducting a Dam Flood Search or what is called Dam Routing. The search can be done with the following equations:

$$I - O = \frac{ds}{dt} \quad (8)$$

with:

I = incoming debit

O = outflow debit

ds/dt = change of reservoir

Simulation of dam operation patterns by calculating the outflow discharge value based on the open channel passing through the spillway with the following underflow gate equation:

$$Q = CLh\sqrt{2gy_1} \quad (9)$$

with:

Q = debit

C = coefficient

L = Length of the watergate

h = height of door opening

y_1 = upstream water depth

River Flood Search using the Muskingum Cunge method. The Muskingum method is a method that reviews the law of continuity, and its equations are obtained empirically. The equations in the Muskingum method include:

$$Q_2 = c_0 I_2 + c_1 I_1 + c_2 Q_1 \quad (10)$$

$$c_0 = \frac{kx - 0{,}5\Delta t}{k - kx + 0.5\Delta t} \quad (11)$$

$$c_1 = \frac{kx + 0{,}5\Delta t}{k - kx + 0.5\Delta t} \quad (12)$$

$$c_2 = \frac{k - kx - 0.5\Delta t}{k - kx + 0.5\Delta t} \quad (13)$$

and

$$c_0 + c_1 + c_2 = 1 \quad (14)$$

with:

Q = outgoing debit

c = coefficient

I = Incoming debit

k =time dimension (hours or days)

x = weighting factor (ranging between 0-1)

Results and Discussion

Hydrological Analysis

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The rain data used is daily rain data from Pacal Station and Gondang Station recorded in 2016-2023 obtained from the Sungai Bengawan Solo Regional Headquarters. The data was analyzed into regional rainfall using the method PolygonThiessen. Thiessen Polygon Map is obtained through GIS application. Synthetic Unit Hydrograph is done using Nakayasu method on each river.

Table 1. Nakayasu Hydrograph Parameters

Parameter	Pacal River	Soko River
A (km^2)	85,93	55,33
L (km)	20,50	19,01
a	1,9	1,8
C	0,59	0,59
Ro (mm)	1	1
tg (hour)	1,59	1,50
Tr (jam)	1,59	0,75
Tp (hour)	3	2
Qp (m^3/dt)	6,05	4,69

The flood discharge value used with the embankment dam type with a dam height (h) of $5 \leq h < 10$ m in determining the flood water level uses the flood discharge value at a return period of 500 years (Kementrian PUPR, 2020) Based on these parameters, the Hydrograph at a return period of 500 years is shown in the following table 2:

Table 2. Nakayasu Q hydrograph$_{500}$

Time (hour)	$Q_{Pacal\ river}$ (m^3/dt)	$Q_{Soko\ River}$ (m^3/dt)	Time (hour)	$Q_{Pacal\ river}$ (m^3/dt)	$Q_{Soko\ River}$ (m^3/dt)
0	0,00	0,00			
1	5,99	12,29	13	40,60	17,13
2	64,45	132,22	14	33,32	13,68
3	265,53	414,66	15	27,34	10,92
4	559,78	346,70	16	22,44	8,72
5	463,81	227,70	17	18,41	6,97
6	310,49	175,07	18	15,11	5,56
7	195,64	137,61	19	12,40	4,44
8	171,21	108,16	20	10,18	3,55
9	134,57	85,02	21	8,35	2,83
10	105,77	63,48	22	6,85	2,26
11	83,14	26,86	23	5,62	1,81
12	63,92	21,45	24	4,61	1,44

