

Three Large Reservoirs Operation In The Cascade System

Citarum River – Indonesia

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1. Introduction

The three reservoirs are all situated on the Citarum, West Java. The Ir. H. Djuanda reservoir, which already exists since 1967 is the most downstream one. The next upstream reservoir is Cirata which is expected to become operational by 1987. The Saguling reservoir is the most upstream one and will start its operation in the most upstream one and will start its operation in the course of 1985. Downstream of Ir. H. Djuanda reservoir two weirs across the Citarum divert water into three main canals; the west tarum canal, the East tarum canal and the north tarum canal.

More than 20 million people are depend on Citarum with three reservoirs for irrigation (240,000 ha), water supply for domestic, municipal and industry (800 million m³/year), Electricity (3,200 MW), flood control and environment water, therefore optimize operation three reservoirs is necessary for maximizes dependable water to meet several needs with existing limitation. Reservoirs can be operated by means of rule curves. These curves relate storage and time, several curves can be applied at the same time. Depending on the position of the release for the next periods are taken. The linier or dynamic programming method is a famous and classic method to optimize a reservoir system, and it was therefore chosen for application here. With this method it is possible to decide under uncertainly with in the most optimal “path” of reservoir level.

For the integrated hydro-power optimization from the three reservoirs cannot be special for the power production, caused by the multipurpose dam in downstream which fulfill water requirements and the system as a whole has to be operated such that flood control is maximal. Ad hoc adjustments are made during emergency situations on daily or even shorter basis. The rule curves produced had been optimized with respect to power production in the system. At the same time monthly target storage was derived with respect to flood protection and water supply for all purposes. Different purposes and various operators on managing reservoir operation induce conflict of interests. Optimization method cannot always be applied considering the complexity of constraints that must be adopted. To overcome the limitation of the method, the policies are brought about in the form of coordination forum. Optimization is conducted by simulation and sometimes without optimizing the hydropower production.

2. Existing Infrastructure Dam In Citarum

The Jatiluhur project conceived in 1957 to supplement the run-of-river technical irrigation systems on the basin was completed in 1981. It is the largest contiguous irrigation system in Indonesia and is major rice production area. It comprises of the main Ir. H. Djuanda reservoir (estimated net capacity 1,860 M m³ in 1997), the associated Jatiluhur dam, hydro-electric power

station (150 MW) and a conveyance system that provides irrigation to about 240,000 ha in West Java through the West Tarum Canal (WTC) system, East Tarum Canal (ETC) system and the North Tarum Canal (NTC) system. In addition, the project provides domestic, municipal and industrial (DMI) raw water supply to DKI Jakarta metropolitan area, to a number of urban center such as Bekasi, Karawang etc., and to industries along the corridor from Jakarta to Cirebon, including the region around Purwakarta. The Project also provides flushing water to Cirebon, including the region around Purwakarta. The project also provides flushing water flush rivers in DKI Jakarta metropolitan area during the dry season.

During the 1980's the State electric Corporation (PLN) constructed two hydro-power projects upstream of the Ir. H. Djuanda reservoir. These are the Saguling Dam (750 MW) completed in 1985 and the Cirata Dam (500 MW) completed in 1988. The capacity of the Citarata hydro-power station is currently being increased by 500 MW. The Saguling (estimated net capacity 620 M m³) and Cirata (estimated net capacity 800 M m³) reservoirs further regulate the flow in the Citarum and thus enable an increase in the utilization of the water resources of the basin. These reservoirs are operated by the State Electricity Company (PLN) instead of the Jasa Tirta II Public Corporation (PJT-II) with the generation of firm peak power as their main objective. The salient data of the Citarum cascade dams and hydropower plants is shown as "Table 1, 2 and 3".

