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Flood Reduction Modelling of Mahakam Cascade Lake towards the Mahakam River - East Borneo - Indonesia

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Abstract: Lake is a water source that has decreased its function and has damaged the ecosystem. The Mahakam cascade lake in the East Borneo-Indonesia consists of Jempang Lake, Semayang Lake, and Melintang Lake, which have the sedimentation problem caused by the land-use change. The sedimentation can cause floods in the Mahakam River. However, the Mahakam River that correlates with the Mahakam cascade lake cannot reduce the happened flood. This study intends to optimize flood reduction modeling of Mahakam Cascade Lake towards the Mahakam River in the Muara Kaman outlet. According to the optimization model, this research aims to simulate the flood reduction modeling due to the 3 discharge conditions: Q_{25}, Q_{50}, and $Q_{100.}$ The food reduction modeling uses the Linear Programming Model, and the model is built integrated due to the Cascade Lake. The methodology consists of a linear programming optimization model due to the 3 scenarios (Q_{25}, Q_{50}, and Q_{100}). However, the analysis of the design flood uses the Nakayasu Synthetic Unit Hydrograph in the watershed and the Rational Method for the discharge in the lake. The capacity of Mahakam Cascade Lake due to the bathymetry data and AWLR is as follow: 1) Jempang Lake: 519,958,550.36 m^3; 2) Melintang Lake: 696,012,192.74 m^3; and 3) Semayang Lake: 1,195,593,435.86 m^3. The optimization model result of flood reduction in the Muara Kaman is as follow: a) Scenario-1 (Q_{25}): $Q_{muara\ Kaman}$ = 32,729.80 m^3/s; b) Scenario-2 (Q_{50}): $Q_{muara\ kanam}$ = 37,432.36 m^3/s; and c) Scenario-3 (Q_{100}): $Q_{muara\ kanam}$ = 39,777.80 m^3/s.

Keywords: cascade lake, flood reduction, optimization, linear programming

玛哈坎瀑布湖向 玛哈坎 河的防洪模型 - 东婆罗洲 - 印度尼西亚

摘要：湖泊是一个功能下降并破坏生态系统的水源。东婆罗洲-印度尼西亚的玛哈坎梯级湖由占邦湖、三马央湖和梅林塘湖组成，存在土地利用变化引起的沉积问题。沉积物会导致玛哈坎 河发生洪水。然而，与 玛哈坎 梯级湖相关的 玛哈坎 河并不能减少发生的洪水。本研究旨在优化马哈坎瀑布湖向穆阿拉卡曼 出口处玛哈坎 河的防洪模型。根据优化模型，本研究旨在模拟 Q_{25}、Q_{50} 和 Q_{100} 三种流量条件下的减洪模型。食物减少建模使用线性规划模型，由于喀斯喀特湖，模型是集成构建的。由于 3 个场景（Q_{25}、Q_{50} 和 Q_{100}），该方法由线性规划优化模型组成。然而，设计洪水的分析使用流域中的中安合成单元水道线和湖中排放的合理方法。 马哈坎瀑布湖的水深数据和 先进的轻水反应堆 的容量如下： 1）占邦 湖：519,958,550.36 米 ^{3}； 2）梅林塘湖：696,012,192.74 米 ^{3}； 3）三马央湖：1,195,593,435.86 米 ^{3}。 河口卡曼 减洪优化模型结果如下： a) 情景一（Q_{25}）：$Q_{卡曼河口}$ = 32,729.80 米 ^{3}/秒； b) 情景 2 (Q_{50})：$Q_{卡曼河口}$ = 37,432.36 米 ^{3}/秒； c) 情景 3 (Q_{100})：$Q_{卡曼河口}$ = 39,777.80 米 ^{3}/秒。

关键词： 梯级湖, 防洪, 优化, 线性规划。

1. Introduction

In ecosystems, the human activities impact has long been recognized. Nowadays, increasing evidence supports the hypothesis that we have entered into an Anthropocene [1]. However, human activities have been documented as one of the main changes of driving forces and causing simultaneous changes in the natural environments [2]. These changes include the availability of ecosystem services and goods [3], the

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landscape spatial pattern [3, 4], and the increasing vulnerability of regional human well-being and biomes to climate change [5, 6].

One of the large problems in applied hydrology related to floods is the problem of flood prediction based on the heavy rain over a watershed or catchment [7]. The hydraulic structure design demands reliable information concerning the design flood or peak flow that is expected after a given probability of event and return period. So, the hydrologist often faces extreme flood events predicted based on historical flood records [8, 9].

