

MULTI CRITERIA IRRIGATION WATER ALLOCATION FOR OPTIMIZING PANDANDURI RESERVOIR OPERATION

Rachmad Jayadi¹, FatchanNurrochmad², Abdul Azis³, Ratih Kusuma Hartini⁴

ABSTRACT

Water utilization for irrigation purpose through reservoir operation often faces problems in the form of uncertainty in water potential either in the amount or in the distribution pattern of flow from water sources. This issue is found in Pandanduri Reservoir, West Nusa Tenggara Province, Indonesia, where a unique mechanism of water reuse persists in which the return flow from drainage system and pond is used for irrigation water supply in the downstream cultivated area. Determination of water allocation based on the water availability according to time and space distribution should be considered in formulating an optimal reservoir operating rule. In this research, a multi-criteria water allocation model was developed to optimize the performance of the reservoir operation in fulfilling irrigation water demand. Standard operating rule method of reservoir simulation was applied in combination with a deterministic linear programming model to control release from the reservoir. The criteria used to measure the performance of water allocation are annual cropping intensity, *k* factor as the ratio between actual release and target release according to water demand, and the reliability of reservoir operation. The result shows that the distribution of return flow discharge can be estimated with a simple Tank model. The optimum reservoir operation concludes that irrigation water supply capacity is characterized by average *k* factor of 0.87 and the reservoir operation reliability is 83%. Moreover, the consistency of the performance of water allocation model was verified using reservoir operation simulation model with input of the generated synthetic stream flows.

Keywords: Return flow, Standard operating rule, Linear programming, Operation reliability.

1. INTRODUCTION

The Southern area of Lombok Island in West Nusa Tenggara Province, Indonesia, consists of agriculture area of 50,000ha that has not been maximally cultivated due to several problems in irrigation water supply (Mott MacDonald International Ltd. 1996). Government has built an interconnection irrigation network in South Lombok to use potential water resources in the west area, i.e. between Babak river and south area. The irrigation water supply flows through High Level Diversion (HLD) of Babak-Renggung-Rutus, which flows the water from Renggung river to Rutus river as supplementary irrigation for irrigation district of Pandanduri, Swangi on Palung river, and irrigation district of Pelapak, Tundak, Penendem, and Pelambik on Gambir river. Water supply from interconnection network of South Lombok has not been fully covering the water demand of those six irrigation districts. In order to have solution for this problem, the Government built Pandanduri Reservoir which is expected to improve the irrigation water allocation into its maximum

1 Department of Civil and Environmental Engineering, Universitas Gadjah Mada (UGM). Jl. Grafika No. 2 Kampus UGM, Yogyakarta, Indonesia. CP. 55281.; E-mail: rjayadi@ugm.ac.id

2 Department of Civil and Environmental Engineering, Universitas Gadjah Mada (UGM). Jl. Grafika No. 2 Kampus UGM, Yogyakarta, Indonesia. CP. 55281.; E-mail: fatchan-nurr@ugm.ac.id

3 Public Works Office of West Nusa Tenggara Province. Jl. Majapahit No. 8, Mataram, Indonesia. CP. 83114; E-mail: abdoelazis.makawaru@yahoo.com

4 Directorate General of Water Resources, Ministry of Public Works and Housing. Jl. Pattimura No. 20, Kebayoran Baru, Jakarta, Indonesia. CP. 12110; Email: ratihkusumahartini@gmail.com

performance. According to that situation, a comprehensive study on optimum water utilization at the Pandanduri Reservoir is needed by considering several criteria to have the right amount and duration (cropping schedule) of irrigation water supply which correspond to the cropping pattern in local area. Figure 1 presents the location of Pandanduri Reservoir in the Lombok Island, Province of West Nusa Tenggara, Indonesia.

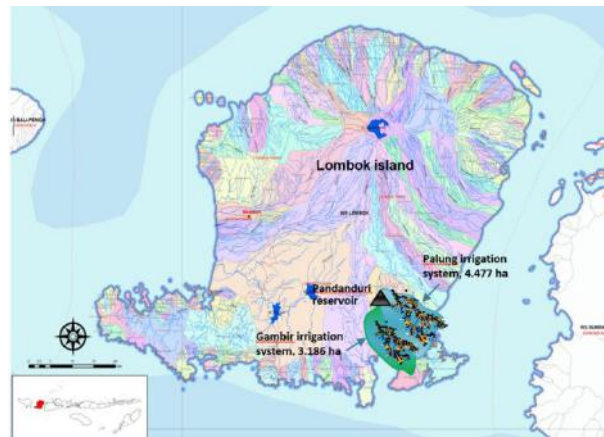


Figure 1. Map of Pandanduri Dam location.

