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Sustaining Batujai Reservoir Operation Using Simulation and Recursive Optimization

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Abstract— *As the oldest water resource in Dodokan River, Batujai need to overcome the problem caused by the changes of hydrology and lack of concern to sustaining the water supply and storage with proportionalities time to time. Due to historical reservoir operation data in 2014-2018, Batujai has experienced 11 time period of storage emptinees. Optimization is using the deterministic-linear programming and combine with recursive iteration, to assuring the objective function is maximum but still have a reliable proportion of water supply portion and storage. By using simulation and recursive optimization in 2014-2018, reservoir performance are increasing; reservoir did not experience a storage emptiness; and high water supply portion. Therefore, based on the comparative result between recursive optimization with non-recursive optimization and historical data, Batujai can be more sustainable, efficient and equal in reservoir operation across time period by using recursive optimization.*

Keywords— *Model; Optimization; Recursive; Reservoir; Sustainability.*

I. INTRODUCTION

With the change of hydrology condition due to the climate change and as the biggest water resource instream, reservoir must maintaining the consistency to serve the water demand in downstream every time [1]. But to serve (supplying) downstream water demand every time, reservoir operation need to concern the impact on storage changes, so that it can be ascertained both the water supply and the storage provision for upcoming period is in the right proportion. The definition of right proportion is explained by using UN-Water criteria [2] i.e., sustainability, efficiency and equity. These principal criteria are in the line with the state constitution (Undang-Undang Dasar Negara Republik Indonesia 1945) in article 33, which explain that water is a public goods (efficiency and equity) and the availability of water must be maintaned (sustainability) from time to time.

Reservoir operation is a common subject in water resources, so is at Batujai on Dodokan River, Lombok river basin, Indonesia. The main problem for Batujai is the proportionality in reservoir operation (water supply and storage provision) from time to time. Batujai is a multi-purpose reservoir, with the main purpose is to supplying raw water and other is to supplying irrigation area of 3390 ha. In 2014 to 2018 (with a period of 10 days), there are 11 times that Batujai had empty storage, and due to this data reservoir is cannot supplying the water demand. Therefore, sustainability of Batujai reservoir operation cannot be achieved.

To assess the reservoir operation, this paper is using reservoir performance equation with 3 criteria i.e., reliability, resiliency and vulnerability [3]. These criteria in reservoir performance is also reflecting the principal criteria of UN-Water [4]. Therefore, the objective of this paper is to compare the reservoir performance between existing data in 2014-2018, the results of optimization in 2014-2018 without recursive technique and the results of optimization in 2014-2018 with recursive technique.

II. RESERVOIR MODELING AND PERFORMNACE CRITERION

A. Reservoir Modeling

Optimization for reservoir operation is commonly used to get the best solution. There are 4 type of optimization technique i.e., i) linear program (LP); ii) non-linear program; iii) dynamic program (DP); iv) genetic algorithm [1]. Deterministic and LP is used in this paper, and combined with recursive method to ensure that objective function is reaching its maximum but still have a reliable proportion of water supply and storage. LP is widely used becaused its simplicity and reliable for large quantities of constraint [5]. On general LP optimization there is only one process to get a maximum result, and the changing variables is only 1 for all time periods and it changes only forward (e.g., 1 to 100) [6]. While in this paper is using two step of optimization process, first is initial process and second is improvement process [7].

Initial process is the first process of changing variables value is change simultaneously for all time periods. These process is to get the minimum value of water supply. Improvement process is the second process of changing variables value is change partially in each of all time periods. These process is to get the maximum value of water supply for each time periods. The value of changing variables is based on simulation and also using LP, where the objective function is to maximize the water supply portion (or release ratio).

To maintaining the sustainability of reservoir operation, there are 3 of 8 constraint in optimization which is about the proportionality of storage provision and the supply portion. These constraint is taken based on the state constitution and the UN-Water criteria. In other words, the optimization process is implicitly containing the main idea of two principal regulation for water resources.