The Mahakam Cascade Lake has the floodplain lake type [10] related to Mahakam River flow. When the lake overflow and floods, the three lakes merge as a very large lake expanse in the rainy season. However, in the dry season, the water in the lake is receding, and the riparian becomes the dry land, or the lake is only leaving the plots and small bottoms that are still flooded by water. The condition of extreme flood-recede happened in 1997 for 192 days. Based on the data in Kotabangun station, the highest water level that has ever happened so far is in 2007 that is in the amount of 14.54 m. According to the information of the related department, this discharge was an extreme flood at that time, and it is equivalence with Q_{50}.

Nowadays, flood disasters have become a problem with no end for society. The flood reason can be caused by nature and the impact of human activity and even the both together [11]. A flood can be caused by increased water level due to normal rainfall, temperature change, levee or dam was broken down, fast snow melting, and delayed water flow on-site detention [12, 13]. According to Kodoatie and Syarif [14], there are 5 types of strategies for decreasing the flood impact in individuals and society: information and education, flood insurance, tax adjustments, emergency actions for flood, and post-flood recovery. Besides it, there is also a strategy for decreasing flood presented by Kodoatie and Syarif [15]: the dam or reservoir or lake, levee, and floodwall, the increasing of drainage channel or river capacity, actions of land improvement, and on-site detention.

2. Materials and Methods

2.1. Research Location

The research location is in Mahakam Lake Cascade (Jempang Lake, Semayang Lake, Melintang Lake). Geographically, the Mahakam Cascade Lake is in south longest of 0°13’24,48” and east longest of 116°27’17,55” on the elevation of 28 feet; in south longest of 0°17’33,82” and east longest of 116°19’42,55” on the elevation of 83 feet, and in the south longest of 0°25’33,87” and east longest of 116°11’41,06” on the elevation of 85 feet (KLH 2011). Map of location is presented in Fig. 1.

