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Optimization of Hydroelectric Reservoir in Indonesia with Dynamic Programming Bellman and "Du Couloir" Iterative Method

(Case Study: Saguling Reservoir – Cascade Citarum)

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Abstract— The increasingly growth of population and industry sector have led to the enhancement demand of electrical energy. One of the electricity providers in the area of Java-Madura-Bali (Jamali-Indonesia) is Saguling Reservoir. Saguling Reservoir is one of the three reservoirs that stem the flow of Citarum River besides Jatiluhur and Cirata Reservoir. The average electricity production of Saguling Reservoir was 2,334,318.138 MWh/year in the period of 1986-2014. This study is devoted to improve the function of Saguling Reservoir in producing electrical energy by optimizing the reservoir management. The determination of the trajectory guideline in Saguling reservoir was divided in dry, normal, and wet years refers to Government Regulation of Indonesia No. 37/2010 on Dam/Reservoir Article 44. Trajectory guideline was conducted based on the electricity price of turbine inflow that various in every month. The determination of the trajectory guideline in various electricity price was done by using Dynamic Programming Bellman (DP Bellman) and "Du Couloir" iterative method which the "Du Couloir" iterative method was development of DP Bellman. "Du Couloir" iterative method can calculate the value of gain with a smaller discretization until 0.1 million m^3 effectively where PD Bellman just can calculate until 10 million m^3 of volume discretization. Correlation value between guideline trajectory and actual trajectory in Saguling reservoir from 1986-2013 was 0.829, this value showed that the smaller discretization can give maximum benefit from electricity production and the trajectory guideline will be closer to trajectory actual then optimization of Saguling operation will be achieved.

Index Terms— Bellman, "Du Couloir" iterative method, volume discretization, reservoir optimization.

1 Introduction

An increased of total population and industry growth in Indonesia increase the demand of population for electrical energy. One of the electricity providers in the area of Java-Madura-Bali (Jamali – Indonesia) is the Saguling Reservoir. Saguling Reservoir is one of reservoirs that stems the flow of Citarum River before Jatiluhur Reservoir and Cirata Reservoir. Saguling Reservoir is 643 m above sea level in altitude with a capacity of 1400 MW. The water intake for Saguling Reservoir is Citarum Upstream Watershed with an area of 2340.88 km².

The optimization of Saguling Reservoir management in this study was deliberate an operational system in the dry years, normal years, and wet years. The determination of trajectory guideline of those years was carried out based on the electricity price for electricity production from turbin which have various values in every month.

Over the past decades, DP Bellman had been used extensively in the optimization of reservoir management. In the discrete form of DP Bellman, storage of each reservoir is discretized into a finite number of levels. By exhaustive enumeration over all possible combinations of discrete levels at each stage for all reservoirs in a system, global optimality can be assured in a discrete sense. However, the well-known ''curse of dimensionality'' limits the application of DP Bellman to multi-state variable problems, as the state space increases exponentially with an increase in the number of state variables. A variety of DP Bellman development, such as incremental dynamic programming (IDP) [Larson, 1968], dynamic programming successive approximations (DPSA) [Larson, 1970], incremental dynamic programming and successive approximations (IDPSA) [Yeh, 1973] and discrete differential dynamic programming (DDDP) [Chow, 1971] have been proposed to alleviate the dimensionality problem.

In this research, the development of DP Bellman that been used was "Du Couloir" Iterative Method which the concept was found by Thirriot, Arwin, EDF-France, 1991 firstly. Reservoir management with Bellman dynamic programming and "Du Couloir" iterative method is an attempt to gain a higher profit from electricity production of Saguling Reservoir, hence, the optimal management of Saguling Reservoir will be achieved in the future.