- *Objective function*

$$Max\ Z = \sum_{t=1}^{T} \sum_{q=1}^{Q} \frac{V_{R\,q,t}}{V_{D\,q,t}} \quad (1)$$

Where Z = objective function (%) for T = 36 time periods, with 1 period = 10 days, and Q = 2 for purposes of reservoir, i.e. irrigation and raw water. The maximum value of Z is 18000%, with total 5 years data in period of 10-day. $V_{R\,q}$ is the total of water supply or release from irrigation and raw water,

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and $V_{D\ q}$ is the total of water demand from irrigation and raw water. Water demand for raw water is supplied 100% constantly in each time period it is because the regulation of raw water stated that raw water is must had a reliability of 99%. Water supply for irrigation is regulated with K factor or;

$$V_{R\ irrigation\ t} = K_t \times V_{D\ t} \quad (2)$$

K = factor of portion for irrigation release (%) and also the changing variables. Generally, K factor is use to indicating the rotational status in irrigation systems. If K > 80% then there are no rotation in irrigation systems or contious flow. But if K < 80% then there are some rotation in irrigation systems, and the minimum of K that indicating heavy rotation in irrigation systems is 20% [2].

- *Constraint function*

In optimization process, the number of constraint is 8 and it is based on the water balance, UN-Water criteria and the state constitution, and the river ecosystem. These are 8 constraint in optimization process:

1. Water balance

$$\Delta S_t = S_t + I_t - O_t \quad (3)$$

Where ΔS_t = storage change (m^3); S_t = inital storage (m^3); I_t = inflow (m^3); O_t = outflow (m^3); t = time period.

2. Effective storage

$$0 < V_{End\ t} \leq V_{Eff} \quad (4)$$

Where $V_{End\ t}$ = end storage or storage change (m^3) and V_{Eff} = effective storage (m^3).

3. Deviation of beginning and end year storage (dV)

$$dV \leq \varepsilon \quad (5)$$

$$dV = \left| \frac{V_{End\ t=1}}{V_{Eff}} - \frac{V_{End\ t=36}}{V_{Eff}} \right| \quad (6)$$

Where dV = deviation of beginning and end year storage (%) and ε = limit value which is iterated from 0% to 50%. The purpose using dV as one of the constraint is to ensure that there is a proportional storage provision for coming years [7].

4. Equality on storage portion ratio (C)

$$|C_t - C_{t+1}| \leq \varepsilon \quad (7)$$

$$C = \frac{V_{End\ t}}{V_{Eff}} \quad (8)$$

This formula was explained by [2], to get both the optimum and proportional result between storage portion ratio (C) in each time period.

5. Equality on water irrigation supply portion ratio (K)

$$|K_t - K_{t+1}| \leq \varepsilon \quad (9)$$

This formula was explained too by [2], to get both the optimum and proportional result between water supply portion ratio (K) in each time period.

6. Irrigation

$$K_{min} \leq K_t \leq 100\% \quad (10)$$

Where K_{min} = 20%, which is minimum value of K based on the heavy rotation in irrigation systems [7].

7. Raw water

Water demand for raw water is supplied 100% constantly in each time period, or:

$$V_{R\ raw\ water\ t} = V_{D\ raw\ water\ t} \quad (11)$$

The value of raw water demand is 180 l/s, and this raw water will be processed by PDAM (local government).

8. River ecosystem maintenance

$$V_{E\ t} = I_t \times 5\% \quad (12)$$

According the standard design of headworks in Indonesia [8] and other research about reservoir operation that include about ecosystem of river [9], the demand of river maintenance ($V_{E\ t}$) for sustaining ecosystems is 5% from the *inflow*.

- *Changing Variable*

As explained before, the changing variable in optimization process is using K factor (%). Where K is iterated with the step of 1% from 100% to 0% in each time period. In initial process, K is moving forward through time period. And in improvement process, K is moving forward and backward simultaneously through time period [7].

$$K_t = \frac{V_{R\ irrigation\ t}}{V_{D\ irrigation\ t}} \quad (13)$$

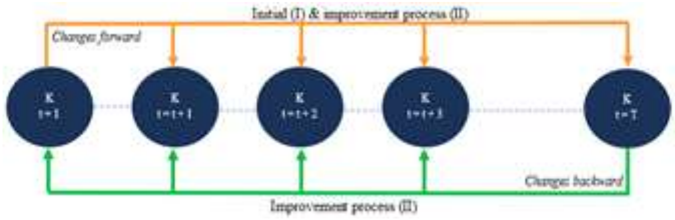

Fig. 1. Recursive Iteration in Optimization Process

B. *Reservoir Performance Criterion*

Reservoir is a man made water resource, by that it is required to evaluate the performance of reservoir. Reliability, resiliency and vulnerability is a criteria to evaluate the performance of reservoir in percentage [1]. First criteria is reliability (α), to measuring the failure (f) of reservoir operation. Second is resiliency (γ), to measuring the quickness of storage can be recover from failure. Third is vulnerability (λ), to measuring severity of reservoir operation from the maximum of deficit water supply on continuous failure (fs). The best performance is when the reliability is 100%, resiliency is 100% and vulnerability is 0%.