There is a specific phenomenon on the use of water in the field, i.e. the return flow from cultivated area to irrigation channel, and from cultivated area to the river channel. It is necessary to analyze the return flow in order to have its number of distributions that can be used to determine the accurate irrigation water demands. Detail information of return flow is also needed for optimization analysis of reservoir operation to compile a proper dam operating rule. The study results could be a valuable input for policy decision maker, as they can have the optimum water resources utilization of Pandanduri Dam and measurable performance of water allocation through application of basic principles of reservoir operations.

2. METHODS

2.1 Description of the Study Area

This research was conducted in the irrigation service area of Pandanduri Dam, i.e. irrigation system of Palung and irrigation system of Gambir. Pandanduri Dam is located in Palung river, East Lombok Regency, West Nusa Tenggara Province of Indonesia, which was initially operated in 2015. The maximum storage and conservation storage of Pandanduri Dam are $27.2 \times 10^6 \text{ m}^3$ (MCM) and 25.93MCM, respectively, with the maximum water surface area of 64.51 km^2 (Balai Wilayah Sungai Nusa Tenggara I 2009). The dam inundation covers three villages of Terara, Santong, and Swangi, with a total area of 315.70ha.

Pandanduri Reservoir water source comes from tributary stream of Rutus, Bendung, and Gading rivers into Palung river. On the Rutus river, there is additional water supply from HLD of Babak-Rutus-Renggung as part of South Lombok Interconnection Irrigation Network. Between the tributaries of Palung and Pandanduri Dam inundation area, there is an automatic water level recorder (AWLR) gauge of Suradadi to monitor the Palung river discharges. The scheme of water resource system in the research area is shown in Figure 2 (Hartini 2013).

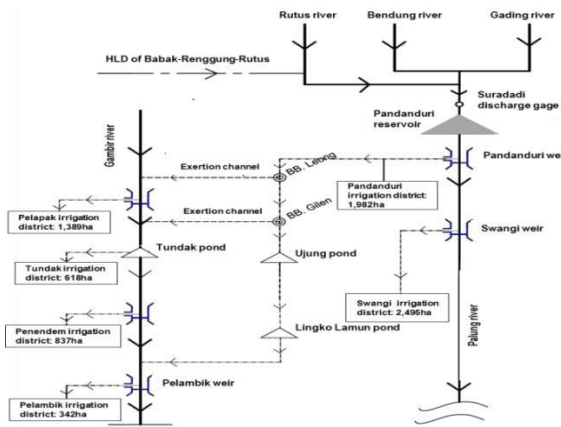


Figure 2. The scheme of water resource system in the research area.

The Palung irrigation system consists of Pandanduri irrigation district (1,982ha) and Swangi irrigation district (2,495ha). Gambir irrigation system receives water supply from Pandanduri Dam that covers four irrigation districts, i.e. Pelapak (1,389ha), Tundak (618ha), Penendem (837ha), and Pelambik (342ha). Azis (2012) has performed a study of return flow with the Tank model which was applied to estimate the amount of return flow from the cultivation area to river channel (river sub-system Tank model), and from the cultivation area to irrigation channel (land sub-system Tank model). The simulated average return flow per cropping season in irrigation district of Pandanduri and Swangi by using river sub-system Tank model is around 10.4%, for cultivation area of Gambir irrigation systems by using land sub-system Tank model is 14%. The return flow in land sub-system is higher because there is a pond (small reservoir) that can accommodate greater water flow from drainage channel.

2.2 Previous Studies on Pandanduri Dam

Study of Integrated Irrigation Sector Project II (IISP-II), Feasibility Study and Detailed Design of Pandanduri-Swangi Dam (Mott MacDonald International Ltd. 1996) determines the benefit of Pandanduri Dam by using Hydrological Simulation Model (HYSIM) method. This study used modeling with consideration of HLD operation for Rutus irrigation system that covers planting area of 8,190ha and Palung irrigation system (Pandanduri and Swangi irrigation district) that covers an area of 5,550 ha. Simulation of irrigation water supply was carried out on daily release from HLD and Pandanduri-Swangi dam according to its water balance analysis result. Study result shows that the maximum cropping intensity is 231%, which is obtained from 5,550ha of land with cropping proportion settings among crop types.

