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MULTI-OBJECTIVE OPTIMIZATIONS OF HYDROELECTRIC EXPLOITATION USING DYNAMIC PROGRAMS IN CITARUM CASCADE RESERVOIRS

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ABSTRACT: Saguling, Cirata, and Jatiluhur are reservoirs built on the Citarum River, in West Java, Indonesia, which have the main function as power plants. It is deemed necessary for Jatiluhur Reservoir to have the right operating pattern to get optimal water management since it is different from other reservoirs. Citarum cascade which has a multi-reservoir operations pattern has a problem because of deviations that occurred on the realization of the trajectory against the planned trajectory guidelines. This happens due to the complex relationship between physical variables and hydrological uncertainty. To overcome this problem the dynamic programming of the Bellman model was used through optimization with forecasts of future discharge. Bellman model is the best approach for non-linear conditions because it can integrate stochastic properties. In addition, to overcome the curse of dimensionality in multi-reservoir operations, the *Du Couloir* iterative method is applied. In optimizing the management of the Citarum cascade reservoirs, a variety of water usage prices per month was used as the economic variable. The results of this research are as follow: a utility function to achieve the goal of maximizing hydroelectric benefits is achieved, the needs of raw water downstream are refilled, and no water will be wasted through spillways. The application of this method to reservoir optimization can overcome dimensional issues with exponentially faster computation times.

Keywords: *Bellman dynamic program, Du Couloir iterative method, Optimization of reservoir management, Multi-reservoir operations, Citarum cascade*

1. INTRODUCTION

Citarum River is one of the strategic drivers in West Java Province, Indonesia. This river flows along 297 km with an average annual flow volume of 5.5 billion m^3. Several reservoirs have been built on this river, namely Saguling, Cirat, a, and Jatiluhur, with each reservoir located at lower elevations receiving water after passing through reservoirs above them.

The main functions of those three reservoirs are used as a power plant that supports future renewable energy with low carbon which must generate 85% electricity by 2050, up from 25% in 2017 [1,2]. Water is a key variable, as its availability affects not only hydroelectric but also other plants that depend on water for some of their processes, such as geothermal, and even carbon capture and storage.

The Citarum cascade reservoirs have other functions, namely flood control, and fulfilling water needs around the reservoir. Specifically, for Jatiluhur, this reservoir is built to meet the water needs of forofkarta (the Capital City of Indonesia) [3]. Therefore, those three reservoirs need a proper operation, so that they can be optimally managed [4-7].

Reservoir management starts from planning and operating, to managing complex variables, such as input discharge, water storage, discharge output, power generation, irrigation, and downstream water requirements. The aim of these is to maximize benefits, minimize costs, and meet various water needs [8]. Optimization technique was developed in reservoir management [5,9] to manage complex variation to eliminate unwanted operating patterns [4], such as the occurrence of deviations from the realization of the trajectory against the planned trajectory guidelines which should function to manage water level elevation, output discharge and operating time [10,11]. This happens because the operation of the reservoir cannot predict the year of the season, due to hydrological uncertainty [12].

Discharge is a hydrological component as a random variable and is stochastic [12,13] so the proper operation of the reservoir requires a hydrological approach with forecasts of future discharge. There are several methodological approaches to completing the optimization of reservoir management, including linear, non-linear, and dynamic programs [14]. Reservoir operation problems occur due to the complex relationship between physical variables and hydrological uncertainty. Non-linear problems and stochastic variables can be easily solved by dynamic programs [8] in which the usage is limited by the curse of dimensionality for multi-reservoir operations

[15,16].

Dynamic programming using the Bellman model is the best solution for non-linear conditions [17]. Bellman model is an optimization technique in solving the decision process through stages [8] and it is used extensively in reservoir optimization [18-21]. This happens because the Bellman method has the convenience of incorporating stochastic properties [22]. Furthermore, to reduce hydrological uncertainty, an accurate flow analysis, which is closest to the real situation, has been carried out. This is done by rationalizing fluctuations in the discharge data to reduce data randomness using the cumulative moving average calculation technique, which is believed as the most suitable model with a minimum residual value [23]. Meanwhile, to overcome the curse of dimensionality in the Bellman model, a special algorithm has been developed, including *Du Couloir* iterative method [24,25].