Table 1. Data of Citarum Cascade Reservoirs

	Saguling	Cirata	Ir. H. Djuanda
Operational	1985	1988	1967
Dam Data			
Type	Rock fill dam with clay core	Rock fill dam with concrete face	Rock fill dam with inclined clay core
Height	99 m	125 m	105
Crest length	301 m	453.5 m	1220 m
Crest elevation	650.20 m	225.0 m	114.5 m

Table 2. Data of Citarum Hydropower Plants

	Saguling	Cirata	Ir. H. Djuanda
Tail level (m)	252	103	27.0
Head loss (m)	28.4	4.0	1.0
Spillway characteristics	Gated spillway	Gated spillway	Un gated (ogee) spillway
Installed capacity (max. power, MW)	750	1000	187.5
Number of turbines	4 units	8 units	6 units
Type of turbines	Francis	Francis	Francis

Table 3. Data of Specific Citarum Reservoir

	Saguling	Cirata	Jatiluhur
Full supply level	643 m	220 m	107 m
Dead storage level	623 m	205 m	56 m [*])
Minimum power level	-	-	75 m
Maximum storage	880 x 10 ⁶ m ³	1,973 x 10 ⁶ m ³	2,970 x 10 ⁶ m ³
Minimum storage	271 x 10 ⁶ m ³	1,177 x 10 ⁶ m ³	599 x 10 ⁶ m ³ ^{**})
Surface area at max operating level	49 km ²	62 km ²	83 km ² ^{***})

In order to operate the whole cascade reservoir consistently, a special working group committee consisting of representatives from Jasa Tirta II Public Corporation, Electrical State Company, Research Institute of Water Resources keeps monthly meetings.

3. Citarum Water Availability And Demand

The Citarum river originates from mountainous area of Bandung region and flows northward to Java Sea through central portion of West Java Province. Bandung City, the capital of the West Java Province with inhabitants of 6,578,829 is located in the mouth of Saguling Reservoir. Topographically, the Citarum catchment upstream of Jatiluhur is characterized by a ring of high mountain ridges around a slightly undulating plain. Saguling dam is located in the upstream ridge while Cirata and Jatiluhur are in the downstream ridge. The seasonal variation in river runoff closely follows the rainfall distribution, marked by a distinct dry and wet season. The dry season fall in April – September and rainy season fall in October – March. The season not always like this, but depended from condition of season every year. Rainfall in the basin varies from about 4,000 mm/year in the mountainous areas in the upper catchment to about 1,500 mm/year along the coast.

Citarum River basin is covering an area of about 12,000 km² with the average annual flow of 12.95 billion m³, out of which 6.0 billion m³ flows in Citarum River and 6.95 billion m³ flows in the other rivers in the basin. By employing water resources infrastructures in basin the water that could be regulated is about 7.65 billion m³ per annum and the rest is wasted flows to the sea. The utilization of water by far is goes to irrigation of 6.0 billion m³ equal to 88%, and to domestics, municipalities, and industries of 800 million m³ equal to 12%.

At the present time the water demands on the Citarum cascade are mainly on Djuanda reservoirs as far DMI and irrigation water are concerned, of which irrigation water is by far the biggest (80%). This means that the actual demand has to be met in Djuanda. Of course, some demands are on Saguling and Cirata as well, but they are not consumptive. Water used for the generation of hydro-power and up in Djuanda reservoir, where it can be used for all other demands.

In the as “Table 3”, total water demands are shown for 2017 in as far they have been used by the preparation of the annual operational plan for the Citarum reservoir cascade, compared with irrigation water demands for a dry, normal and wet year, from Djuanda only, i.e, unregulated flows of the rivers intercepted by the West Tarum Canal, North Tarum Canal, East Tarum Canal system have already been taken into account. Although the demands are to be met by the reservoir system as whole, the location of the demands is from Djuanda Reservoir.

Table 3. Water demands (m³/sec) from Ir. H. Djuanda Djuanda Reservoir in 2017 according the Annual Operational Plan for the Citarum Reservoir Cascade.