PT. Indra Karya Consulting Engineers (2006) has performed a study on Design Details Review of Pandanduri-Swangi Dam to re-review the detail design of Pandanduri-Swangi dam, which is derived from the Feasibility Study, and Detailed Design of Pandanduri-Swangi Dam (Mott MacDonald International Ltd, 1996). The study produced detail design of Pandanduri-Swangi Dam (Pandanduri Dam) and water management using water balance analysis method by taking into account the components of irrigation water requirement for Pandanduri and Swangi irrigation district, the water requirement for rivers conservation, and losses. This study result recommends cropping pattern of rice-secondary crop-secondary crop. The beginning of first cropping season is at mid-November with the optimum annual cropping intensity of 300% and reservoir operation reliability of 85%.

Azis (2012) has continued the studies of Pandanduri Dam utilization from the research of Mardiani (2010), which focus on the effort to fulfill irrigation demand at Pandanduri and Swangi irrigation district that covers 4,447ha of planting area and back up irrigation water supply from Pandanduri irrigation district to SI Gambir irrigation system for about 30% of Pandanduri irrigation district water demand. This study also calculated the return flow at Pandanduri irrigation district using river sub-system and land sub-system Tank model. Analysis of optimum irrigation water supply is carried out using Linear Program optimization method. The optimal condition is achieved and resulted annual cropping intensity of 237.2% for 4,477ha planting area, with reservoir operation reliability of 90.0% and average value of ratio between actual water supply and water demand (*k* factor) of 0.920. Irrigation water is distributed with rotation system for three blocks cultivation area, rice-rice/secondary crop-secondary crop as the cropping pattern, and the first cropping season starts in October. Hartini (2013) has performed a study of optimum water utilization in Pandanduri Reservoir with more detail focused on the potential water supply to Gambir irrigation system; they are Pelapak, Tundak, Pelambik, and Penendem irrigation district.

2.3 Evaluation of Existing Water Utilization

Cultivation condition data prior to the existence of Pandanduri Reservoir consists of cropping patterns, cropping schedules and types of plant that has been analyzed based on Cropping Realization Report 2008 – 2012, issued by the Public Works Office of East Lombok Regency, West Nusa Tenggara Province, and interviews with irrigation areas observers. Common cropping patterns that have been generally applied are rice - rice/secondary crop/tobacco - secondary crop/tobacco which starts in mid-September for the cropping season-1 at Palung irrigation system. As for Gambir irrigation system, it starts in early October. Average annual cropping intensity for the the sixth irrigation districts is 211%, as shown in Table 1.

Table 1. Existing annual cropping intensity of Palung and Gambir irrigation system

Irrigation district	Cropping intensity			Annual
	Cropping season-1	Cropping season-2	Cropping season-3	
Pandanduri	100%	58%	71%	230%
Swangi	100%	82%	47%	229%
Pelapak	100%	43%	90%	233%
Tundak	100%	67%	71%	238%
Penendem	100%	20%	62%	182%
Pelambik	100%	34%	21%	155%
Average	100%	51%	60%	211%

2.4 Water Requirement Estimation with Return Flow

Crop water requirement is calculated using the observed hydrological data from 1974 to 2012, i.e. daily rainfall data at the rainfall station of Keruak and Sepit, daily climatological data at the Keruak station, daily discharge data of Palung river at Suradadi AWLR, as well as discharge data recorded from intake and over flow of weirs and ponds in the service area of Pandanduri Reservoir. Daily rainfall data is used to calculate effective rainfall in cultivation fields, climatological data is used to calculate potential evapotranspiration according to the method of Penman-Monteith (Allen et al. 1998). The observed discharge at Suradadi AWLR is used to analyze global water availability potential, whereas discharge data at the intake of primary channel for each irrigation district is used for analysis of water availability in the irrigation district level (local). The theoretical water requirements for each irrigation district are calculated based on water balance principle on the land system by

calculating the return flow components, i.e. surface flow and sub surface flow from cultivation fields (Kim, HK, et al. 2009).

