The Validation of Linear Method in Cascade Reservoir System for Prediction of Energy Production

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Abstract*—this paper discusses the validation of a stochastic model of Thomas and Fearing that applied to energy prediction of three large scale reservoir in west java. They are Saguling Cirata, and Jatiluhur. The Saguling produces 700MW, Cirata produces 500 MW, and Jatiluhur produces 150MW of electricity energy. The method is applied the stochastic model to prediction supply, demand, and energy production for 2000-2005. The primer used the historical data inflow from 1988-2000. The result of the calculation is then compared to the real measurement on 2000-2005. Conclusion of this paper is the average increase number of monthly demand for next year as much as 4.47%. By increasing the number of demand, the need is still fulfilled. The average energy of those reservoirs between 2001 and 2005 is 4,952 GWH, while real energy is 4,638 GWH. The initial period of operation that fulfills optimal requirement is in April because it can fulfill the objective function and its obstacles. There is the increasing number of demand for irrigation need, industry and drinking water and it should become a priority, the movement of reforestation or the maintenance of Drainage Basin of Citarum River in upstream or downstream has to be carried out continuously, so the inflow of each reservoir can be fulfilled.

Keywords—Optimization, Multi-reservoir Operation, Purpose Function, Prediction

I. INTRODUCTION

Operating reservoir involves various capacities of storage that are divided into some parts based on the function having planned in reservoir operation. The type of reservoir operation implicates some regulations that influence decision making, including storage capacity and water outflow management with various purposes.

They are operating multi-reservoir with multi-purpose needs to pay attention to the importance and function of each reservoir [1]. One objective function probably used is to maximize the electrical energy with the required water release from the downstream reservoir must be higher than or same as required constraints. Besides, the multi-reservoir operation should pay attention to the required constraints and constraints that fulfill many interests. In general, the followings are some constraints that are often used in operating the multi-reservoir system:

1. Final water level ≥ Initial water level.
2. The final water level of each reservoir ≤ Maximum operating water level.
3. The final water level of each reservoir ≥ Minimum operating water level.

Water release from multi-purpose reservoir ≥ Irrigation needs.Related to operation optimization of reservoirs in a Journal entitled; "Optimal crop plans for a multi-reservoir system having intra-basin water transfer using multi-objective evolutionary algorithms coupled with Chao" as follows a surface water reservoir serves multiple purposes such as irrigation, hydropower generation, industrial and domestic water supply, flood control, navigation, recreation, etc. Among these purposes, irrigation is most significant in India since irrigated agriculture is the largest consumer of water.

A. Rule Curves and Water Control Diagrams

The terms *rule curve* and *guide curve* are typically used to denote operating rules which define ideal or target storage levels and provide a mechanism for release rules to be specified as a function of storage containers. Rule curves are typically expressed as water surface elevation or storage volume versus time of the year [2].

B. Hydroelectric Power

Hydroelectric power is typically used for peak load, while thermal plants supply the baseload. Hydroelectric power plants can assume load rapidly and are very efficient for meeting peak-demand power needs. In some regions, hydroelectric power is a primary source of electricity, supplying much or most of the baseload as well as the peak load.

C. Linear Programming Format

Linear programming consists of finding values for a set of n decision variables ($x_1, x_2, \ldots, x_n$) that minimize or maximize an objective or criterion function x_0 of the form. Constants are given by a_{ij}, b_i, and c_j are constants. The linear

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programming model is expressed is more concise notation as minimize (or maximize).

$$x_0 = \sum_{j=1}^{n} c_j x_j \tag{1}$$

$$\text{Subject to } \sum_{j=1}^{n} a_{ij} x_j \le b_i \; for\; i = 1, 2, ..., m$$

and $x_j \ge 0 \; for\; j = 1, 2, ..., m$

where x_0 is the objective function, x_j are the decision variables. c_j, a_{ij}, and b_i are constants, n is the number of decision variables, and m is the number of constraints. The less than or equal sign in the constraint inequalities may be replaced by a greater than or equal sign to suit the particular problem being modeled. Maximizing $-x_0$ is equivalent to minimizing x_0. The objective function and all constraints are a linear function or the decision variables. A set of values for the and variables is called a decision policy [3].