Condition	Dry year	Wet Year	Normal Year
Month			
Jan	116,8	82,4	83,7
Feb	88,3	79,1	79,1
Mar	109,6	90,3	90,3
April	137,3	103,8	105,5
May	183,4	119,1	143,2
June	247,0	167,9	220,9
July	255,5	203,5	242,5
Aug	154,5	133,3	149,7
Sept	72,7	54,6	68,6
Oct	165,8	126,9	156,0

Nov	189,0	107,5	152,7
Dec	162,1	94,2	115,8
Average	156,8	113,5	134,0

The demand of the system can be generalized into three parts: (i) irrigation water supply to the North, East, and West Tarum areas, (ii) raw water supply to drinking water treatment plants for the districts and municipalities in the corridor of the canals including Jakarta, and (iii) to industrial zone along the corridor from Capital District of Jakarta to Indramayu, including the region around Bekasi, Karawang, Purwakarta, Subang district. These demands can partially be satisfied by rivers which are intersecting the main canals. The balance has to come from the Citarum, which are the greatest part of the intake requirements at the diversion weirs has to come from the Jatiluhur reservoir. As the biggest consumer and the largest contiguous irrigation area, irrigation water supply should be arranged into several crop plantation schedule. To cope with the available water resources, the irrigation plan is prepared as major input for Citarum cascade reservoirs operation.

The methodology to develop normal system operations in a multipurpose reservoir, include development of optimal end-of-month storage which maximize the expected value of selected primary objective function for the system, subject to satisfying other system objectives based on the specification of target performance levels. The domestic, municipal, and industry water demands (DMI) and irrigation water requirement as calculated from the previous procedure become an input to the reservoir operation model and synchronized with hydro-power to evaluate reservoir rule curves. Based on this model, an annual operational plan for Citarum cascade reservoirs is made using expected demands, statistical inflows based on dry, wet, normal years (each month). In this plan, the total energy of the system is maximised subject to a number of conditions:

- The demands at Jatiluhur reservoir should at least be met.
- The upper and lower rule curves for the reservoirs should be observed as much as possible.
- At the end of the year (or planning period) certain reservoir levels should be met.
- The maximum water level at the end of rainy season.
- To provide two times of yearly flood intercept and retain falling water and to control the flood periodically which released from Cirata reservoir (peak load).
- In order to prevent individual reservoir levels from changing to much from month to month, the relative net. storage of each reservoir with respect to the total net storage in the system should be kept constant.

For the preparation of the annual operation plan by working group for the monthly meeting, historical inflows since 1988 when the complete cascade was in operation are used by analyses Log Normal type 3 (LN-3). For Saguling, the inflows are derived from observations at Nanjung and intermediate inflows from reservoir balance calculations at Saguling. For Cirata and Djuanda historical inflows are calculated from reservoir balance calculations only. A problem with these calculations is that they notoriously inaccurate and difficult to check. Improvement by installing good automatic hydrometric stations just of each reservoir is therefore highly recommended.

Definition of wet and dry, and the way to calculate this is not universal. For instance NEDECO, 1985 uses a definition based on annual totals, but adjusted over the months by 2 two methods:

- Dry or wet year is defined according to the total annual flows. Monthly flows are distributed proportionally to the total annual flows.
- Dry or wet year is defined according to the total annual flow. Wet period monthly flows are distributed proportionally to the total wet period flow, while the remainder is distributed over the dry months.

Dry is defined as annual total 80% of the observation exceeded, wet as 20% exceeded (statistically known as the 80- and 20- percentile respectively). No underlying spastically distribution is used. If long historical records are used, additional years of data do not influence the picture very much. Based on any of the two approaches mentioned, additional very dry and very wet years can be defined. The biggest problem is, of course, to determine whether the present month belongs to a dry, normal or wet year.

4. Reservoir Cascade Operation

4.1 Reservoir Operation Concept

The Citarum cascade reservoirs have a combined effective volume of $3,276 \times 10^6 \text{ m}^3$ which is approximately 57% of annual mean run off of Citarum, indicating that the system was not designed to provide carry-over storage during year-long periods. Using non-shared optimised reservoir operation, the total water released of the Citarum cascade reservoirs can reach $5,531 \times 10^6 \text{ m}^3$, which is nearly 100% of water resources potential has been controlled. The water resources potential in the Citarum river is around $6 \times 10^9 \text{ m}^3$ annually. The biggest consumer so far is irrigation which uses up about 87% of total regulated water from Ir. H. Djuanda reservoir and other rivers in the system.