The amount of net water demand that must be supplied from Pandanduri Reservoir is determined by calculating the potential return flow and water storage in several ponds that are managed by the government and the farmer groups. The basic concept of Tank model (Sugawara et al. 1984) was applied based on the water balance principle to develop Tank model structures that are in accordance with the hydrologic processes in land sub-system and river sub-system. The developed Tank models are used to simulate return flow for each water allocation period (half monthly). The return flow and additional potential supply from ponds are calculated as a factor in reducing irrigation water requirement (r) to determine net irrigation water requirement, as shown in Equation 1.

$$WRn_t = \frac{r_t WR_t}{IE} \quad (1)$$

where:

WRn_t = net water requirement in period t

WR_t = theoretical water requirement in period t

r_t = reduction factor of water requirement in period t

t = period of irrigation water supply ($t = 1, 2, 3, \dots, 24$)

IE = the overall irrigation water delivery

2.5 Multi Criteria Optimization Model

The optimal water release from Pandanduri Reservoir intends to guarantee the availability of water in every operation period (fortnightly) and it can be used for supplying water with maximum planting area for three cropping seasons in a year, also considering the reservoir inflow and return flow. In other words, the goal is to maximize annual cropping intensity. In order to fulfill irrigation water demand and avoid water shortage at each water supply period, some criteria of optimization should be considered to measure the performance of irrigation water utilization, as follows:

- (i) Cropping intensity, which shows ratio between actual planting area, and common planting area, is usually stated in percentage (%). If all planting area could have water for all 3 cropping seasons, then annual cropping intensity reaches 100%. Cropping intensity was evaluated for each cropping season and the average value was counted.
- (ii) In order to observe the capacity of the reservoir in providing irrigation water, it is necessary to have maximum value of the ratio between the actual water supply and net water requirement, thus the plant physiological processes could produce normal growth. The actual ratio factor value of supply-demand is called as a k factor.
- (iii) Reservoir operation reliability is important to indicate the performance of water release arrangement for irrigation water service by considering the risk of crop failure. Reliability of reservoir operation is stated in percentage from total period of successful experience, i.e., release period (t , half month) where the actual water supply should not less than value of k_t .
- (iv) Applicability of optimization results need to be taken into account in the formulation of optimization model. The farmers generally have conservative behaviour in conducting cultivation. Therefore, the determination of the water release target should be based on cropping patterns, cropping schedule, and existing crop type that has been conducted so far by the farmers. In order to

accommodate this requirement, it is necessary to arrange some constraints formulation of the optimization models for Pandanduri Reservoir.

Based on the four multicriteria aspects, optimization model for water allocation of Pandanduri Reservoir to the six irrigation districts can be formulated using Linear Programming method which can be applied simultaneously with a simulation model of water release arrangement according to the Standard Operating Rule method (Mays & Tung 1992). Formulation for optimization model is described as follows:

Objective function:

$$Max Z = \frac{100}{CA} \sum_{i=1}^3 \sum_{j=1}^6 \sum_{k=1}^7 A_{ijm} \quad (2)$$

where:

- Z = average annual cropping intensity (%)
 A_{ijm} = decision variables, i.e. planting area in cropping season i in the irrigation district j for crop type m (ha)
 i = cropping season index
 j = irrigation district index; 1: Pandanduri, 2: Swangi, 3: Pelapak, 4: Tundak, 5: Penendem, 6: Pelambik
 m = crop type index: 1: rice, 2: corn, 3: soybeans, 4: chilies, 5: red onions, 6: beans, 7: tobacco

Release target:

$$RT_t = MF_t + \sum_{j=1}^6 WRn_{t-j} \quad (3)$$

where:

- RT_t = release target of period t
 MF_t = flow maintenance of period t
 WRn_{t-j} = net irrigation water requirement of period t in the irrigation district j

Constraint in relation to common area for each cropping season:

$$\sum_{m=1}^7 A_{jm} \leq CA_j \quad (4)$$

where:

- A_{jm} = planting area in the irrigation district j for crop type m (ha)
 CA_j = common area of irrigation district j

Planting area distribution at each irrigation district should have the same specification with existing condition, that is based on planting area ratio for every crop type towards the common area (CA_j). Optimization of irrigation water allocation is performed with the following two scenarios:

- (i) Scenario-1: during cropping season 1, there is no constraint such that cropping intensity for all irrigation districts should be 100%.
- (ii) Scenario-2: during cropping season 1, there is constraint applied, cropping intensity for all irrigation district should be 100%, similar to the achievements of existing cultivation condition (prior to the construction of Pandanduri Dam).