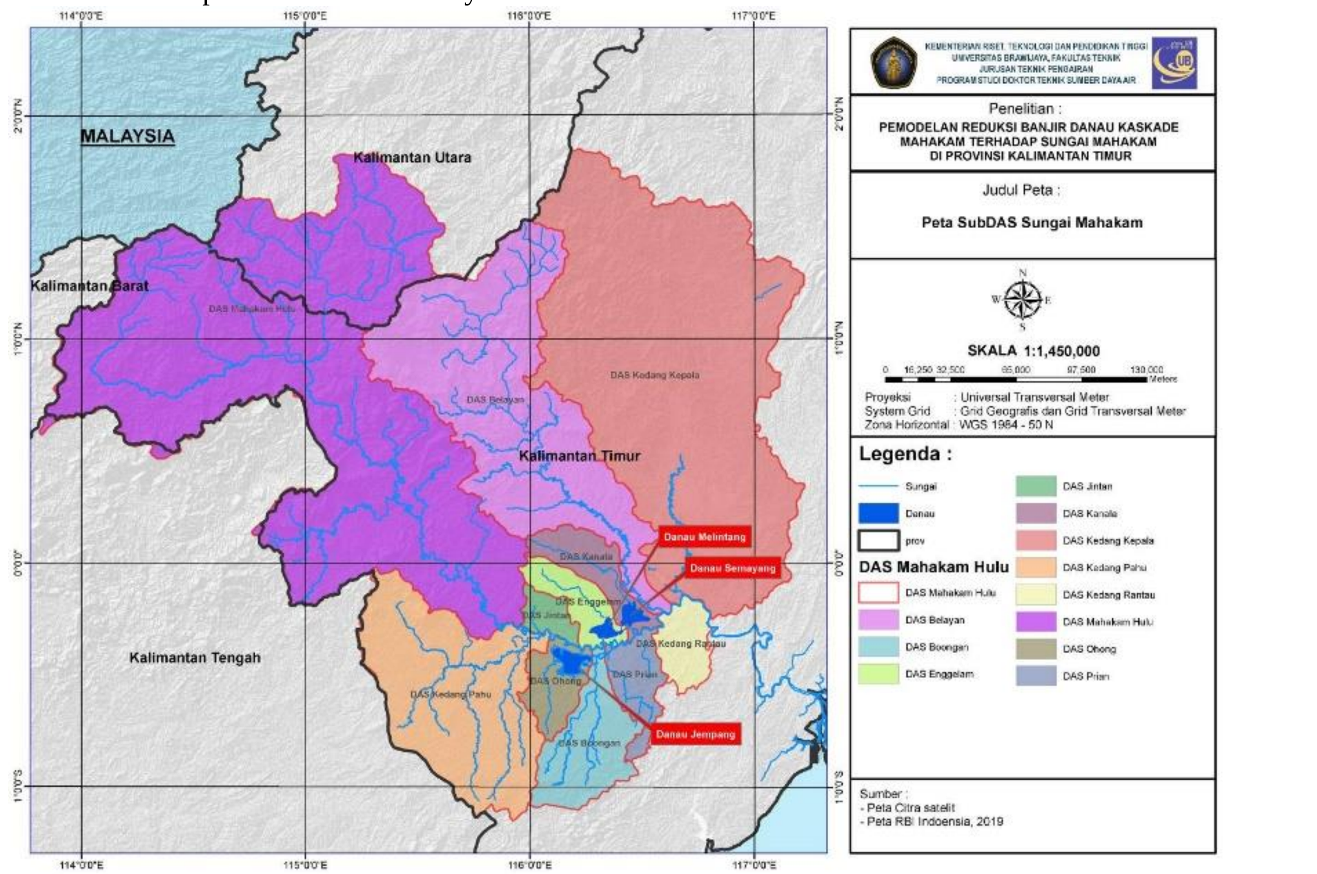

Fig. 1 Map of Jempang, Semayang, and Melintang cascade lake

The inundation area of Semayang Lake and Melintang Lake stretched in 5 villages and 4 districts as follow: Semayang Village – Kenohan District, Pela Village – Kota Bangun District, Melintang Village and Enggelam -Muara Wis District, and Tanjung Batuq Village - Muara Muntai District.

2.2. Research Data

The data collecting is detail carried out. It consists of rainfall data, TMS data, DEM data, topography data, RBI data, and land use data.

2.3. Stage of Research

The stages of research are as follow:

1. To collect the technical data.
2. To carry out the consistency test of the rainfall station.
3. To analyze the design flood.
4. To build the flood reduction modeling of Mahakam Cascade Lake.
5. To report the evaluation result of the optimization model of flood reduction modeling.

2.4. Methodology

This research uses the linear programming optimization model. The optimization is carried out after evaluating existing flood modeling with the 3 (three) scenarios using the design flood of Q_{25}, $Q_{50,}$ and Q_{100}. The scheme of Mahakam Cascade Lake is presented as in Fig. 2.