All of those criteria is requiring a fixed boundary value that can explain if the storage on a certain period is failing or not. And in this paper, a fixed boundary value is based on K_{min} value with the explanation that when water irrigation supply from reservoir is ≤ 0 (with water demand > 0) then it is the same as water cannot flow through the irrigation system or water runs out on the channel. Reservoir performance is the key to evaluate if the reservoir operation are sustainable or not, because it is a reflection of proportionality on how reservoir operation can supplying water downstream continuously. The formula of reservoir performance is as follows [1]:

$$\alpha = 1 - \frac{f}{T} = 1 - \frac{\sum_{t=1}^{T}(K_t < K_{min})}{T} \quad (14)$$

$$\gamma = 1 - \frac{fs}{f} = 1 - \frac{\sum_{t=1}^{T-1}(K_{t+1} \geq K_{min} | K_t < K_{min})}{\sum_{t=1}^{T}(K_t < K_{min})} \quad (15)$$

$$\lambda = \frac{\sum_{g}^{fs} Max(Def_g)}{fs} \quad (16)$$

III. Data and Methods

The data that will be used in this paper are from Water

Allocation Unit, BWS NT-I (local government for water resources). Details of data values are as follows:

TABLE I. Data Specification

Type of data	Data length	Data values
Reservoir operation	2014-2018	Attached below
Updated storage area (m^2)	-	8900000
Raw water (l/s)	-	180
Irrigatian Area (ha)	-	2889
Updated effective storage (m^3)	-	1828720
Normal water level (m)	-	+92.50
Minimum operation level (m)	-	+88.00

Batujai Dam is located on Dodokan river, and it has been operated and recorded since 1982. In this paper, evaluation of reservoir performance is started from 5 years before because there is some data between 1982 and 2013 that not fully recorded. From Water Allocation Unit, data of end storage 2014 to 2018 is as follows:

TABLE II. End Storage of 2014 to 2018 ($10^6 m^3$)

Period	V_{End}				
	2014	2015	2016	2017	2018
Oct I	1.39	0.00	14.29	8.60	2.30
Oct II	1.30	0.00	13.88	10.99	2.13
Oct III	1.21	0.00	14.09	9.12	1.92
Nov I	1.02	0.00	14.36	8.28	2.22
Nov II	1.92	0.00	13.82	11.13	5.86
Nov III	1.65	0.00	14.09	12.86	5.82
Dec I	4.10	0.00	13.82	13.20	9.44
Dec II	5.46	0.11	14.92	14.37	10.93
Dec III	10.01	4.86	14.92	14.47	10.38
Jan I	10.94	12.94	3.68	14.10	14.61
Jan II	11.77	11.45	2.03	14.72	14.70
Jan III	12.09	10.88	3.51	14.85	14.67
Feb I	11.85	12.48	10.69	0.45	14.50
Feb II	11.29	14.43	15.34	2.72	14.82
Feb III	10.52	15.06	15.34	2.76	15.15
Mar I	15.27	15.48	15.20	14.23	15.11
Mar II	14.92	15.34	14.43	14.43	15.00
Mar III	15.13	15.62	14.71	14.95	14.98
Apr I	15.06	15.06	15.34	14.75	13.93
Apr II	14.99	15.27	15.34	14.54	12.14
Apr III	15.20	15.62	14.36	14.90	10.29
May I	14.45	15.13	14.50	13.91	8.25
May II	13.42	14.02	14.78	11.20	6.21
May III	12.16	11.90	13.68	10.38	4.52
Jun I	10.51	10.63	12.88	8.71	2.89
Jun II	6.91	8.82	13.88	8.15	1.78
Jun III	4.86	6.76	15.20	7.90	1.34
Jul I	3.43	5.14	15.06	8.18	1.35
Jul II	2.42	3.51	15.13	9.63	3.69
Jul III	3.19	2.35	14.78	9.79	3.42
Aug I	3.22	1.17	14.92	9.60	3.35
Aug II	2.83	0.18	14.02	9.06	3.22
Aug III	2.53	0.00	13.41	8.99	2.98
Sep I	2.35	0.00	12.22	7.71	2.94
Sep II	2.48	0.00	12.22	6.78	2.78
Sep III	1.87	0.00	14.29	6.34	2.55

The end storage (V_{End}) data is use for calculating the reservoir performance later. Other data from reservoir operation of 2014 to 2018 is use for simulation, such as losses(V_{Loss}) from evaporation and filtration, and also water demand. For inflow (I), it is need to calculate by using water balance equation [Eq. 3]. All of analysis process in this paper is using Visual Basic for Application (VBA).