2 Research Methods

Essential data in this research was discharge inflow from Saguling station. Data was collected from 1986-2013 in every month. Beside that, the other important data was characteristic of Saguling reservoir that will be used as constraints in DP Bellman to determine the trajectory guideline. The characteristic of Saguling reservoir consits of: water level in Saguling reservoir (623-643 meter above sea level); maximum volume in Saguling reservoir which is 609 million m³; and installed turbine capacity in Saguling reservoir (112 m³/s – 224 m³/s for 4 turbines).

2.1 Study Location

This research was conducted in Saguling Reservoir in Upstream Citarum Watershed. Saguling reservoir is a part of kaskade reservoirs in Citarum besides Cirata Reservoir and Jatiluhur resevoir. Coordinat location of Saguling reservoir is 6°56'25"S 107°25'19"E.

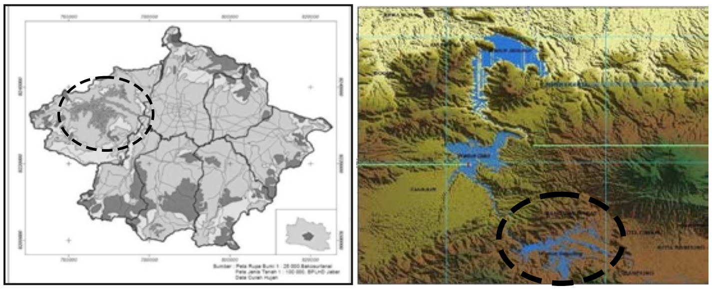


Figure 1. Study Location

2.2 Flowchart of Metodology

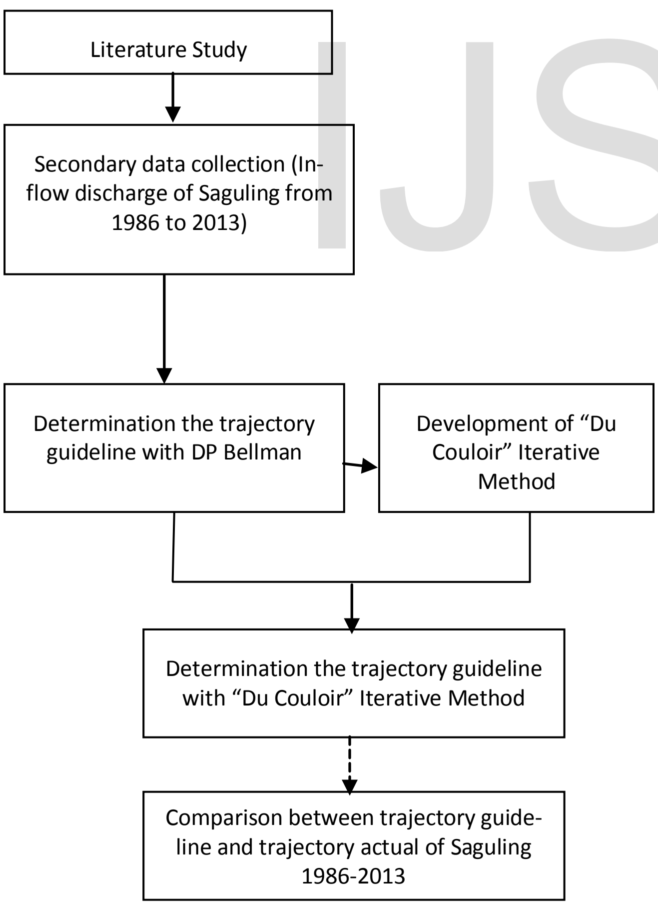


Figure 2. Flowchart of Metodology

The research flow was describe in Figure 2. From data inflow of Saguling reservoir, we can determine the trajectory guideline for Saguling operation in wet, normal, and dry years that will produce the maximum gain from production of electricity. "De Couloir" Iterative Method was done to alleviate the "curse of dimensionality" in DP Bellman.