2. SIGNIFICANCE OF THE STUDY

Based on issues that have been observed in the operation of the Citarum cascade reservoirs, the significance of the study is the use of a hydrological approach in water resource development by calculating future flow forecasts with the Markov discrete model. Another proposed solution is to implement the "one river, one management" concept in the Citarum reservoir cascade. This would simplify the conceptual method of the hydrological regime in the Citarum reservoir cascade, making the input to any reservoir the sum of the output of the reservoir immediately upstream and local flows.

3. METHOD

3.1 Principle of Reservoir Operation

The key principle in the operation of a reservoir is conservation of mass, whereby the amount of water stored (S) at the beginning of the next month (t+1) equals the storage (S) at the beginning of the current month (t), plus the number of inflows (Q_{in}) over the month (t) and less the outflows (Q_{out}) over the month (t) [8,26-35], mathematically expressed in the following "eq. (1)":

$$S_{(t+1)} = S_{(t)} + Q_{in\,(t)} - Q_{out\,(t)} \tag{1}$$

The operation of a reservoir requires a defined objective such as to maximize hydroelectric power generation (P_i) over a given period (Δt) within certain time intervals (n), expressed in the following "eq. (2)":

$$f_1 = max\ \frac{1}{n} \sum_{t=1}^{t=N} P_i\ .\ \Delta t \tag{2}$$

to maximize the fulfillment of water requirements in downstream regions (Q_{Rt}) over a given span of time (Δt), expressed in the following "eq. (3)":

$$f_2 = \max\ \frac{1}{n} \sum_{t=1}^{t=N} Q_{Rt}\ .\ \Delta t \tag{3}$$

and to minimize outflows (Q_{xt}) through the spillway over a given period (t) [11], expressed in the following "eq. (4)":

$$f_3 = min \frac{Q_{xt} \leq Q_{max}}{N} \tag{4}$$

It is also necessary to determine a set of constraining functions for reservoir operations, such as:

- Storage capacity of the reservoir ($0 \leq S_t \leq S_{max}$);
- Water surface elevation limits ($H_{min} \leq H_t \leq H_{max}$);
- Turbine capacity limits ($T_{min} \leq T_t \leq T_{max}$); and
- Downstream water demands.

3.2 Benefit Equations and Water Price Variation

The Bellman dynamic model is used to determine the evolution of the reservoir's volume (Ω) over time (t) along an optimum Bellman trajectory with a certain amount of input flow (an at t = 0) and output flow (q at t = N). This method allows the discretization of volume (ΔΩ) and time (Δt) by defining the volume-over-time Ω(t) as Ω(0) to Ω(N). Reservoir volume as a function of time Ω(t) is an unknown function, so it is assumed that the reservoir volume (Ω) at the beginning of the next period (t+1) is the same as at the beginning of the current period (t), while the evolution of periodic flows can be expressed as Ω(t+1) = Ω(t), where Ω(t) should be adjusted to obtain the maximum benefits.

As long as the reservoir is not empty or filled, water flows in and out of the reservoir [17] can be expressed in the following "eq. (5)":

$$q(t) = a(t) - \frac{d\Omega}{dt} \tag{5}$$

This inflow value affects the utility function c(t) that in turn can affect the constant price c(0) and variable price, as expressed in the term Δc(t) = c(t) – c(0), to calculate the benefit (B) by the following "eq. (6)":

$$B\ \int_0^T q(t)\ .\ c(t)\ .dt \tag{6}$$

with the state function Ω(t) defined as above, the maximum benefit [24] can be calculated by the following "eq. (7)":

$$B_{max} = \int \Omega(t)\ .\ \frac{dc}{dt}(t)\ .dt \tag{7}$$

In maximizing the hydroelectric benefit, economic variables must be applied to the water inflow into the reservoir [24,36]. Theoretically speaking, the input flows a(t) is sinusoidally modulated by the seasons over the year by the following "eq. (8)":

$$a(t) = a_0\,[1 + \alpha \sin(2\pi t + \theta)] \quad (8)$$

while the price of water as a utility function also varies sinusoidally over the year, as in the following "eq. (9)":

$$c(t) = c_0\,[1 + \gamma \sin(2\pi t + \phi)] \quad (9)$$

so that the water storage (S) needs to be regulated according to the reservoir's capacity [24]. The price of water (*niveau de Prix*) as an economic instrument has been academically proposed with modifications by *Electricite de France* (EDF) that incorporate monthly variations [NP = F(t)] [17,24], as seen in Fig. 1.