3. RESULTS AND DISCUSSION

3.1 Global Water Balance and Potential Utilization of Return Flow

The calculation of global water balance was performed based on the mean half-month discharge at Suradadi AWLR during 2002 - 2012 as reservoir inflow discharges, where the first cropping season begin in mid-September. Moreover, the calculation is also conducted to the half-month discharge of theoretical water requirement and net water requirement with similar condition of planting area distribution for all crop type every cropping season as in the existing conditions. The annual cumulative volume of reservoir inflow can be known using all three components of global water balance, also for theoretical water requirement and net water requirement. Figure 3 shows the time series graphic of cumulative volume for the three global water balance components.

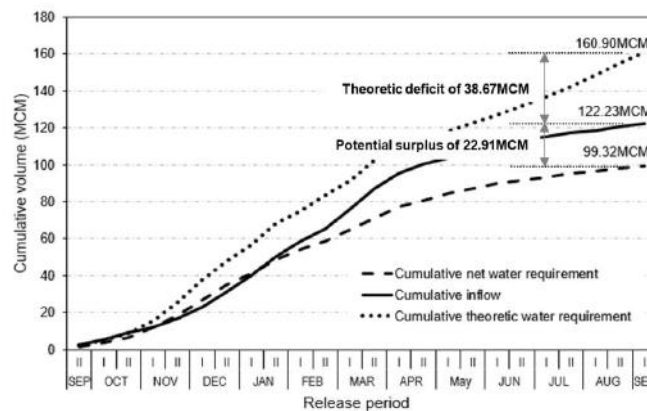


Figure 3. Global water balance assessment with return flow.

The graph in Figure 3 shows that theoretically, the annual total flow of water availability is insufficient for irrigation, which is indicated by cumulative deficit risk of 38.67 MCM. By calculating the return flow, the actual water requirement, that is net water requirement, indicates smaller annual cumulative volume than potential water of Pandanduri Reservoir that has been used so far. The study results of this global water balance show that there is annual surplus of 22.91 MCM; hence, the reservoir release optimization may increase the actual planting area at irrigation systems of Palung and Gambir.

3.2 Performance of Optimization Results Based on Historical Inflow Data

Considering the variability of cropping pattern and cropping schedule in the study area, the calculation of optimum irrigation water allocation for Pandanduri Reservoir using scenario-1 and scenario-2 is simplified as shown in Figure 4. Cropping schedules for all irrigation district in an irrigation system are assumed to be the same, both for irrigation systems of Palung or Gambir.

Optimization results of scenario-1 and scenario-2 for annual cropping intensity is shown in Table 2. It can be observed that optimum water allocation increasing cropping intensity from 211% of the existing condition up to 239.9% for scenario-1 and 254.9% for scenario-2. Despite an increasing annual cropping intensity, the cropping season-1 in scenario-1 has yield a not quite good results because the cropping intensity is only 85%. The difference of cropping intensity for cropping season-3 is not that significant, that is only around 5% (see Table 1). A very

significant increase is achieved during cropping season-2, which is from 51% to 100%.

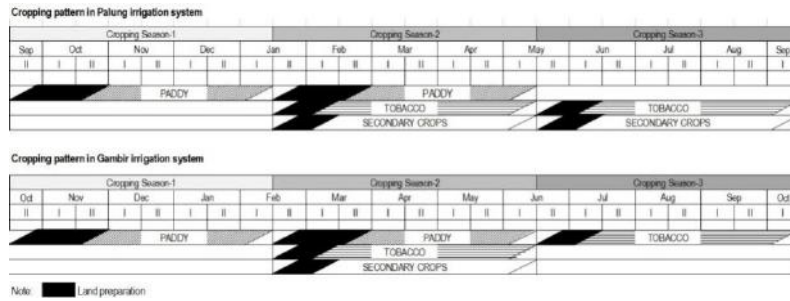


Figure 4. Cropping pattern and planting schedule for optimizing water allocation.

Table 2. Performance of cropping intensity optimization

Cropping season	Cropping intensity	
	Scenario-1	Scenario-2
Cropping season-1	85.0%	100.0%
Cropping season-2	100.0%	100.0%
Cropping season-3	54.9%	54.9%
Annual	239.9%	254.9%

According to analysis of existing condition, the water balance status, with considering the return flow, potentially has a little deficit at the end of cropping season-1, which is around 1.01MCM. However, at the end of cropping season-2, the cumulative inflow volume is bigger than the volume of net water requirement, as there is a potential surplus around 19.5MCM, hence the cropping season-2 can yields 100% cropping intensity based on the optimization results of scenario-1 and scenario-2. The optimization results of scenario-2 show the cropping intensity of 100% in cropping season-1, or it increases by 15%. However, it will decrease performance of the other criteria, i.e. *k* factor and reliability of reservoir operation. Cropping intensity in cropping season-3 for scenario-1 decrease by 5% than the existing condition because this is a dry season where inflow discharge of the reservoir is very small.