2.3 Dynamic Programming Bellman (DP Bellman)

Dynamic programming is a form of problem-solving by providing a variety of optimization techniques where decisions are made sequentially or one stage at a time. DP Bellman was marked by the presence of time discretization and volume discretization. The establishment of reservoir management model in the format of dynamic programming was carried out as follows:

1. Determine Volume Discretization

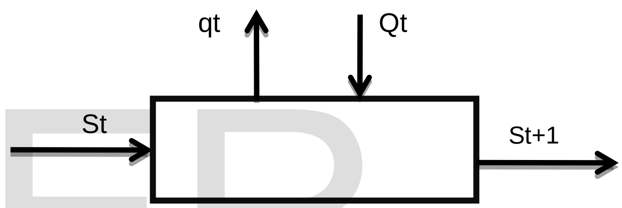
Volume discretization of reservoir in this study included 10; 25; 50; and 100 million m³, it was adjusted to the expected accuracy.

2. Determine The State and Decision Variable

The state variable was the reservoir volume and the decision variable was the turbine discharge.

3. Determine The 'State-Equation'

In this system, the equation of 'mass-balance' of reservoir is the 'state equation'.



St+1 = St + Qt - qt

Figure 3. State Equation of Reservoir

4. Determine The Objective Function

The objective function of the operational system of Saguling Reservoir is to maximize the obtained gain from electricity production multiple by its unit price in every month.

$$G = \sum_{1}^{12} PV_i(t_i, S_i, T_i)\ xNP_i \tag{1}$$

Where:

St = volume reservoir at time (t)
St+1 = volume reservoir at time (t+1)
Qt = inflow discharge in Saguling reservoir
G = gain (unit GWH)
PV = production *valorisess* (GWH)
NP = *niveau de prix* (electricity price)

$$PV = 2{,}725x\ 10^{-3} \times \eta \times qt \times H(t) \tag{2}$$

η = turbine efficiency
= 0.916 x 0.96 = 0.879
q(t) = turbine discharge (million m³)
H(t) = water pressure height (m)

2.4 "Du Couloir" Iterative Method

"Du Couloir" Iterative Method was the development of PD Bellman. Discretization process of "Du Couloir" iterative

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method was commenced by rough discretization of 200 m^3 in a volume to obtain a trajectory of intermediary reservoir volume towards the stable ideal optimal trajectory processus by forming a channel of reservoir volume trajectory that moves synchronically with the bisection discretization processus.

Basically, it is explicated that “Du Couloir” iterative method was the determination of a trajectory processus of stable ideal reservoir volume. Discharge used in dynamic programming study by “Du Couloir” iterative method was the average input discharge of Saguling in wet, normal, and dry years.

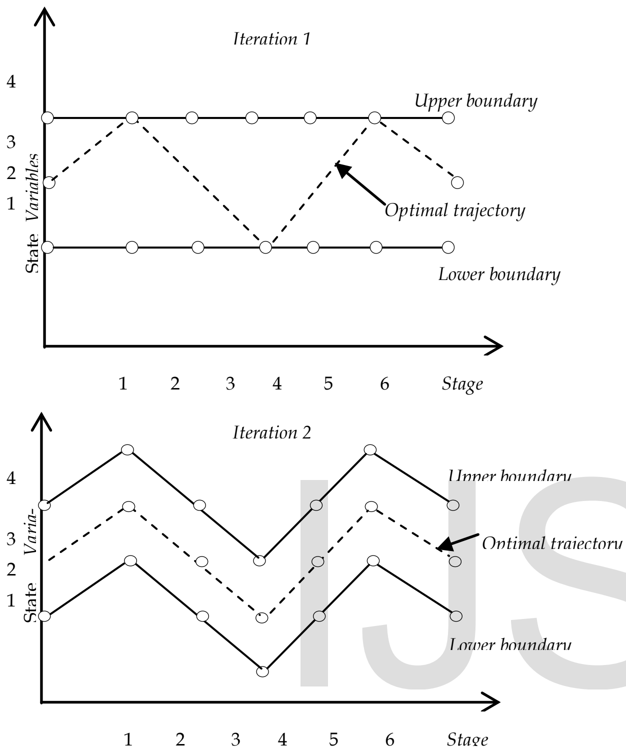


Figure 4. Diagram Concept of “Du Couloir” Iterative Method

3 Result and Discussion

3.1 Effect of Volume Discretization to Gain Value

Volume discretization affects the completion time of each stage of reservoir management based on DP Bellman. In this study, a variety of volume discretization was examined including 100 m^3, 50 m^3, 25 m^3, to 10 million m^3. The management system of Saguling Reservoir with those volumes is presented in Figure 5.