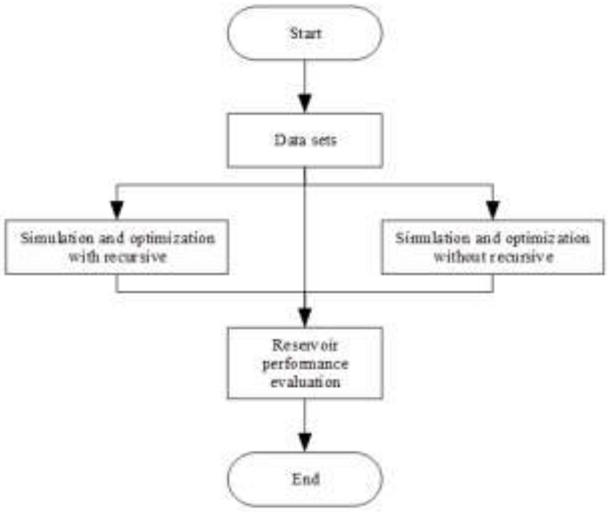

Fig. 2. Flowchart of Methodology

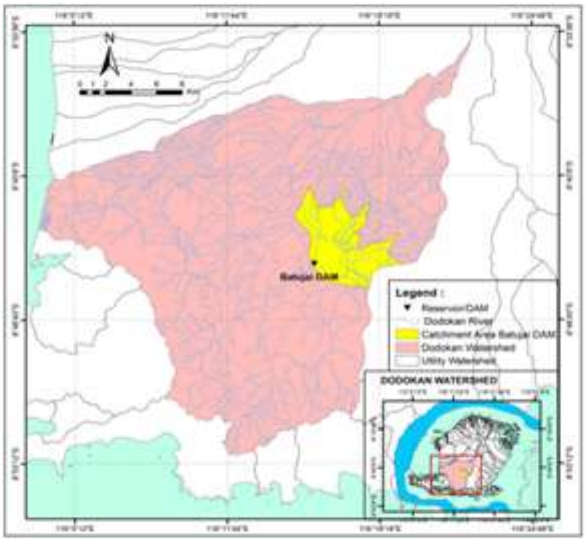

Fig. 3. Catchment Area of Batujai Dam

IV. RESULTS AND DISCUSSIONS

A. *Result and Discussion of Evaluation on Historical Data*

The reservoir performance from historical data of reservoir operation is calculated first, in order to compare it with 2 different method of optimization later. The best performance of reservoir for each criteria is reliability = 100%; resiliency = 100%; vulnerability = 0%.

TABLE III. Historical Reservoir Performance

Performance Criteria	2014	2015	2016	2017	2018
α (%)	75	83	97	92	83
γ (%)	11	17	0	0	0
λ (%)	11	17	50	25	14

With K_{min} is 20% for boundary value to determined wheter the storage is failing or not, the result in Table III shows that

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there is no performance criteria value of Batujai has reach its best performance. As the data in 2014 to 2018 is also shows in Table II that the storage is experiencing 11 times of empty storage (V_{End} = 0 m^3). Herein, based on the result that Batujai reservoir operation is not in sustainability state. Because the water supply and storage had no proportionality, or in other words that inequality of storage for each time period is caused by total water supply portion (V_R/V_D) of irrigation and raw water that is not in the right proportion.