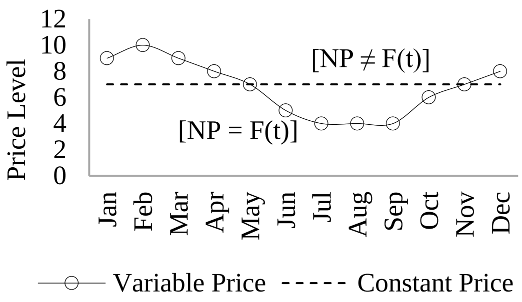

Fig 1. Academic Variations in Water Prices as an Economic Instrument

3.3 The *Du Couloir* Iterative Method

The Bellman dynamic model has limitations in dealing with very small values of discretized volume ($\Delta\Omega$), in which case it may be impossible to perform calculations to reach the desired volume. One way to mitigate this is the use of an approximation technique to reduce the dimensional and computation time issues with the *Du Couloir* iterative method. This technique is a procedure to lighten the computation load through a dichotomous discretization process [24].

The principle behind the *Du Couloir* iterative method is to take the solutions obtained from the discretization step ($\Delta\Omega^k$) and carry on the discretization into smaller values in a further step ($\Delta\Omega^{k+1}$) within the subdomain (Ω,t) where (k) is the notation for individual steps. The technique used in this method is to get around the trace of the solution obtained in the step ($\Omega_i^{(k)}$, t_i), by extending the subdomain in two steps $\Delta\Omega^{(k)}$ on both sides and cutting down the subdomain by one step $\Delta\Omega^{(k+1)}$ [24], which can be expressed as follows given (n) as a notation for the interval (t) by the following "eq. (10)":

$$\Delta\Omega^{(k+1)} = \frac{\Delta\Omega^{(k)}}{n^{(k+1)}} \quad (10)$$

as such, the single-step discretization in this method can be expressed in the following "eq. (11)":

$$\Delta\Omega^{(k+1)} = \frac{1}{4}\,\Delta\Omega^{(k)} \quad (11)$$

with a maximum width of $4.\Delta\Omega^{(k)}$.

3.4 Dichotomic Processes

The dichotomic process is applied to the volumetric steps ($\Delta\Omega_k$), with a numerical expression within a binary system that allows a significant reduction in computation time and produces an extrapolation that permits an ideal approximation. A dichotomic process allows a reduction in the number of time steps (Δt) and volumetric steps ($\Delta\Omega$), thus allowing the production of a sustainable solution economically [24].

The following dichotomic processes [24] can be applied to multi-reservoir operations on the Citarum cascade:

- simple dichotomic, which constitutes splitting the volume state (Ω) into 2 stages, such as $\Delta\Omega$ 10 and $\Delta\Omega$ 1 million m^3.
- pure dichotomic, where the volume state (Ω) is split out sequentially as such: $\Delta\Omega$ 200, $\Delta\Omega$ 100, $\Delta\Omega$ 50, $\Delta\Omega$ 25, $\Delta\Omega$ 25/2, $\Delta\Omega$ 25/4, $\Delta\Omega$ 25/8, $\Delta\Omega$ 25/16, $\Delta\Omega$ 25/32 million m^3; and
- hybrid dichotomic, where the volume state (Ω) is split out sequentially with a hybrid process, with the following result: $\Delta\Omega$ 200, $\Delta\Omega$ 100, $\Delta\Omega$ 50, $\Delta\Omega$ 25, $\Delta\Omega$ 10, $\Delta\Omega$ 5, $\Delta\Omega$ 2, and $\Delta\Omega$ 1 million m^3.