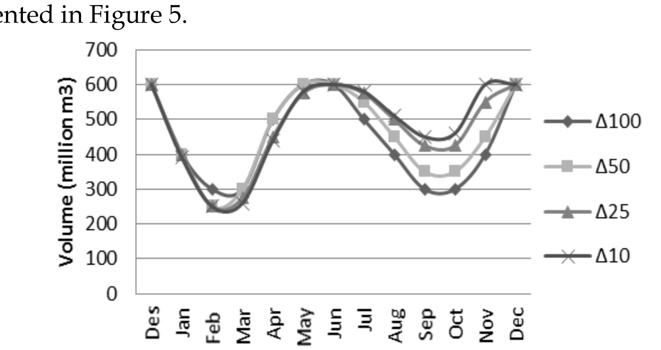
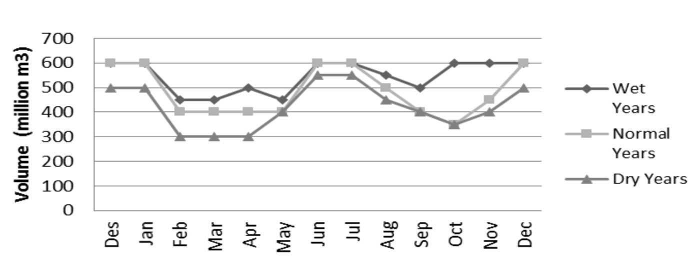


Figure 5. (a) Management system of Saguling Reservoir with diverse volume discretizations, and (b) the gain of each volume discretization.

It can be identified from Figure 5 that the highest gain of operational Saguling was attained by smaller volume discretization with DP Bellman which was 10 million m^3.

3.2 Determination of Trajectory Guideline in Saguling Reservoir by Analyzing the Wet, Normal, and Dry Discharge

Volume discretization producing the maximum gain had been determined, subsequently, the completion of dynamic program with the conditions of wet, normal, dry years was carried out. The detail illustration of the completion and the gain of electricity production that produced for every condition was presented in Figure 6.



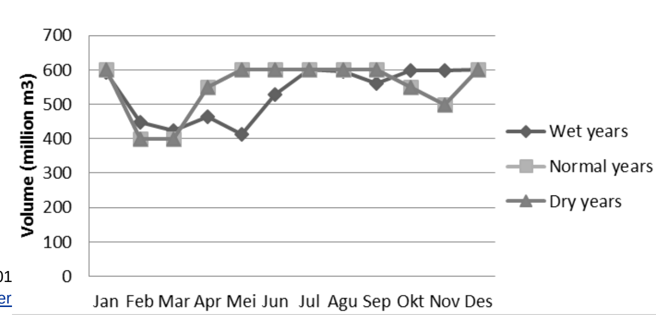
Gain Produced (unit GWH)	
Wet Years	26359
Normal Years	22319
Dry Years	16801

Figure 6. Trajectory Guideline of Saguling in Wet, Normal, and Dry Years with DP Bellman

Figure 6 showed the maximum gain generated by, respectively, the wet, normal, and dry years. The turbine’s maximum performance in the wet years is the main reason of the optimum gain.