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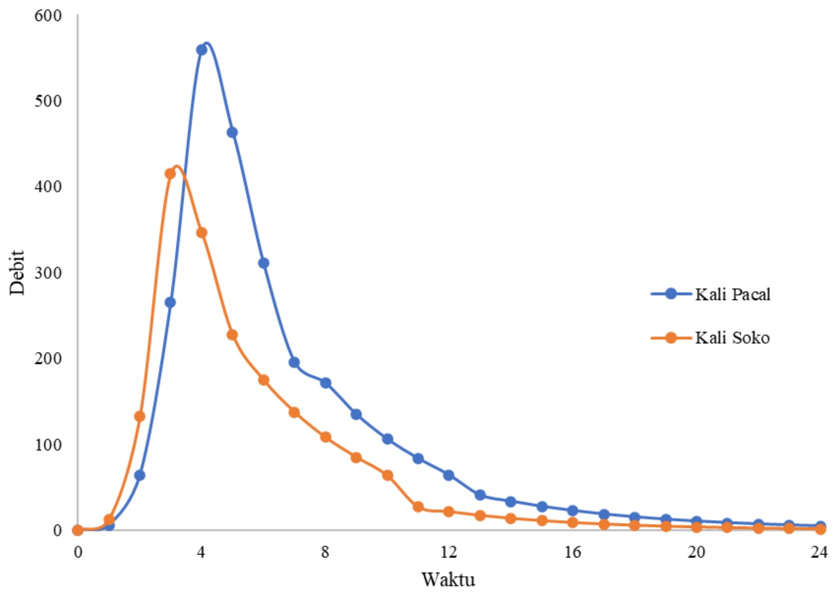

Figure 4. Nakayasu HSS hydrograph

Hydraulic Analysis

Flood control simulation in the operation of semi-cascade dams depends on the operation of the Pacal Dam gate. This study creates four conditions with the following scenarios: a) Scenario 1: In scenario 1, the spillway gates of the Pacal dam are completely closed. The overflow only passes through the right and left overflow thresholds; b) Scenario 2: In scenario 2, the spillway gates at Pacal dam are opened by 50% of the gate height, which is 2.5 m. The outflow discharge is simulated through the right and left overflow thresholds and three spillway gates with an opening of 2.5 m from the bottom of the spillway; c) Scenario 3: In scenario 3, the spillway gates at Pacal dam are opened to 75% of the gate height, which is 3.75 m. The outflow discharge is simulated through the right and left overflow thresholds and three spillway gates with an opening of 3.75 m from the bottom of the spillway; d) Scenario 4: In scenario 4, the spillway gates at Pacal dam are opened 100% or fully opened, which is 5 m high. The outflow discharge is simulated through the right and left overflow thresholds and three spillway gates with an opening of 5 m from the bottom of the spillway.

Pacal Dam Routing

Pacal Dam Routing is a simulation analysis of semi-cascade dam operations in the first stage. Pacal Dam has a Normal Elevation TMA of +115 m, and a dam crest elevation of +118 m. The type of spillway structure of the Pacal structure is a combination of overflows on the right and left, and also has doors. The Pacal Dam spillway gates are 3 pieces with a height of 5 m each. The storage capacity at normal water level is 21,306,000,000 m^3. This analysis is carried out by calculating the inflow discharge obtained from the previously calculated Nakayasu hydrograph, then routing is carried out using the equation method $H\text{-}S - Q$.

Table 4. Pacal Dam Routing Scenario 4

t	Q_{inflow}	$Q_{inflow\ mean}$	ψ	φ	$Q_{Outflow}$	H	Water Level Elevation
(hour)	(m^3/dt)	(m^3/dt)	(m^3/dt)	(m^3/dt)	(m^3/dt)	(m)	(m)
0	0,00				0,00	0,00	115,00
1	5,99	2,99	0,00	2,99	0,89	0,00	115,00
2	64,45	35,22	2,11	37,33	11,05	0,06	115,06
3	265,53	164,99	26,28	191,28	52,51	0,29	115,29
4	559,78	412,66	138,76	551,42	92,60	0,89	115,89
5	463,81	511,80	458,83	970,62	121,10	1,52	116,52