3.5 Optimum solution

The Bellman optimization principle states that every step ($\Delta\Omega^k$) along the optimal trajectory is an optimum value in its own right [17]. The optimum value is stationary, so the optimum locus can be determined by interpolating and assimilating the F($\Delta\Omega^k$) curve like a parabola around the optimum value. Therefore, with the application of the *Du Couloir* iterative method, it can be hypothesized that the optimum solutions would lie within the corridor [24] as follows $\Omega^{(k)} \pm \Delta\Omega^{(k)}$.

4. RESULTS AND DISCUSSION

4.1 Gap in Prior Studies

Other researchers have conducted prior studies on water resources along with the Citarum cascade reservoirs, including the modeling of water resources and energetic exploitation in the upper Citarum watershed with the Bellman dynamic model on a single reservoir [24]. There has also been a reliability analysis of the optimum operation of the Citarum cascade reservoirs to fulfill water demands, using a chance-constrained linear program on multiple reservoirs [37]. Another studied the integrated management of water resources in the Saguling reservoir in the interest of developing a potable water supply system, applying the mass-balance method to a single reservoir [26]. Yet another studied the commercial utilization of the Citarum cascade reservoirs for water supply development under a deterministic model with the mass-balance method, and the commercial optimization of the reservoirs with continuous and discrete Markov methods on multiple reservoirs [3]. Finally, there was a study on optimizing the hydroelectric exploitation of the Saguling reservoir under a fluctuating price regime for electrical power, using the Bellman dynamic model with the *Du Couloir* iterative method on a single reservoir [25].

To conclude, there is still a gap that has not been covered by previous studies. The gap is about the study of how to optimize the water demands in multi-reservoir cascades such as in Saguling, Cirata, and Jatiluhur. Our research explains the optimization of the water demand using water price as an economic instrument of a fluctuating utility function using the Bellman dynamic model with the *Du Coulouir* iterative method which has never been used in a previous study. Our research also uses the constraining functions as the effective reservoir volume, turbine capacity, and downstream water demand (R5). In addition, the use of variations in water price air (*niveau de prix*) is based on an academic proposal with modifications by the *Electricite de France* (EDF) with monthly variations [NP = F(t)] according to the economic situation in Indonesia as a result of cosmic factors and electrical power demands [24].

4.2 Effects of Volume and Time Discretization

The discretization of volume ($\Delta\Omega$) and time (Δt) is bound to the inflow value (Δa) as (a-q) Δt, with ($\Delta\Omega$) as a fraction of (a) over the duration (Δt), which is expressed as $\Delta\Omega = \Delta a.\ \Delta t$. Discretization of volume ($\Delta\Omega$) would determine the amount of water resulting in benefits. The smaller $\Delta\Omega$ over time (Δt), the smaller would the benefit as an economic function also be. Conversely, a larger $\Delta\Omega$ would cause a harmonization evolution in the optimal trajectory.

Meanwhile, the discretization of time (Δt) would determine the number of steps and the size of flows (Δa), and the amount of computation time needed to find a solution. The smaller Δt, the more steps there would be to solve, and the flow value (Δa) used as an input for each stage would also be smaller. Thus, calling for a longer computation time, but conversely, it would accelerate the balancing process in volumetric evolution ($\Delta\Omega$) towards stationary stability along the optimum trajectory.

In this way, smaller granularity in the discretization of volume ($\Delta\Omega$) and time (Δt) has produced greater benefits in the Citarum cascade reservoirs, although the effect is very weak for $\Delta\Omega$ < 50 million m^3 in previous studies [17,24].

4.3 Performance of the *Du Couloir* Iterative Method

The optimization calculations for the multi-reservoir operations along the Citarum cascade were made with the discretization of time (Δt) into one-month chunks and volume ($\Delta\Omega$) in a hybrid dichotomic manner as follows: Ω 200; $\Delta\Omega$ 100; $\Delta\Omega$ 50; $\Delta\Omega$ 25; $\Delta\Omega$ 10; $\Delta\Omega$ 5; $\Delta\Omega$ 2,5; $\Delta\Omega$ 1; $\Delta\Omega$ 0.5; $\Delta\Omega$ 0.25; $\Delta\Omega$ 0.1; $\Delta\Omega$ 0.01; $\Delta\Omega$ 0.001; and $\Delta\Omega$ 0.0001 million m^3. The results of optimization for multi-reservoir operations on the Citarum cascade under normal flow conditions, using the *Du Couloir* iterative method, have been shown to produce greater benefits compared to the Bellman model as seen in Table 1.