TABLE IV. Historical Total Water Supply Portion Ratio (%)

Period	V_R/V_D				
	2014	**2015**	**2016**	**2017**	**2018**
Oct I	7	7	49	52	290
Oct II	7	6	8	19	9
Oct III	9	6	666	50	397
Nov I	19	9	411	644	106
Nov II	7	41	1626	1411	7981
Nov III	5	7	1637	286	17433
Dec I	3	4	224	53	388
Dec II	117	80	160	162	287
Dec III	474	55	70	362	100
Jan I	557	221	142	71	51
Jan II	412	209	403	106	63
Jan III	1228	441	1397	851	66
Feb I	233	91	219	846	49
Feb II	142	58	115	1548	51
Feb III	72	77	735	155	28
Mar I	118	1204	181	137	56
Mar II	855	85	124	199	89
Mar III	122	101	139	192	89
Apr I	62	49	52	105	52
Apr II	67	98	57	49	80
Apr III	94	357	92	65	96
May I	95	141	85	40	126
May II	101	117	112	18	135
May III	85	130	151	36	80
Jun I	123	30	188	26	94
Jun II	138	82	292	84	69
Jun III	102	63	165	15	6
Jul I	83	148	136	34	20
Jul II	63	183	239	34	46
Jul III	17	314	91	98	44
Aug I	100	190	79	93	17
Aug II	62	206	209	150	100
Aug III	18	36	45	25	11
Sep I	23	130	148	169	10
Sep II	45	42	514	52	752
Sep III	45	32	489	172	488

The cells with grey colors is explained when V_R/V_D > 100% or when the water supply portion is exceeded the water demand, or inefficient. Herein, the data is assumes right and was supervised by Water Allocation Unit (local government). The possible probability of inefficiencies is occur in Batujai are illegal water withdrawal along the irrigation channel, but this problem is not discussed further on this paper.

B. Result and Discussion of Simulation and Optimization with Recursive Iteration

By using simulation and deterministic-LP of recursive optimization with VBA for 5 years data, the result is as follows:

TABLE V. Total Water Supply Portion Ratio (%) with Recursive Optimization

Period	V_R/V_D				
	2014	**2015**	**2016**	**2017**	**2018**
Oct I	31	100	100	100	100
Oct II	30	100	100	100	100
Oct III	33	100	100	100	100
Nov I	47	100	100	100	100
Nov II	31	100	100	100	100
Nov III	48	100	100	100	100
Dec I	92	100	100	100	100
Dec II	100	100	100	100	100
Dec III	100	100	100	100	69
Jan I	100	100	100	100	56
Jan II	100	100	100	100	56
Jan III	100	100	100	100	56
Feb I	100	100	100	100	55
Feb II	100	100	100	100	55
Feb III	100	100	100	100	55
Mar I	100	100	100	100	55
Mar II	100	100	100	100	56
Mar III	100	100	100	100	55
Apr I	100	100	100	93	45
Apr II	100	100	100	91	44
Apr III	100	100	100	91	44
May I	74	100	100	91	45
May II	73	88	100	91	46
May III	72	88	100	91	45
Jun I	72	88	100	91	45
Jun II	72	87	100	91	45
Jun III	72	87	100	91	45
Jul I	72	87	100	91	45
Jul II	74	88	100	91	53
Jul III	74	91	100	91	50
Aug I	77	94	100	93	54
Aug II	78	91	100	93	54
Aug III	75	89	100	91	50
Sep I	75	89	100	92	48
Sep II	74	88	100	92	96
Sep III	74	88	100	92	100
Total (%)	**2820**	**3443**	**3600**	**3447**	**2322**

From Table V, total water supply portion ≤ 100% or in other word it means that there is no water supply > water demand, or water supply is efficient. In 2016, reservoir can supply 100% on water demand constanly because there is enough storage provision and large inflows. Also from Table V, the minimum value of V_R/V_D is 30%, which is > K_{min} and it mean that rotational in irrigation system is not heavy. As the objective function is total water supply portion ratio (see Eq. 1), then the result of objective function (Z) for optimization with recursive iteration is 15632%.

Result for end Storage (V_{End}) of optimization with recursive iteration shows that there is no value is equal to 0 m^3 or empty storage. Deviation of beginning and end of each year storage or dV is below the ε (limit value for iteration), and so for all constraint function. With dV < ε for each year, it means that there is a proportional storage provision for the coming years to maintain the consistency of sustainable reservoir operation.

From the result of optimization, reservoir performance is calculated with (14) to (16). And the result from Table VI is showing that Batujai can reach the best performance. The reason that optimization with recursive iteration reach the best

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performance is because there are no water supply portion ratio or V_R/V_D (with orange line on Figure 4) below the K_{min}.