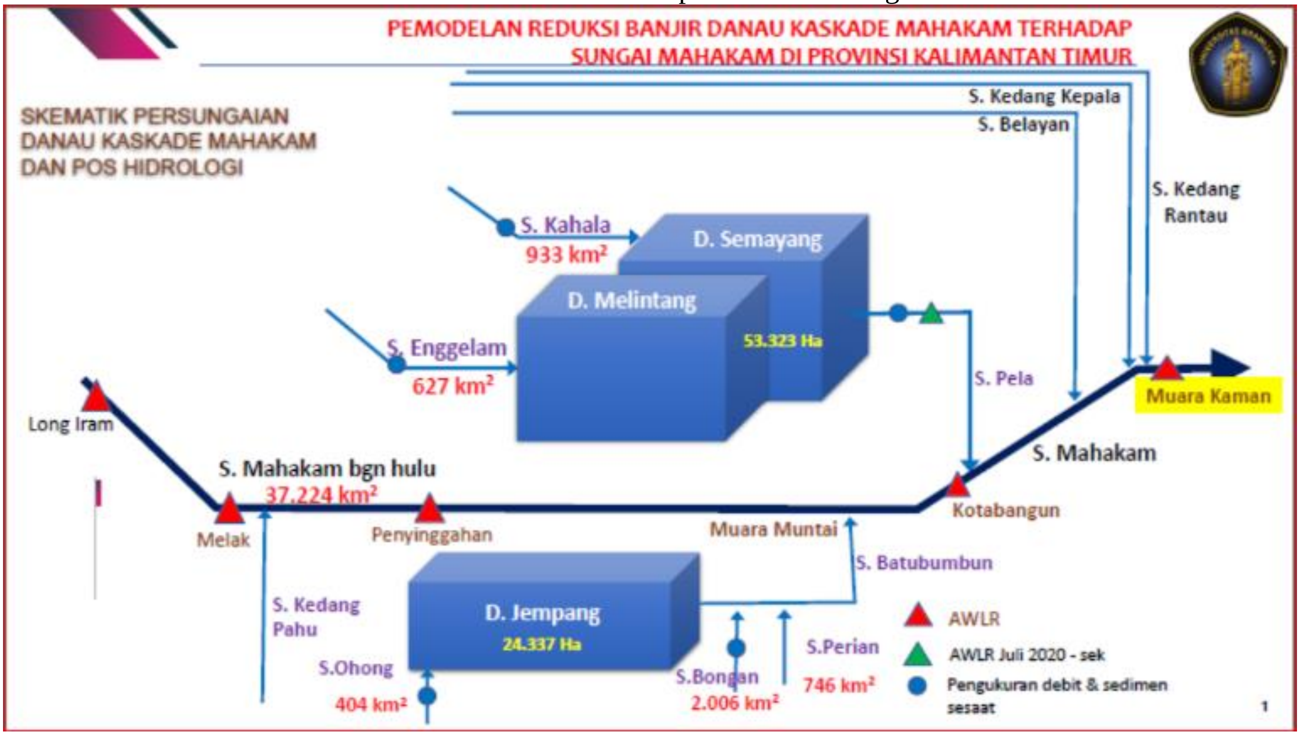

Fig. 2 Scheme of Mahakam cascade lake and hydrology station

Table 1 Maximum rainfall in the upstream Mahakam rainfall station

No	year	Maximum rainfall in the rainfall station of							
		Beringin	Barong Tongkok	Damai	Kambang Janggut	Long Iram	Muara Kaman	Penyinggahan	Tanjung isuy
1	2010	153.00	80.20	80.20	12.80	200.00	74.60	124.00	200.20
2	2011	95.00	33.60	23.50	33.20	120.80	84.60	164.80	97.00
3	2012	157.00	155.30	9.60	9.40	124.50	98.30	142.00	180.00
4	2013	113.00	130.00	33.60	31.40	130.90	119.80	95.70	80.80
5	2014	161.00	179.70	64.50	30.30	121.00	92.30	104.60	40.10
6	2015	164.00	135.00	31.60	7.10	120.70	108.50	110.40	50.20
7	2016	137.00	95.40	120.60	10.30	121.00	150.10	97.60	70.20
8	2017	143.00	83.30	113.70	14.00	120.70	140.00	158.00	60.10
9	2018	132.00	83.30	113.50	37.00	110.30	97.00	60.70	110.20
10	2019	146.00	110.50	87.90	49.00	81.00	79.00	145.10	150.00

3. Results and Discussion

3.1. Rainfall

There are 8 rainfall stations in the upstream Mahakam watershed. The available rainfall data is from 2010 until 2019. Table 1 presents the maximum rainfall in the upstream Mahakam rainfall station.

3.2. Watershed Parameter and the Influenced Rainfall Station

11 sub-watersheds are considered in the analysis that will be carried out. Therefore, the influenced area will be considered in the aspect of the 11 sub-watersheds. Some effects that are considered in the analysis based on the sub-watersheds are as follows:

1. Thiessen influenced area
2. Watershed area
3. Main river length
4. Land cover
5. Mean elevation of the watershed

Fig. 3 presents the map of the Thiessen polygon in the Mahakam watershed. Fig. 4 presents the map of land use in the Mahakam watershed. Fig. 5 presents the map of elevation in the Mahakam watershed. Table 2 presents the Thiessen influence on the Mahakam sub-watersheds.