D. Stochastic Model

In statistics, the word of stochastic has a similar meaning with random. In hydrology, stochastic is particularly used in a time series in which some of them are random. In deterministic hydrology, a variable of time is important. Formulation of a model for monthly storage is developed by Thomas and Fearing, as follows [4].

$$q_{i,j} = \bar{q_j} + b_j(q_{i-1,j-1} - \bar{q_{j-1}}) + t_{i,j} \cdot S_j \cdot \sqrt{(1-r_j^2)} \tag{2}$$

where I is month in sequence, j = month in a year, j from January to December, $q_{i,j}$ is stored in the first month, j month in that year, $q_{i-1,j-1}$ is storage of previous month j, $\bar{q_j}$ is storage in month *'j'* (average of month j (12 months are measured), b_j is regression coefficient from storage of months j and j-1 *is* r_j. s_j/s_{j-1}, (12 months are measured), and r_j is correlation coefficient between storage of months j and j-1 (12 months are measured), S_j is deviation standard of month j (12 months are measured), $t_{i,j}$ is random variate, with an average of 0 and variant of 1.

In 1998, reservoir operation system was used for multi-reservoir operation pattern planning with an objective function to maximize the energy. There is a difference between the plan and its realization [5]. The prediction of monthly reservoir inflow is inappropriate with its realization. In consequence, there is a need to evaluate the pattern used to maintain the operation, including the initial water level and final water level, inflow and outflow, and electricity production [6].

Mathematic Model and Water Flow Pattern in Multi-purpose Reservoir. The formula is [7]:

$$V_{ij} = V_{Sij-1} + I_{ij} - Q_{ij} - Q_{ij} - O - E_{vpij-1} - I_{spilij} \tag{3}$$

Where, i is the reservoir index, j is the time index, S is reservoir index, I is inflow, O is water flow for irrigation, Q is outflow for powering turbine, E_{vpij} is water loss due to evaporation, I_{spilij} is water release through spillway [8].

II. Method and Material

In Citarum River, it successively spreads out three reservoirs from upstream to downstream, namely Saguling with a maximum capacity of 889 x 10^6 m^3, Cirata (1,976 x 10^6 m^3), and Jatiluhur (2,458 x 10^6 m^3). The main function of Saguling and Cirata reservoirs is as hydroelectric power with each capacity of 700 MW (4x175 MW), 1000 MW (6x175 MW). Besides, Jatiluhur reservoir (6x30 MW) also provides irrigation water need for farmland of 260,000 ha, raw water for PAM Jaya and Industries.

Fig.1 is a historical data inflow of the Saguling, Cirata, and Jatiluhur reservoir measured from 1988-2000. This historical data is then analysed using the stochastic model from Thomas and Fearing, as in equation (1). The analysis result is a projection of Saguling, Cirata, and Jatiluhur reservoir inflow data for 2001-2005. Then the projection results are then compared with 2001-2005 field measurement data that has been provided from the Research and Development of Water Resources (Puslitbang Air) Bandung.

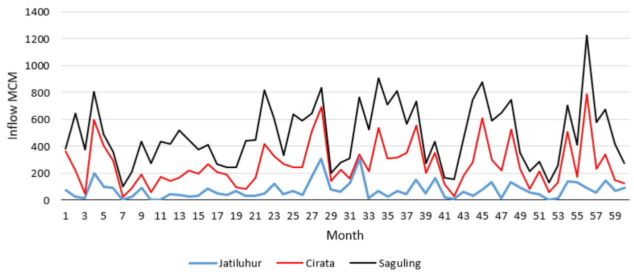

Fig.1. The historical data inflow of the Saguling, Cirata, and Jatiluhur reservoir measured from 1988-2000.

The comparison results are then validated by Thomas and Fearing's Stochastic Model accuracy. If the results of the comparison of projections resemble the field measurements, it can be said that the Thomas and Fearing model is valid for the inflow character in the Saguling, Cirata, and Jatiluhur reservoirs.