The present cascade operation is based on the guidelines produced by PLN-P2B in 1991. First an annual operational plan is made using expected demands, statistical inflows based on dry, wet and normal years (by each month). This plan forms the basis of the reservoir operation. It result in a recommended rule curve for the year under consideration actual operation is adjusted during monthly consultative meetings group Citarum Basin. Ad hoc adjustments are made during emergency situations on a daily or even shorter basis. In this plan the upper two reservoirs are operated for power production, while the bottom reservoir, Ir. H. Djuanda, has to meet the water supply requirements. The systems as a whole has to be operated such that flood control is maximal

Main difficult with this way of operations are ; (1) the established of upper and lower rule curves, (2) how to adjust in an optimum manner if the actual situation differs from the planned one, (3) how to decide on the actual situation with the respect to very dry, dry, normal, wet or very wet situation, and (4) how to forecast inflows into the reservoir. Apart from these major issues, other difficulties arise from:

- Maintenance (e.g. power plant units cannot be used, water levels are restricted due to maintenance of the dams, intake gates, etc)
- Water quality aspects (e.g. extra water for dilution is required to offset over-feeding of fish farms)
- Certain high water level are desired for recreational purposes.

In the following, a procedure will be shown, to derive an annual plan in a relatively simple and very flexible manner using a spreadsheet and its standards (non) liner optimization solver add-in.

The reservoir cascade has a combined net storage capacity of 2800 Mm³, where net storage is defined as the storage between the spillway crest level and minimum storage level. The later level is the minimum operating level for hydro-power generation. For Saguling, Cirata and Ir. H. Djuanda these level and storages have been taken as “Table 6”.

Table 6. Data of Water Level Citarum Cascade Dams

	Saguling		Cirata		Ir. H. Djuanda		Total Cascade
	(m +MSL)	(Mm ³)	(m +MSL)	(Mm ³)	(m +MSL)	(Mm ³)	
Maximum Level	643	889	220	1,977	107	2,458	5,324
Min. Storage	623	272	205	1,177	75	599	2,048
Net Storage (Mm ³)	617		800		1,859		3,276
Net storage (%)	18.8 %		24.4 %		56.8 %		100.0 %

The Citarum basin at Jatiluhur is about 5,750 Mm³. Thus the combined net storage capacity is about 49% of the MAR, indicating that the system was not designed to provide carry-over storage during year long drought periods. This is typical for a reservoir in Java where there are very pronounced dry and wet seasons.

Before the construction of Saguling and Cirata, the multipurpose Ir. H. Djuanda reservoir, operated by Jasa Tirta II Public Corporation, had to meet the following water supply objectives, ordered by priority based on the Water Resources Law No. 7/2004 as follows:

- Requirement of human life (drinking water, sanitation etc)
- Domestic, Municipal and Industry
- Irrigation
- Generation of (peak) hydro-power

Apart from these objectives, there is a standing operational obligation with respect to flood control. The following remarks can be made on the list.

4.2 Concept the Rule Curves

Reservoirs can be operated by means of rule curves. These curves relate storage and time (month). Several curves can be applied at the same time. Depending on the position of the actual storage at a certain moment, decisions on the release for the next period are taken. Quite often two rule curves are in use; an upper rule curve and a lower rule curve. If the reservoir storage at the start of a month is greater than the storage indicated by the upper rule curve an above target amount of water is released from the reservoir in order to come back to the curve. In this way one can observe the required storage capacity for floods, or spill can be prevented later on by routing an additional amount of water through the turbines. If the reservoir level drops below the lower curve water conservation measures have to be taken, which can be: (1) reduce the power target, (2) reduce the release target. Because above target releases for water supply do not yield any extra benefits, one can only prevent spill by producing more electricity.

If the upper rule curves is not meant to prevent spill or to provide storage for floods, a different decision may be assigned to it. This could be the case if the curve is used to maximize the average power output. In that case one may decide to release the expected average inflow plus the difference in storage which is indicated by the (gradient) rule curves. The function of the lower curve is mainly to prevent a great failures, either in irrigation or in power and to replace it by a controlled reduction in output. The number of organized failures through is greater that if nothing is done at all.