3.3 Trajectory Guideline with “Du Couloir” Iterative Method

Benefit from “Du Couloir” Iterative Method usage in this research that we can obtain the trajectory guideline with smaller discretization volume until 0.1 million m^3 so that maximum profit can be achieved along with computional efficiency. Determination of trajectory guideline and gain produced with 0.1 million m3 discretization volume by analyzing the wet, normal, and dry discharge that was done by “Du Couloir” Iterative Method is presented in Figure 7.

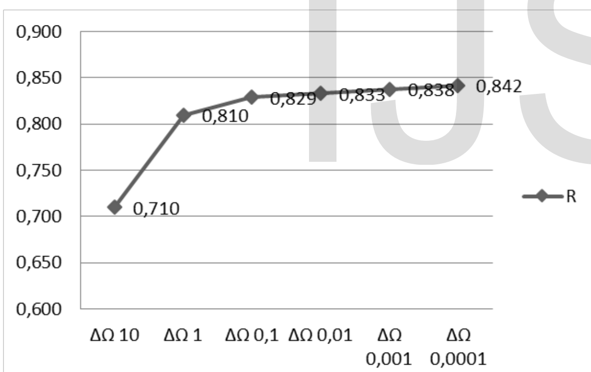


Gain Produced (unit GWH) with discretization of 0.1 million m3	
Wet Years	**26912.65**
Normal Years	**20188.61**
Dry Years	**13186.58**

Figure 7. Trajectory Guideline and Gain Produced of Saguling in Wet, Normal, and Dry years with "Du Couloir" Iterative Method

3.3 Optimization of Saguling Reservoir with Trajectory Guideline from "Du Couloir" Iterative Method

Optimization of reservoirs in this study was performed using trajectory guideline from "Du Couloir" iterative method with various values of discretization volume. Optimization of reservoir would be achieved if the correlation value of trajectory guideline and trajectory actual (R) was closer to one. Based on Figure 8, it can be seen that the increasing of discretization volume did not provide a significant increament to the value of R after discretization volume of 0.1 million m^3. So discretization 0.1 million m3 produced an optimal management in Saguling reservoir.



ΔΩ (million m^3)	**R**
ΔΩ 0.0001	0.842
ΔΩ 0.001	0.838
ΔΩ 0.01	0.833
ΔΩ 0.1	0.829
ΔΩ 1	0.81
ΔΩ 10	0.71

Figure 8. Correlation Value of Trajectory Guideline and Trajectory Actual with Various Discretization Volume

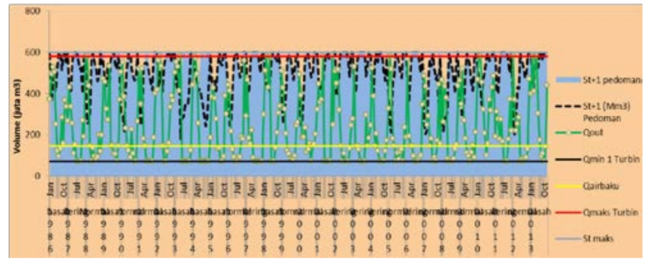


Figure 9. Optimal Management of Saguling Reservoir 1986-2013 with Discretization Volume in Trajectory Guideline as 0.1 million m^3

4 Conclusion

Discretization volume was influenced the gain produced from reservoir operation. Smaller discretization volume that been used, then higher gain value that will produced. This research showed that "Du Couloir" iterative method was capable to solve the discretization problems faster than the conventional DP Bellman. "Du Couloir" iterative method could reach discretization volume until 0.1 million m^3 with efficient computational time. Trajectory guideline in this reserach was conducted for wet, normal, and dry years condition. Gain produced of 0.1 million m3 with "Du Couloir" iterative method in wet years was 26912.65 unit GWH, in normal years was 20188.61 unit GWH, and in dry years was 13186.58 unit GWH. Determinaton of trajectory guideline of Saguling reservoir with smaller discretization volume was important because it can give maximum benefit from electricity production and the trajectory guideline will be closer to trajectory actual so optimization of Saguling operation will be achieved.

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