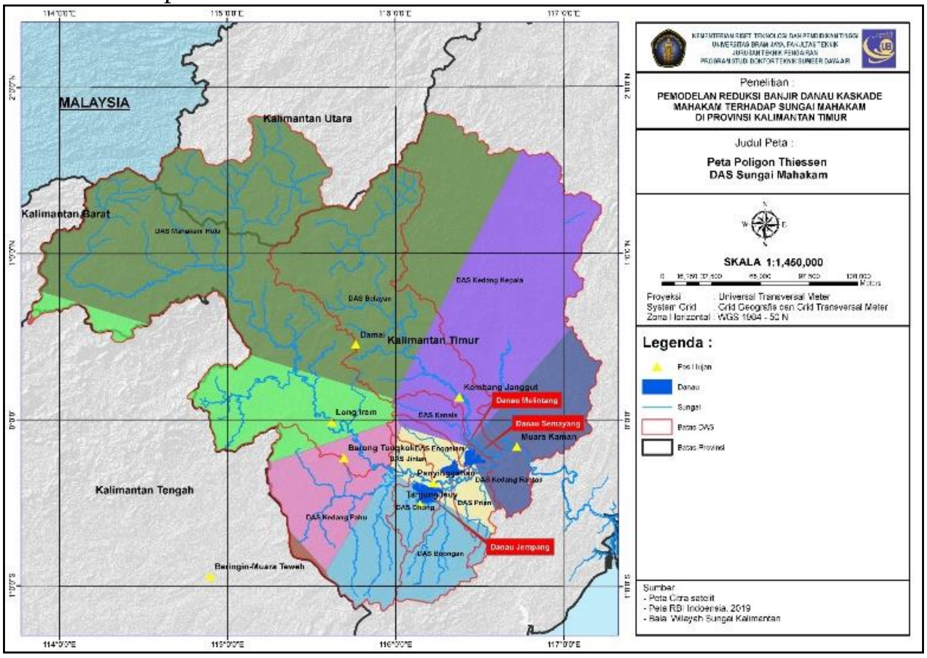

Fig. 3 Map of Thiessen polygon in the Mahakam watershed

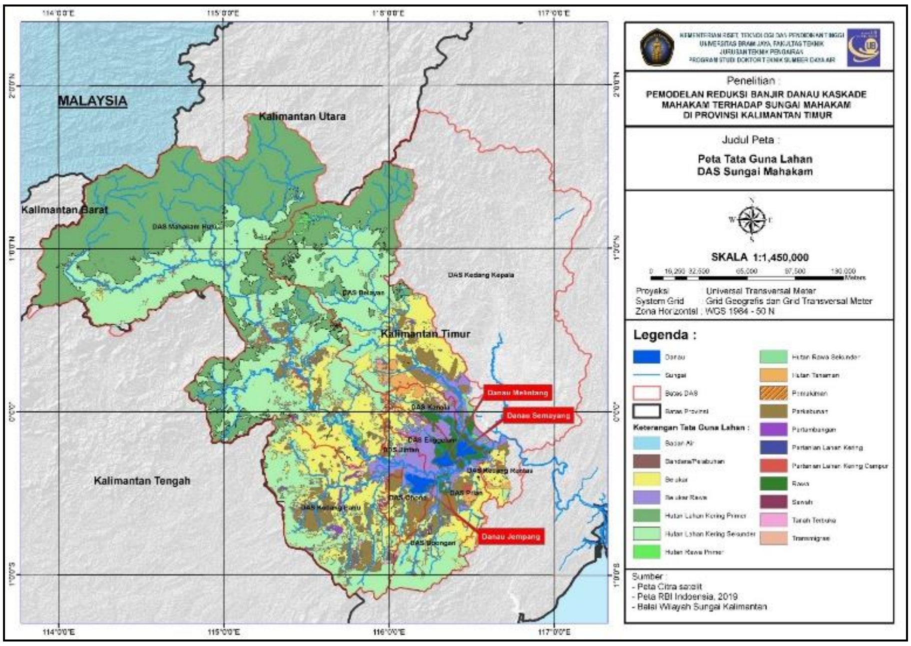

Fig. 1 Map of land use in the Mahakam watershed

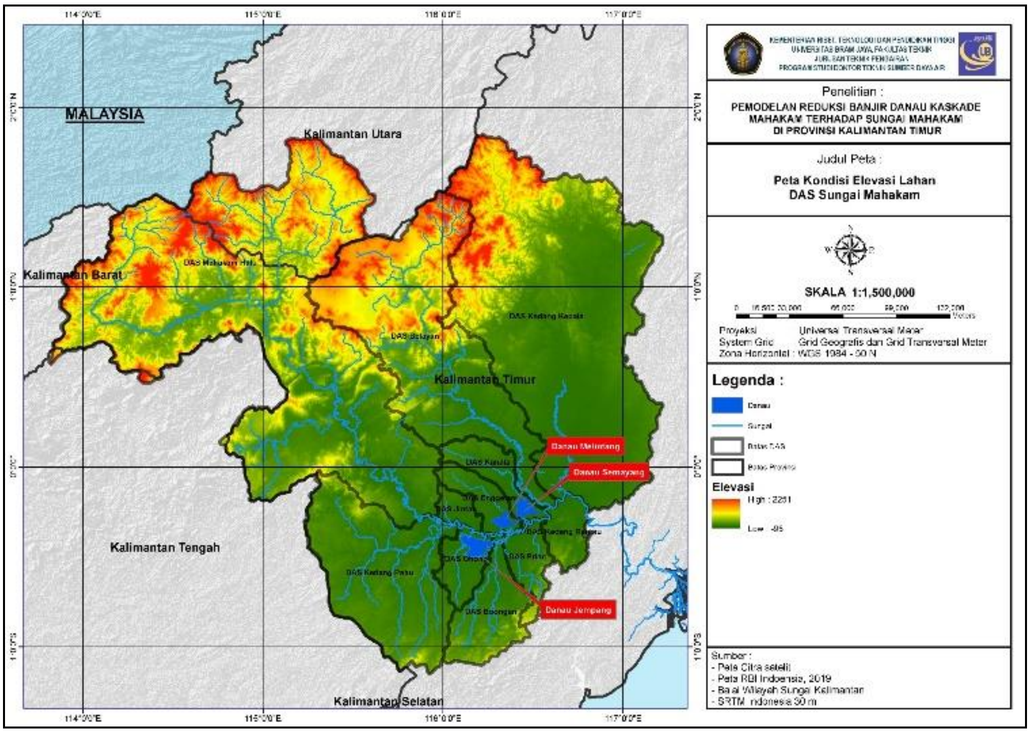

Fig. 2 Map of elevation in the Mahakam watershed

Table 2 Thiessen influence on the Mahakam sub-watersheds

No	Name of sub-watershed	Watershed area (km^2)	Main river length (km)	Influenced station	Coefficient of Thiessen
1	Belayan	10808.72	310.092	Damai	0.798
				Kembang Janggut	0.184
				Muara Kaman	0.018
2	Boongan	2274.05	76.854	Tanjung isuy	0.945
				Penyinggahan	0.055
3	Enggelam	1044.19	27.153	Penyinggahan	0.751
				Kembang Janggut	0.180
				Long Iram	0.009
				Barong Tongkok	0.060
4	Jintan	512.80	15.387	Penyinggahan	0.922
				Barong Tongkok	0.078
5	Kanala	1262.45	56.625	Kembang Janggut	0.742
				Long Iram	0.010
				Penyinggahan	0.128
				Muara Kaman	0.120
6	Kedang Kepala	19551.34	323.881	Muara Kaman	0.188
				Kembang Janggut	0.521
				Damai	0.291
7	Kedang Pahu	6874.80	117.246	Barong Tongkok	0.511
				Tanjung isuy	0.390
				Penyinggahan	0.009
				Long Iram	0.063
				Beringin-Muara Teweh	0.027
8	Kedang Rantau	999.14	29.406	Muara Kaman	1.000

Continuation of Table 2

9	Mahakam Hulu	25848.81	537.168	Damai	0.731
				Long Iram	0.232
				Barong Tongkok	0.038
10	Ohong	1141.06	23.842	Tanjung isuy	0.826
				Penyinggahan	0.174
11	Prian	1092.03	44.624	Penyinggahan	0.628
				Tanjung isuy	0.260
				Muara Kaman	0.111

3.3. Areal Mean Rainfall