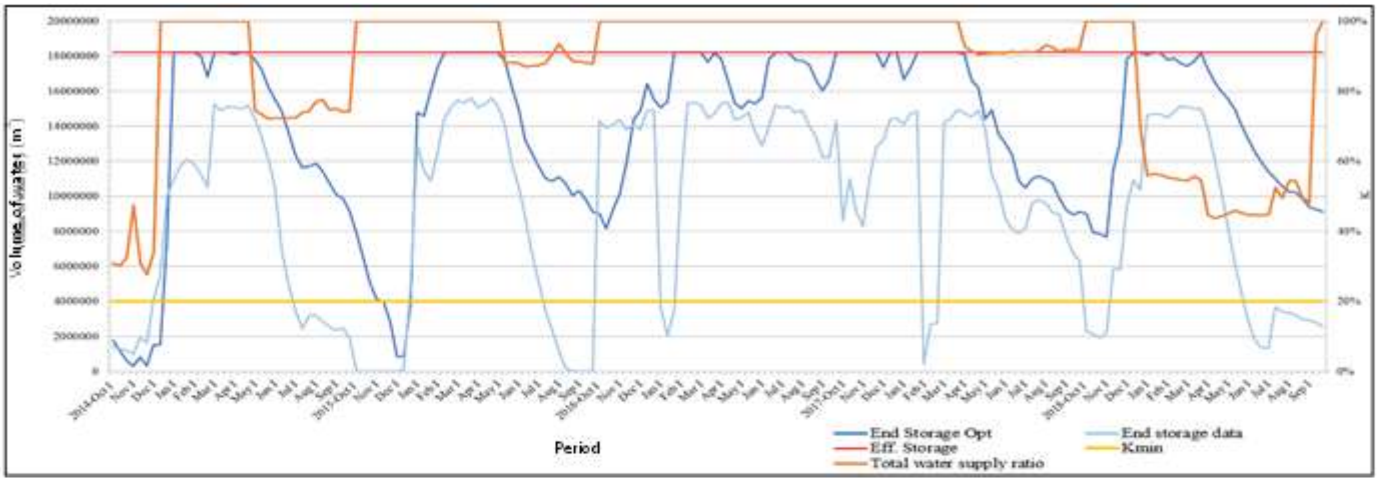

Fig. 4. Comparative Result of Optimization with Recursive Iteration and Historical Data

TABLE VI. Result of Reservoir Performance with Recursive Optimization

Performance Criteria	2014	2015	2016	2017	2018
α (%)	100	100	100	100	100
γ (%)	100	100	100	100	100
λ (%)	0	0	0	0	0

B. Result and Discussion of Simulation and Optimization Without Recursive Iteration

Optimization without recursive iteration is resulting that there is some end storage (V_{End}) ≈ 0 m^3 or empty. The result of optimization without recursive iteration is as follows:

From Table VII, total water supply portion ≤ 100% or in other word it means that there is no water supply > water demand, or water supply is efficient. In 2016, reservoir can supply 100% on water demand constanly because there is enough storage provision and large inflows. Also from Table VII, the minimum value of V_R/V_D is 43%, which is > K_{min} and it mean that rotational in irrigation system is not heavy. As the objective function is total water supply portion ratio (see Eq. 1), then the result of objective function (Z) for optimization without recursive iteration is 15609%. Z value from optimization without recursive iteration is less 23% than optimization with recursive iteration.

Result for end Storage (V_{End}) of optimization with recursive iteration shows that there is some value is ≈ 0 m^3 or empty storage, in 2 period (November III and December I of 2014). Deviation of beginning and end of each year storage or dV is below the ε (limit value for iteration), and so for all constraint function. With dV < ε for each year, it means that there is a proportional storage provision for the coming years to maintain the consistency of sustainable reservoir operation.

From the result of optimization without recursive iteration, reservoir performance is calculated with (14) to (16). And the result from Table VIII is showing that Batujai can reach the best performance without recursive optimization, but there is some critical level of storage in period November III and December I. The reason that optimization without recursive iteration reach the best performance is because there are no water supply portion ratio or V_R/V_D (with orange line on Figure 5) below the K_{min}.