In Jatiluhur Reservoir, there are six units of the turbine with the installed power of 187 MW and average electrical energy of 1,000 million kWh/month. Additionally, Jatiluhur Reservoir provides irrigation water for rice fields of 260,000 ha (twice planting period in a year), raw water, drinking water, fishery cultivation, flood control. Due to its vital function, water flowed from the Jatiluhur Reservoir must be higher than or the same as irrigation water needs.

This study aims to conduct an optimization with an operational simulation of multi-reservoir regarding monthly inflow in five years in Saguling, Cirata, and Jatiluhur Reservoirs. This optimization intends to maximize the energy of each reservoir. The flow chart is shown in Fig.2 and the reservoir arrangement is shown in Fig.3.

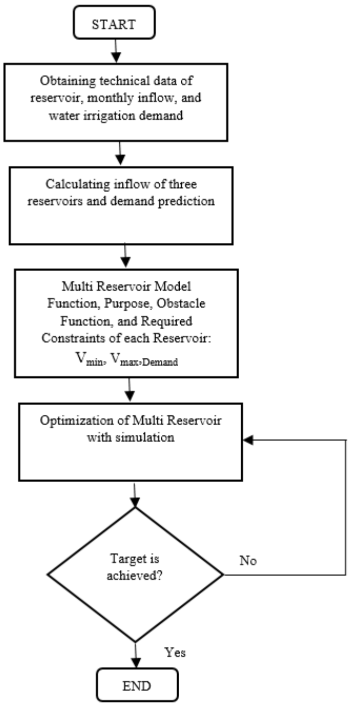

Fig. 2. Research flow chart

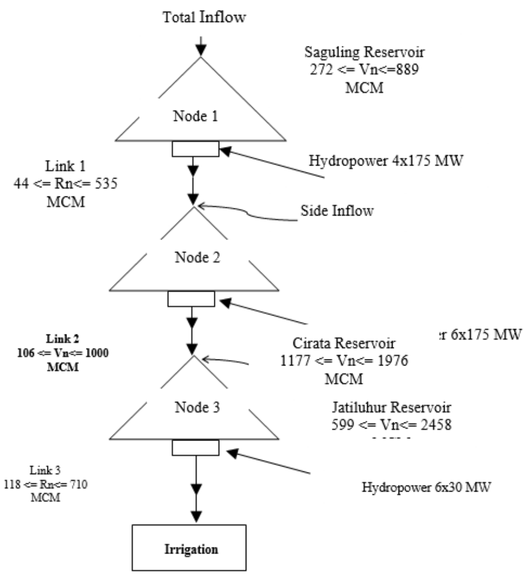

Fig. 3. Reservoir model

Constraints:

$$V_{ij,\min} \leq V_{ij+1} \leq V_{\max} \tag{4}$$

$$I_{2j} = VG_{ij} + S_{ij} - \Delta_{ij} \tag{5}$$

$$E_{ij} = a_{ij} \cdot A_{n,\text{average}} \tag{6}$$

The following asumptions apply:

- $V_{i13} = V_i = V_{i\max}$ means that target is achieved
- $V_{i13} > V_{i\max}$ means that target is achieved and able to be raised
- $V_{i1} < V_{i3}$ or $V_{ij+1} < V_{i\min}$ means that target is failed
- $V_{ij+1} \geq V_{i\max}$ means overflowing
- $S_{ij+1} = V_{ij+1} - V_{i\max}$ means overflow

where E_{ij} is the monthly evaporation of each reservoir. W_i is Water volume of each reservoir, P_{ij} is Electrical Power of each reservoir, f_{ij} is Overflow of each reservoir, V_{ij} is storage of each reservoir, I_{ij} is Inflow of each reservoir, S_{ij} is Irrigation Needs, G_{ij} isTurbine Needs. See Fig.4.