Table. 1. Comparison of Benefits Between the Bellman Models and The *Du Couloir* Iterative Methods

	Benefit (GWh unit prices)		
	Saguling	Cirata	Jatiluhur
The Bellman Models	31,313.38	8,037.72	4,676.00
The *Du Couloir* Iterative Methods	31,353.11	8,038.86	4,676.20

This happens because the usage of the Bellman model is limited by the curse of dimensionality for multi-reservoir operations, so the reservoir optimization could be solved until $\Delta\Omega$ 0.5 million m^3. The application of the *Du Couloir* iterative method to reservoir optimization can overcome dimensional issues, and the discretization of volume ($\Delta\Omega$) will be able to reach optimal trajectory solutions up to 0.0001 million m^3.

By applying the *Du Couloir* iterative method, the objective of maximizing hydroelectric benefits can be achieved, although the improvement is weak for $\Delta\Omega$ < 10 million m^3. This is visible in the correlation value (r) between the realized trajectory (actual S_{t+1}) and the planned guideline trajectory, as seen in Table 2. Thus, the guideline trajectory planned out with the *Du Couloir* iterative method comes closer to the actual conditions as shown in Fig. 2, Fig. 3, and Fig. 4.

Table 2. Correlation Value (r) Between the Realization of The Trajectory (S_{t+1}) and Guideline Trajectory According to The Bellman Models and The *Du Couloir* Iterative Methods

Reservoir	Correlation value (r)	
	The Bellman Models	The *Du Couloir* Iterative Methods
Saguling	0.791	0.792
Cirata	0.863	0.864
Jatiluhur	0.632	0.633