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6	310,49	387,15	849,52	1236,67	135,75	1,91	116,91
7	195,64	253,06	1100,92	1353,98	141,39	2,07	117,07
8	171,21	183,42	1212,58	1396,01	143,20	2,13	117,13
9	134,57	152,89	1252,80	1405,69	143,62	2,14	117,14
10	105,77	120,17	1262,07	1382,24	142,61	2,11	117,11
11	83,14	94,45	1239,63	1334,08	140,54	2,05	117,05
12	63,92	73,53	1193,55	1267,08	137,36	1,96	116,96
13	40,60	52,26	1129,72	1181,98	132,86	1,83	116,83
14	33,32	36,96	1049,12	1086,08	127,64	1,69	116,69
15	27,34	30,33	958,44	988,77	122,13	1,55	116,55
16	22,44	24,89	866,64	891,53	116,31	1,40	116,40
17	18,41	20,43	775,22	795,64	110,42	1,26	116,26
18	15,11	16,76	685,22	701,98	104,14	1,13	116,13
19	12,40	13,75	597,84	611,60	97,95	0,99	115,99
20	10,18	11,29	513,65	524,94	90,24	0,85	115,85
21	8,35	9,26	434,70	443,96	82,68	0,71	115,71
22	6,85	7,60	361,28	368,88	74,83	0,59	115,59
23	5,62	6,24	294,05	300,29	67,14	0,47	115,47
24	4,61	5,12	233,14	238,26	58,82	0,37	115,37

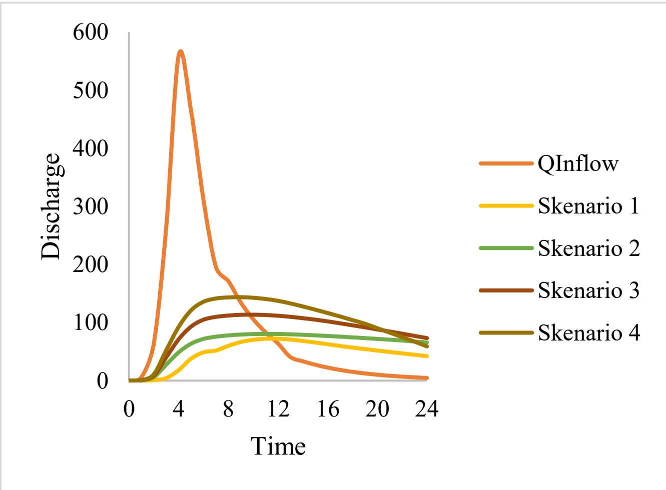

Figure 5.Pacal Dam Routing Hydrograph

The following are the results of the Pacal Dam routing summary:

Table 5. Pacal Dam Routing Recap

Scenario	**$Q_{outflowmaximum}$ (m³/dt)**	**high water in above spillway (m)**
1	72,12	6,16
2	80,39	2,68
3	113,49	2,37
4	143,62	2,14

So, the result of Pacal Dam routing in scenario 1 is overflow above the spillway beacon of Pacal Dam which indicates that Pacal Dam is not safe. Then, the result of Pacal Dam routing in scenarios 2, 3, and 4 Pacal Dam is safe from overflow.

Jono River Routing

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The Jono River routing was carried out using the Muskingum-Cunge Method. The Jono River is a flow channel that exits through the Pacal Dam spillway which flows to the intake at the Gongseng Dam. The Jono River has a river length of 1.82 km with a slope of 0.0116. Therefore, the outflow discharge from the Pacal Dam becomes an additional inflow at the Gongseng Dam.