The mean rainfall depth is obtained by using Thiessen Method [16]. Based on the Thiessen method, the drawing is carried out by placing the station points on the map. Then, each polygon's area is determined using the plan-meter, and it is expressed as the percentage of the total area. Table 3 presents the result of the areal mean rainfall.

Table 3 Result of the areal mean rainfall

Year	Area mean rainfall					
	Belayan watershed	**Boongan watershed**	**Enggelam watershed**	**Jintan watershed**	**Kanala watershed**	**Kedang Kepala watershed**
2010	67.71	195.99	102.00	120.57	36.26	44.01
2011	26.39	100.75	132.85	154.52	57.08	40.04
2012	11.16	177.90	118.72	143.04	38.17	26.17
2013	34.75	81.62	86.45	98.39	51.21	48.66
2014	58.72	43.66	95.82	110.48	48.14	51.89
2015	28.48	53.53	93.32	112.33	33.61	33.28
2016	100.86	71.71	81.93	97.43	39.34	68.64
2017	95.85	65.51	127.24	152.15	48.61	66.66
2018	99.14	107.46	58.21	62.47	47.95	70.51
2019	80.59	149.73	125.14	142.39	65.23	65.95

Year	Area mean rainfall				
	Kedang Pahu watershed	**Kedang Rantau watershed**	**Mahakam Hulu watershed**	**Ohong watershed**	**Prian watershed**
2010	136.94	74.60	107.94	186.96	138.33
2011	66.72	84.60	46.42	108.78	138.23
2012	162.91	98.30	41.72	173.40	147.02
2013	110.08	119.80	59.78	83.39	94.51
2014	120.31	92.30	81.94	51.31	86.45
2015	101.54	108.50	56.15	60.66	94.52
2016	88.31	150.10	119.74	74.96	96.31
2017	78.90	140.00	114.17	77.11	130.52
2018	96.58	97.00	111.61	101.60	77.62
2019	125.32	79.00	87.15	149.15	139.02

3.4. Design Rainfall

After obtaining the value of area mean rainfall, analyze the design rainfall. The design rainfall can be analyzed using Gumbel, Log Pearson, Log Normal, and Normal [17].