TABLE VII. Total Water Supply Portion Ratio (%) with Recursive Optimization

Period	V_R/V_D				
	2014	2015	2016	2017	2018
Oct I	66	100	100	100	100
Oct II	48	100	100	100	100
Oct III	50	100	100	100	100
Nov I	61	100	100	100	100
Nov II	48	100	100	100	100
Nov III	46	100	100	100	100
Dec I	92	100	100	100	100
Dec II	100	100	100	100	100
Dec III	100	100	100	100	100
Jan I	100	100	100	100	100
Jan II	100	100	100	100	47
Jan III	100	100	100	100	44
Feb I	100	100	100	100	44
Feb II	100	100	100	100	44
Feb III	100	100	100	100	45
Mar I	100	100	100	100	44
Mar II	100	100	100	100	47
Mar III	100	100	100	100	44
Apr I	100	100	100	95	44
Apr II	100	100	100	91	43
Apr III	100	100	100	91	43
May I	100	100	100	91	44
May II	100	95	100	91	45
May III	100	86	100	91	44
Jun I	100	86	100	91	45
Jun II	100	86	100	91	45
Jun III	61	86	100	91	45
Jul I	45	87	100	91	45
Jul II	49	87	100	91	53
Jul III	49	91	100	91	50
Aug I	54	93	100	93	54
Aug II	55	90	100	93	54
Aug III	49	88	100	91	50
Sep I	50	88	100	92	48
Sep II	48	87	100	92	95
Sep III	48	87	100	92	100
Total (%)	2817	3438	3600	3448	2305

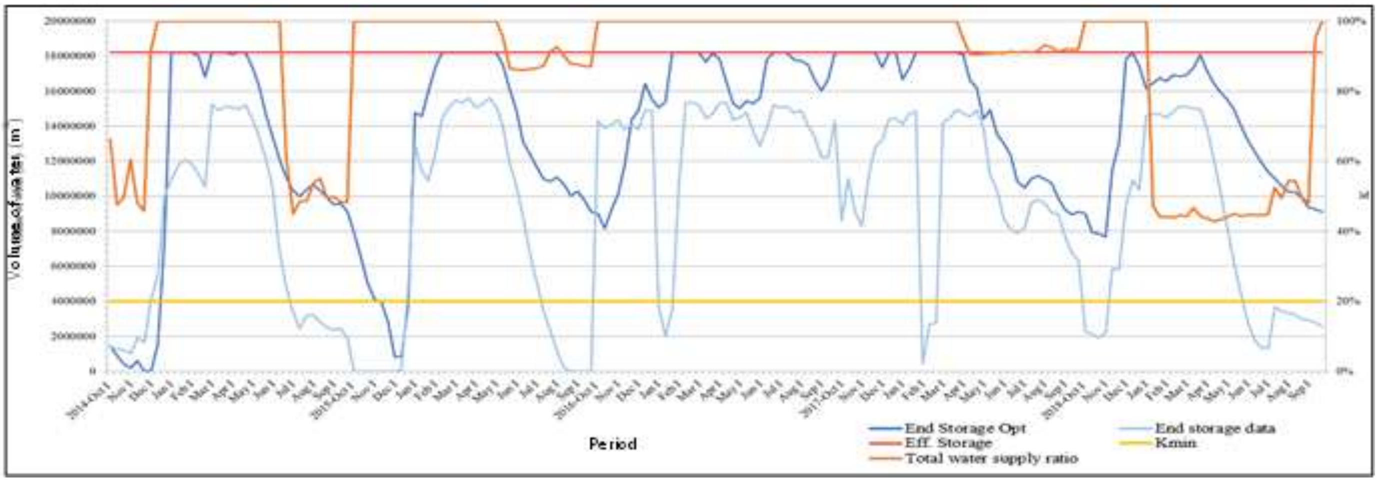

Fig. 4. Comparative Result of Optimization without Recursive Iteration and Historical Data

TABLE VIII. Result of Reservoir Performance without Recursive Optimization

Performance Criteria	2014	2015	2016	2017	2018
α (%)	100	100	100	100	100
γ (%)	100	100	100	100	100
λ (%)	0	0	0	0	0

V. CONCLUSION

This paper is concentrated to maintaining the consistency of sustainability in Batujai reservoir operation, and based on the result there are some point of conclusion as:

1. Using recursive and non-recursive optimization is having a better and contrast result rather than historical operation data, such as reservoir performance, end period storage and water supply portion.
2. Recursive optimization is giving proportional end storage provision for all time period; high water supply portion; more gradually on fluctuation of water supply portion; and achieving best performance of reservoir operation.
3. Non-recursive optimization is giving proportional end storage provision, but not for all time period (i.e., November III and December I of 2014); high water supply portion; fluctuation of water supply is dropping suddenly; and achieving best performance of reservoir operation.
4. Recursive optimization is more sustainable, efficient and equal across all time period compare to the non-recursive optimization and historical data.

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