Table 3 shows average capacity of irrigation water supply and reliability of reservoir operation for every cropping season and annually as a result of water release optimization with a 10 years historical inflow. A low *k* factor and reliability may cause harvest failure because the water release is insufficient to supply water and this condition may occur in a relatively long period. Optimization as a way to maximize annual cropping intensity give a low value to both criteria optimization of cropping season-1 because rice become the only plantation in the field that needs a highwater requirement. However, during the middle to the end of cropping season-1 is rainy season, therefore the probability of water deficit will be low. The *k* factor and reliability in cropping season-2 and cropping season-3 for both scenario-1 and scenario-2 is considerably satisfying, which is above 0.9. This optimization result still can be considered good to be applied by considering high probability of rain that exceed the land effective rainfall value as basic calculation of high water requirement for rice, which is 80%.

Table 3. Supply capacity and reliability of reservoir operation with historical inflows

Cropping season	<i>k</i> factor		Reliability	
	Scenario-1	Scenario-2	Scenario-1	Scenario-2
Cropping season-1	0.722	0.700	63.8%	57.5%
Cropping season-2	0.959	0.973	93.8%	93.8%
Cropping season-3	0.957	0.941	93.8%	93.8%
Annual average	0.879	0.871	83.8%	81.7%

3.3 Performance of Optimization Result by Using Synthetic Stream Flows

Verification on performance of optimization result for Pandanduri Reservoir operation in the future was carried out with release simulation of irrigation water based on optimum planting area in every cropping season for all type of crops in each irrigation district. A synthetic stream flows of discharge generation data at Suradadi AWLR was used as reservoir inflow for 20 years according to the Thomas and Fiering Seasonal Model method (McMahon, 1986). Recapitulation of the simulation performance was evaluated for cropping scenario-1 and the result is presented in Table 4. Verification of reservoir operation performance with this synthetic stream flows shows similar pattern with historical inflow data, where the *k*factor and reliability during cropping season-1 is lower than the cropping season-2 and cropping season-3. The difference of annual average for *k* factor and reservoir operation reliability is not significant. Therefore, it can be concluded that the irrigation water allocation performance is quite stable.

Table 4. Verification on performance of the optimum irrigation water allocation

Cropping season	<i>k</i> factor	Reliability
Cropping season-1	0.625	51.9%
Cropping season-2	0.921	90.0%
Cropping season-3	0.964	95.6%
Annual average	0.837	79.2%

4. CONCLUSIONS

Return flow in irrigation systems with water supply from Pandanduri Reservoir has been reviewed and the result could be used as the estimation of accurate irrigation water requirements. In this research, the calculation of return flow component is conducted using Tank model, which is applied for the land sub-system and river sub-system to find out the half-monthly return flow discharge. Assessment result of global water balance that includes the availability of extra water potential from return flow in the study area shows annual surplus water of 22.91MCM. In conclusion, there is optimal utilization of water for larger planting area.

Assessment of the performance of irrigation water utilization is not only based on the planting area, but also considering the level of water supply capacity and its continuity throughout the cropping season and it should reach its maximum results. Therefore, this study used *k*factor and reliability criteria of reservoir release arrangement to evaluate the optimization performance of potential water utilization in the Pandanduri Reservoir for irrigation. Two optimization scenarios in relation to the constraint of planting area for rice was applied to the water supply simulation for the 2 irrigation systems, which consist of 6 irrigation districts with a total common area of 7,663ha. Simulation of optimum water allocation through reservoir operation uses 10years historical inflow discharge data and result of synthetic stream flow generation for period of 20 years.

Annual cropping intensity can be improved from 211% to 239.9% with optimization scenario-1, and 254.9% with optimization scenario-2. The annual average value of *k* factor for both scenarios is quite good, that is 0.879 and 0.861. Reliability of reservoir operation for scenario-1 and scenario-2 is respectively 83.8% and 81.7%. This optimization results have been verified by applying the simulation of reservoir operation with synthetic stream flow data. Finally, it can be concluded that the multi criteria optimization results proved to be applied to water management in Pandanduri Reservoir of South Lombok Island.

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