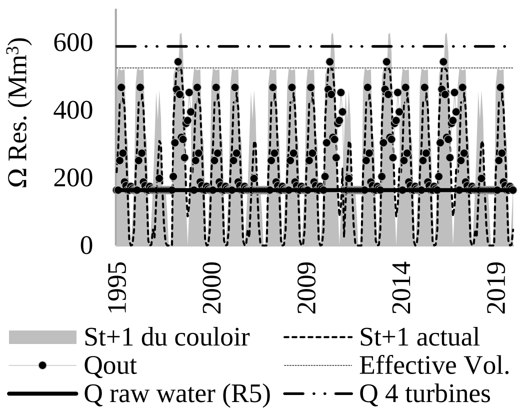

Fig 2. Optimization of the Saguling Reservoir Changed Utility Function

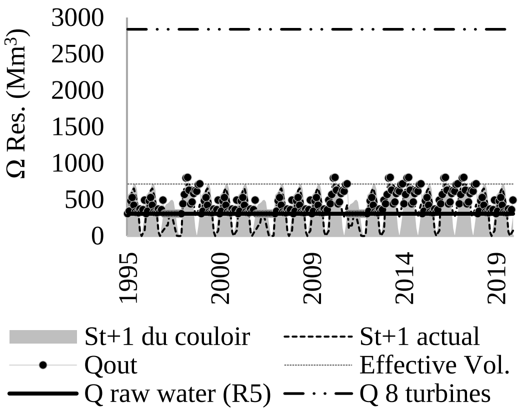

Fig 3. Optimization of the Cirata Reservoir Changed Utility Function

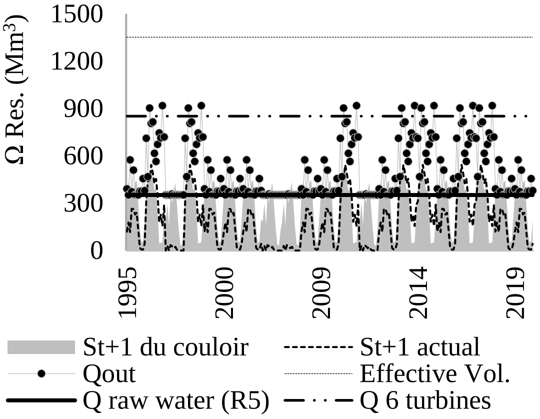

Fig 4. Optimization of the Jatiluhur Reservoir Changed Utility Function

In Fig. 2 and Fig. 4, the optimized management in the Saguling and Jatiluhur reservoirs made it possible to utilize the entire inflow to power the full 4-turbine and 6-turbine capacities without exceeding the reservoirs' effective volumes. Meanwhile, Fig. 3 shows that the Cirata reservoir would have to take an inflow volume that exceeds the reservoir's effective capacity to operate 3 out of the 8 available turbines. The results of this optimization achieved the objective of avoiding any water discharge through the spillways in any of the three reservoirs. In addition, the objective of meeting raw water needs downstream can also be achieved, which is the availability of drinking water discharge (R20) of 81.43 m^3/second for Jakarta's raw water needs of 31.87 m^3/second in 2030.

4.4 Computation Times

Calculations with the Bellman model could be performed down to the discretization of volume ($\Delta\Omega$) 0.5 million m^3, with a computation time of 106,007.205 seconds, constrained by the curse of dimensionality in multi-reservoir operations. Indeed, previous studies ran into an even higher limit at $\Delta\Omega$ 10 million m^3 [17,24]. On the other hand, calculations under the *Du Couloir* iterative method could reach the discretization of volume ($\Delta\Omega$) 0.0001 million m^3, which met the desired volumetric goal with a computation time of 67.995 seconds in finding an optimum trajectory solution for $\Delta\Omega$ of 0.5 million m^3 as shown in Fig. 5.

The application of this method to reservoir optimization can overcome dimensional issues with exponentially faster computation times as shown in Fig. 6.

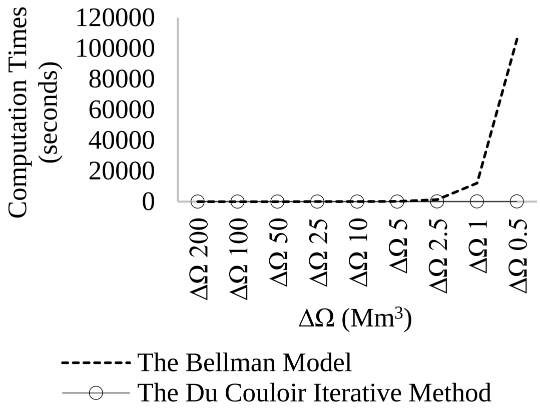

Fig. 5. Comparison of Computation Times between the Bellman Model and the *Du Couloir* Iterative Method

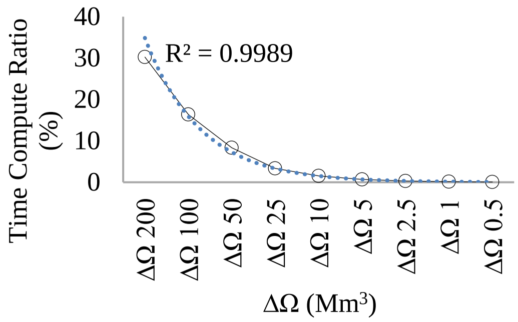

Fig. 6. Time Compute Ratio (Computation Times the *Du Couloir* Iterative Method Divided by The Bellman Model)

5. CONCLUSION

The problems of non-linearity and stochastic variables in reservoir operation due to the complex relationship between physical variables and hydrological uncertainty could be easily solved using dynamic programming of the Bellman model until ΔΩ 0.5 million m^3, while the application of the *Du Couloir* iterative method was able to overcome the curse of dimensionality and reached up to ΔΩ 0.0001 million m^3 according to the desired volume.

The smaller discretization of volume (ΔΩ) and time (Δt) has resulted in increased benefits, although the result is still very weak approximately for ΔΩ < 10 million m^3, with exponentially much faster computational times in the application of *Du Couloir's* iterative method. The water usage prices as a utility function that vary every month used as economic variables can optimize the management of the Citarum cascade reservoirs. By using this process, the objective of maximizing hydroelectric benefits, meeting raw water needs downstream and making sure that no water is wasted through spillways can be achieved.

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