4.3 Optimal Integrated Operation

This method derived for a truly integral operation of the three reservoir together. For this purpose an optimization model has been developed which is based on the dynamic programming method. Three features of the model however have to be mentioned here.

- The dynamic programming model can only solve the problem for a set of discrete storages into which the reservoirs are schematized. The answer produced by the model is expressed as required storages at every time step, which always are one of the set of discrete stages. It is clear that by increasing the number of discretization a more precise answer is obtained. It must however be stressed here that the computational effort involved, is a quadratic function of the number of stages. In the present model, the number of stages is limited to 10. In some cases this even proved to be unpractical. The calculations were then first executed roughly with smaller number of stages. Then the 10 stages were introduced, but allowing only a limited range around the first solution.
- Secondly the optimization is only possible when a set of values, which are attributed to outflows and power productions are available. The problems are solved by using factious values. They do not represent real values in rupiahs but express more the priorities of several goals. The object is to find an operation which protects irrigation and urban water supply, and taking that into account maximizes the energy and power output. Producing power does yield a higher income at increase levels. In general 1,000 points per MW continuous production are allocated. The gain in power is of a much lower order of magnitude than the loss which is involved in not giving the release target. In this way, a solution which does not match the release target is highly improbable.
- The model is able to solve the operational problem for a dry, average wet year of for a combination of all three. The last method computes at every moment the benefits in a wet, average and dry case and combines the benefits according to the ration 3:4:3. This, because its is assumed that a 90% dry year and a 90% wet year each represent 30% of all possibilities and the average 40%. This is very roughly what is called "stochastic" dynamic programming. It would be better even to use all historical inflow data and to compute the value in each case. The final value attributed to a certain decision is then just the average benefit. In the practical situation, such a model would be useless due to the core capacities of the minicomputer and because computer times were already very extensive (12 hours for a full calculation).

The optimal operational patches found in this way were tested with the simulation model. This verification was necessary to see whether violations of the criteria do occur. In that case adaption's of the optimal lines have to be made. This difference may occur due to the different set of flow data which are used in both models.

4.4 Present Annual Operational Plan preparation

Each year, the representative of State electricity Company (PLN), Research Institute of Water Resources and PJT II prepare an operational plan for monthly meeting. It is based on the

predicted Domestic, Municipal, Industry and irrigation demands, existing reservoir levels and expected inflows, and evaporation and tries to optimize the total power output of the system by varying the monthly outflows of the individual reservoirs. This is done on a monthly basis by hand.

A few other principles (constraints) are adhered to as well; (1) spilling is not allowed, (2) the ending reservoir water level is the same, or higher than the starting water level, (3) the principle of shared in each month is kept constant, at 21,12 %, 28,94 % and 49,94 % for Saguling, Cirata and Djuanda respectively. In regular (at least monthly) consultative meeting of during the year this plan then is revised according to the real situation.

5. Conclusion

The three reservoirs are all situated on the Citarum River, West java, The Ir. H. Djuanda reservoir is the most downstream one, the next upstream reservoir is Cirata and the Saguling reservoir is the most upstream one. Downstream of Ir. H. Djuanda reservoir two weirs across the Citarum divert water into the three main canal.

Reservoirs can be operated by means of rule curves. These curves relate storage and time, several curves can be applied at the same time. Depending on the position of the release for the next periods are taken. The linear programming method is a famous and classic method to optimize a reservoir system, and it was therefore chosen for application here. With this method it is possible to decide under uncertainty with in the most optimal "path" of reservoir level.

Analysis and optimization of the annual operation plan by spreadsheet is both very flexible and easy to do with the built in solver. From the annual operation plan analysis by spreadsheet, it has been shown that operational principles have a large influence on the generation of (firm) power. In particular, a marked difference in result exists between so-called shared and non shared operation. Existing rule curves have not been updated in accordance with the latest flow figures. Similarly, elevation area capacity data for the three reservoirs are not recent. At least not for Ir. H. Djuanda. Local flow are determined by indirect reservoir balance calculations. Flow forecasting is not used for reservoir operation.

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