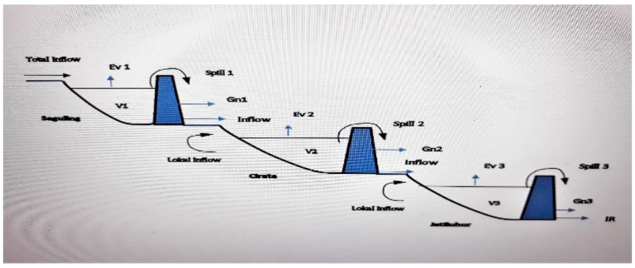

Fig. 4. A balance model of a multi-reservoir system.

III. Result and Discussion

Generating data from the three reservoirs have similarities with data resulted by observation from 2001 - 2005 while the results of optimization with simulation as boundary condition with priority scale, energy and Irrigation demand can be met as shown in the table and graph, which one :

Inflow data of each hydroelectric power is used as an input for optimization with simulation. This section is a trial period of the initial operation.

The initial period of operation for Cascade Reservoir is in April. Water irrigation needs or demand based on the result of prediction with linear regression between 2001 and 2005 indicates that Demand Projection increases with the average number of 4.47%.

The result of optimization with simulation obtains the average number of monthly power, high flow of each link, release, downstream release, monthly storage of reservoir, spill, and supply for the demand.

If the storage of each reservoir in a certain month is lower than the minimum water level, it seems that the reservoir will be unstable. Consequently, to make the operation of each reservoir in a year in a balanced state, the storage of each reservoir at the end of operation has to become in a similar condition by decreasing target of energy. The decreasing of the target of energy deals with the decreasing capacity of a link or changing the beginning period of operation.

The optimization with simulation between 2001 to 2005, in which April become the beginning period of operation, reveals an optimal result and become target output of energy that is appropriate with demand constraint given. This implies that from April 2001 to April 2005, those reservoirs can be maintained well. April is still in the rainy season, so the storage of the reservoir is in full condition.

The management of multi-reservoir system for flood control is applied considering a high rainfall. For example, in Java island from January to April or even to June, July or August, rainfall is in high intensity. Hence, a huge flood will happen around those months.

One function of Saguling, Cirata, and Jatiluhur reservoirs are to control flood. For example, if flood level being controlled is twice minimum water level of the reservoir, storage of each reservoir at the moment of the flood is below:

1. Saguling: $V \leq V_{max} - 2\ V_{min}$

$= 889 - 2(272) = 345$ MCM.

2. Cirata : $V \leq V_{max}$

$= 1976 - (1976 - 1177)$ 1576,5 MCM.

3. Jatiluhur : $V \leq V_{max} - 2V_{min}$

$= 2458 - 2\ (599) = 1260$ MCM.

Fig.5 shows the prediction results of Cubic Milion Inflow Meter (MCM) in 2001-2005, for each Saguling, Cirata, and Jatiluhur inflow reservoir, using the stochastic method from Thomas and Fiering model as in equation (1). Calculation is done by using the normal distribution. From the prediction results, the average inflow values obtained in the predicted year are 222 MCM for Saguling Reservoir, 190 MCM for Cirata, and 73 MCM for Jatiluhur Reservoir.

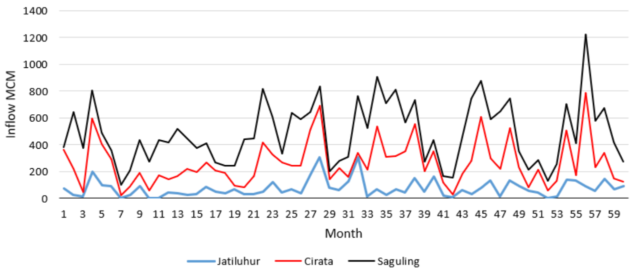

Fig 5. Inflow prediction Saguling, Cirata, and Jatiluhur 1988-2000

Fig.6 is the measured real data, obtained from the head office of the research and development of water resources (Puslitbang Air) Bandung. From the results of monthly measurements on the three reservoirs, the average inflow values obtained in the predicted year are 290 MCM for Saguling Reservoir, 190 MCM for Cirata, and 52 MCM for Jatiluhur Reservoir.