Table 4 presents the design rainfall in each watershed.

Table 4 Design rainfall in each watershed

No	Name of watershed	Design rainfall (m^3/s)							
		2 years	5 years	10 years	20 years	50 years	100 years	200 years	1000 years
1	Belayan	57.09	97.10	123.60	149.01	181.90	206.55	231.10	287.99
2	Boongan	99.62	162.82	204.67	244.81	296.77	335.71	374.50	464.36
3	Enggelam	103.27	123.47	132.94	141.94	147.10	151.25	154.66	161.02
4	Jintan	122.00	146.09	156.31	165.16	169.75	173.17	175.76	181.94
5	Kahala	45.42	54.41	59.97	66.66	71.45	76.12	80.71	91.28
6	Kedang Kepala	50.03	68.96	81.49	93.51	109.06	120.72	132.34	159.24
7	Kedang Pahu	105.96	140.21	162.89	184.65	212.81	233.91	254.94	303.64
8	Kedang Rantau	100.07	123.10	138.61	158.53	173.70	186.92	204.98	244.08
9	Mahakam Hulu	76.85	90.84	92.70	94.43	95.51	86.88	87.68	89.22
10	Ohong	96.41	140.83	173.19	217.33	252.43	289.62	329.10	431.50
11	DAS Prian	112.29	136.52	150.50	166.47	177.36	187.51	197.16	217.69

3.5. Design Flood

Design flood is analyzed for the 13 watersheds and 3 lakes. Nakayasu Synthetic Unit Hydrograph is used for analysis design flood in the watershed; however, in the lake, there is used the Rational Method. Table 5 presents the design flood for each watershed and lake.

Table 5 Design flood for each watershed and lake

No	Name of watershed/ lake	Design flood (m^3/s)		
		25 years	50 years	100 years
1	Belayan	2859.47	3481.57	3947.75
2	Boongan	2901.70	3514.35	3973.44
3	Enggelam	1017.54	1054.16	1083.66
4	Jintan	975.86	1002.83	1022.89
5	Kahala	461.29	493.68	525.26
6	Kedang Kepala	4922.51	6406.91	7533.44
7	Kedang Pahu	11403.28	13741.83	15506.12
8	Kedang Rantau	1249.26	1367.58	1470.81
9	Mahakam Hulu	12295.28	12434.47	11319.68
10	Ohong	2115.26	2455.22	2815.39
11	Prian	1137.80	1211.46	1280.19
12	Kota bangun	3498.50	3506.99	3513.02
13	Muara Kaman	5522.48	5695.37	5837.17
14	Jempang Lake	Capacity	388.32	
15	Melintang Lake	Capacity	140.10	
16	Semayang Lake	Capacity	82.05	

3.6. Capacity of Cascade Lake

The Mahakam Cascade Lake includes the Jempang, Melintang, and Semayang Lake merged with the Mahakam River. The three lakes will be found the effective volume for knowing the capacity of effective discharge. The volume of storage is obtained from the contour elevation multiplied by the inundation area of the lake on elevation. The capacity curve of the lake is necessarily analyzed for knowing the value of discharge. Fig. 6 presents the capacity curve of Mahakam Cascade Lake.

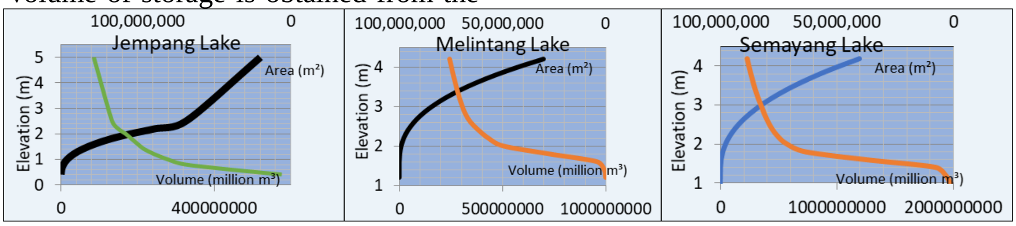

Fig. 3 Capacity curve of Mahakam Cascade Lake

3.7. Simulation Model of Flood Reduction

Linear programming is one of the operation research techniques that can solve optimization problems. In this research, the objective function is to minimize the flood discharge of the Mahakam River in the Muara Kaman. It is due to some simulations of flood reduction by minimizing the $Q_{muara\text{-}kaman}$. However, the constraints are as follows.