Table 6. Routing Jono River Scenario 4

t (hour)	Q_{inflow} (m^3/dt)	C_0I_2	C_1I_1	C_2O_1	$Q_{outflow}$ (m^3/dt)
0	0,000	0,000	0,000	0,000	0,000
1	0,886	0,749	0,000	0,000	0,749
2	11,046	9,340	0,877	-0,626	9,591
3	52,512	44,400	10,932	-8,010	47,322
4	92,598	78,294	51,969	-39,522	90,740
5	121,104	102,397	91,639	-75,784	118,252
6	135,752	114,782	119,851	-98,762	135,871
7	141,393	119,552	134,347	-113,477	140,422
8	143,205	121,084	139,930	-117,278	143,736
9	143,622	121,437	141,723	-120,046	143,114
10	142,611	120,582	142,136	-119,526	143,192
11	140,535	118,827	141,136	-119,591	140,371
12	137,358	116,140	139,081	-117,235	137,986
13	132,864	112,340	135,937	-115,243	133,034
14	127,643	107,926	131,489	-111,107	128,308
15	122,132	103,266	126,322	-107,160	122,428
16	116,312	98,345	120,868	-102,250	116,964
17	110,422	93,365	115,109	-97,686	110,788
18	104,139	88,052	109,280	-92,528	104,804
19	97,948	82,818	103,061	-87,530	98,349
20	90,243	76,303	96,935	-82,139	91,098
t (hour)	Q_{inflow} (m^3/dt)	C_0I_2	C_1I_1	C_2O_1	$Q_{outflow}$ (m^3/dt)
21	82,683	69,911	89,309	-76,083	83,136
22	74,829	63,270	81,827	-69,433	75,663
23	67,141	56,769	74,054	-63,193	67,631
24	58,818	49,732	66,446	-56,484	59,694

Gongseng Dam Routing

Gongseng Dam Routing is a simulation analysis of semi-cascade dam operations at the final stage. Gongseng Dam receives inflow supply from 2 streams, namely from Kali Soko and from the spillway flow of Pacal Dam (Kali Jono).

Gongseng Dam is capable of accommodating water capacity at normal water levels of 21,790,000,000 m^3. Dam tracing is needed to review whether the capacity of Gongseng Dam is able to receive all inflow by determining the peak discharge and flood hydrograph. Gongseng Dam routing is carried out based on previously conducted scenario simulations.

Table 7.Gongseng Dam Routing Scenario 4

t	Q_{inflow} Kali Soko	Q_{inflow} Kali Jono	Q_{total} inflow	Q_{mean} inflow	ψ	φ	Q Outflow	H	Water Level Elevation
(hour)	(m^3/dt)	(m^3/dt)	(m^3/dt)	(m^3/dt)	(m^3/dt)	(m^3/dt)	(m^3/dt)	(m)	(m)

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0	0,00		0,00				0,00	0,00	93,00
1	12,29	0,749	13,03	6,52	0,00	6,52	1,01	0,02	93,02
2	132,22	9,591	141,81	77,42	5,51	82,93	13,62	0,27	93,27
3	414,66	47,322	461,98	301,90	69,32	371,21	110,23	1,11	94,11
4	346,70	90,740	437,44	449,71	260,99	710,70	251,73	1,93	94,93
5	227,70	118,252	345,96	391,70	458,97	850,66	312,32	2,23	95,23
6	175,07	135,871	310,95	328,45	538,35	866,80	319,38	2,27	95,27
7	137,61	140,422	278,03	294,49	547,42	841,90	308,57	2,22	95,22
8	108,16	143,736	251,90	264,96	533,33	798,30	289,92	2,12	95,12
9	85,02	143,114	228,13	240,01	508,37	748,39	268,58	2,02	95,02
10	63,48	143,192	206,67	217,40	479,81	697,21	245,61	1,90	94,90
11	26,86	140,371	167,23	186,95	451,60	638,55	219,00	1,76	94,76
12	21,45	137,986	159,43	163,33	419,55	582,88	194,98	1,63	94,63
13	17,13	133,034	150,16	154,80	387,90	542,70	177,74	1,53	94,53
14	13,68	128,308	141,99	146,07	364,96	511,03	164,64	1,46	94,46
15	10,92	122,428	133,35	137,67	346,39	484,06	153,81	1,39	94,39
16	8,72	116,964	125,69	129,52	330,25	459,77	144,06	1,33	94,33
17	6,97	110,788	117,75	121,72	315,71	437,43	135,09	1,28	94,28
18	5,56	104,804	110,37	114,06	302,34	416,40	126,96	1,23	94,23
19	4,44	98,349	102,79	106,58	289,45	396,02	119,41	1,17	94,17
20	3,55	91,098	94,65	98,72	276,61	375,33	111,75	1,12	94,12
21	2,83	83,136	85,97	90,31	263,58	353,89	103,81	1,07	94,07
22	2,26	75,663	77,93	81,95	250,07	332,02	95,72	1,01	94,01
23	1,81	67,631	69,44	73,68	236,30	309,99	87,40	0,95	93,95
24	1,44	59,694	61,14	65,29	222,59	287,87	78,99	0,89	93,89