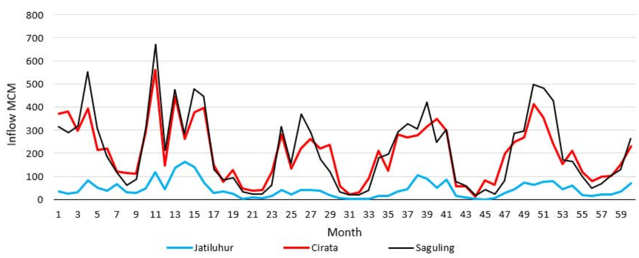

Fig. 6. Real inflow 2001 – 2005.

Fig.7 is a comparison chart of energy produced from the three reservoirs, which for Real energy data is obtained from Perum Jasa Tirta II (PJT.II) with an average energy each year from the three reservoirs of 4142 GWh while prediction of the average energy obtained from the results of optimization with simulations in 4997.4 GWh.

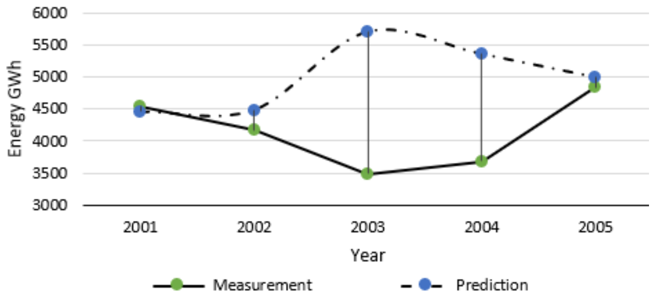

Fig. 7. Real energy and energy prediction in GWh.

In Fig.8, it is a comparison between demand for irrigation (MCM) against prediction results using equation (1) and the measurement data from the three reservoirs. It is known that the irrigation demand for agricultural purposes, for around the reservoir area in 2001-2005, can be fulfilled by the availability of water in the Jailuhur reservoir. As in Fig 3, know that the Jatiluhur reservoir is a final reservoir which functions to meet agricultural irrigation needs.

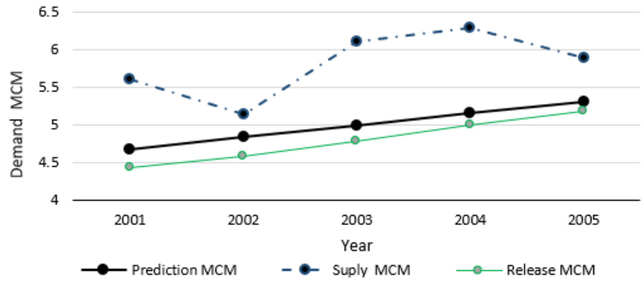

Fig. 8 Demand in year in Jatiluhur reservoir.

From Fig.8, it is known that the growth of irrigation needs, which is 5 MCM/year is 4.8 (MCM), while the predicted results of the capacity of the Jatiluhur reservoir are not much different from the field measurement results, which is 5.81 MCM, thus it can be concluded that Jatiluhur is able to serve the needs irrigation.

From the results of this analysis, it is known that equation (1) of Thomas and Fearing can be used as an alternative in analyzing the predicted growth of reservoir capacity on energy needs and agricultural irrigation needs.

IV. Conclusion

The result of this paper has obtained some facts that can highlight the current condition in the field and future research. The average increase of monthly demand for next year is as much as 4.47%. By increasing the number of demand, the need is still fulfilled. The average energy of those reservoirs between 2001 and 2005 is 4,952 GWH, while real energy is 4,638 GWH. The initial period of operation that fulfills optimal requirement is in April because it can fulfill the objective function and its obstacles. There is the increasing number of demand for irrigation need, industry and drinking water and it should become a priority, the movement of reforestation or the maintenance of Drainage Basin of Citarum River in upstream or downstream has to be carried out continuously, so the inflow of each reservoir can be fulfilled.

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