1. Outflow of Jempang_Lake: X6 = $Q_{s.ohong}$ + $Q_{s.Bongan}$ + $Q_{S.Prian}$ - X3
2. Outflow of Melintang+Semayang_lake: X7 = Q s.Enggelam + Q s.Kalaha - X4 - X5
3. Reduction of Jempang Lake: X3 ≤ C Jempang Lake
4. Reduction of Melintang Lake: X4 ≤ C Melintang Lake
5. Reduction of Semayang Lake: X5 ≤ C Semayang Lake:
6. Debit di Muarakaman: X1 = $Q_{s.Kedang\ pahu}$ + $Q_{s\ Belayan}$ + $Q_{s.Kedang\ kepala}$ + $Q_{s.Kedang\ rantau}$ + $Q_{s.Mahakam}$ + X6 + X7

where X1 = $Q_{muara\text{-}kaman}$; X2 = $Q_{kotabangun}$; X3 = $Q_{reduction\text{-}jempang}$; X4 = $Q_{reduction\text{-}melintang}$; X5 = $Q_{reduction\text{-}semayang}$; X6 = $Q_{lake\_jempang}$; X7 = $Q_{lake\_melintang\_semayang}$; C = capacity.

The result of each simulation is as follows:

- Simulation-1:

Optimization of flood reduction in the Muara Kaman due to the design flood of Q_{25}:

$Q_{Muara\ Kaman}$ = $Q_{S.Kedang\ pahu}$ + $Q_{S.Belayan}$ + $Q_{S.Kedang\ kepala}$ + $Q_{S.Kedang\ rantau}$ + $Q_{S.Mahakam}$ + $Q_{Danau\ Jempang}$ + $Q_{danau\ melintang\ semayang}$ = 11,403.28 + 2,859.47 + 4,922.51 + 1,249.26 +12,295.28 + 5,766.43 + 1,256.68 = 32,729.80 m^3/s;

- Simulation-2

Optimization of flood reduction in the Muara Kaman due to the design flood of Q_{50}

$Q_{Muara\ Kaman}$ = $Q_{S.Kedang\ pahu}$ + $Q_{S.Belayan}$ + $Q_{S.Kedang\ kepala}$ + $Q_{S.Kedang\ rantau}$ + $Q_{S.Mahakam}$ + $Q_{Jempang\ lake}$ + $Q_{melintang\ semayang\ lake}$ = 13,741.83 + 3,481.57+ 6,406.91+ 1,367.58+12,434.47+ 6,792.70+ 1,325.69 = 37,432.36 m^3/s;

- Simulation-3

Optimization of flood reduction in the Muara Kaman due to the design flood of Q_{100}

$Q_{Muara\ Kaman}$ = $Q_{S.Kedang\ pahu}$ + $Q_{S.Belayan}$ + $Q_{S.Kedang\ kepala}$ + $Q_{S.Kedang\ rantau}$ + $Q_{S.Mahakam}$ + $Q_{Jempang\ lake}$ + $Q_{melintang\ semayang\ lake}$ = 15,506.12 + 3,947.75+ 7,533.44+ 1,470.81+11,319.68+ 7,680.69+ 1,386.77 = 39,777.80 m^3/s

4. Conclusion

This study intends to optimize flood reduction modeling of Mahakam Cascade Lake towards the Mahakam River in the Muara Kaman outlet. According to the optimization model, this research aims to simulate the flood reduction modeling due to the 3 discharge conditions: Q_{25}, Q_{50}, and Q_{100}. The food reduction modeling uses the Linear Programming Model, and the model is built integrated due to the Cascade Lake.

Based on the analysis and discussion above, it can be concluded that Mahakam Cascade Lake's capacity is as follows: Jempang Lake is 519,958,550.36 m^3; Melintang Lake is 696,012,192.74 m^3; Semayang Lake is 1,195,593,435.86 m^3. The result of three simulations indicate that the condition of $Q_{muarakaman}$ is still safe from flood, remembering that the flood has ever happened is in the amount of 5,685.37 m^3/s; however, the result of the simulation can store 32,729.80 m^3/s for the design flood of Q_{25}; 37,432.36 m^3/s for the design flood of Q_{50}; and 39,777.80 m^3/s for the design flood of Q_{100}.

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