The following is a graphical image of the Gongseng Dam routing in each scenario:

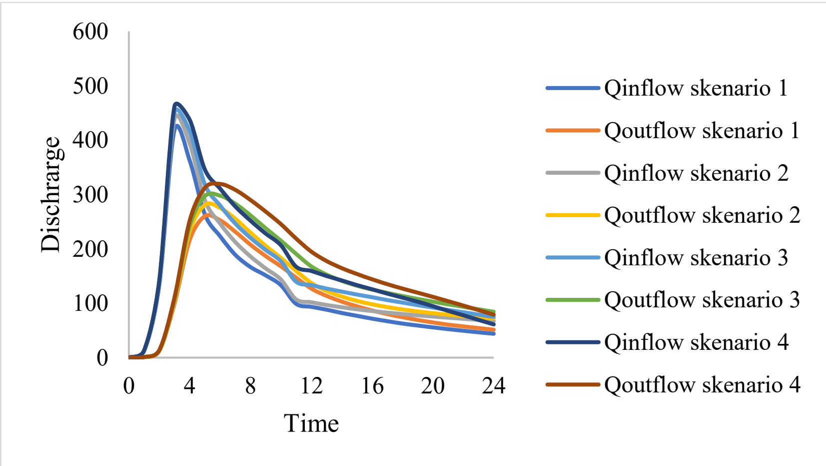

Figure 6. Gongseng Dam Routing Hydrograph

The following are the results of the Gongseng Dam routing summary:

Table 8. Gongseng Dam Routing Recap

Scenario	**$Q_{outflowmaximum}$**	**high water in above spillway**
	(m^3/dt)	**(m)**
1	260,15	1,98
2	280,89	2,08
3	297,90	2,16
4	319,38	2,27

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The water level elevation at the Gongseng Dam spillway is +93 m, and the Gongseng Dam Peak Elevation is +98 m. Therefore, the results of the Gongseng dam routing in scenario 1, scenario 2, scenario 3, and scenario 4 are safe from overflow.

Conclusion

The operating pattern of semi-cascade dams in flood control should consider the balance of each dam. Dam operation in this study depends on the opening of the Pacal Dam gate. Operational simulation results based on the opening of the Pacal Dam gate with Q500 using four scenarios, namely if the gate is completely closed, there will be an overflow at the Pacal Dam with a water level above the spillway crest of 6.16 m, but the capacity of the Gongseng Dam is safe.

Scenario 2, if the Pacal Dam gate is opened at an opening of 50% of the maximum debit outflow at the Pacal Dam of 80.39 m3/dt with a water height above the spillway crest of 2.68 m and a maximum outflow discharge at Gongseng Dam of 280.89 m3/dt with a water level above the spillway crest of 2.08 m. In this scenario, Pacal Dam and Gongseng Dam are safe from flood overflow.

Scenario 3, if the Pacal Dam gate is opened 75% of the maximum debit outflow at the Pacal Dam is 113.49 m3/dt with a water height above the spillway crest of 2.37 m and a maximum outflow discharge at Gongseng Dam of 297.90 m3/dt with a water level above the spillway crest of 2.16 m. In this scenario, Pacal Dam and Gongseng Dam are safe from flood overflow. Then, if the Pacal Dam gate is opened, the total maximum debit outflow at the Pacal Dam is 143.62 m3/dt with water levelonThe spillway is 2.14 m and the maximum outflow discharge at Gongseng Dam is 319.38 m3/dt with water levelonspillway 2.27 m. In this scenario, Pacal Dam and Gongseng Dam are safe from flood overflow. So, if Q occurs500 the best scenario to use considering the high level of care of the Pacal Dam is scenario 4, by fully opening the gates of the Pacal Dam.

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