# Optimization of Multi-reservoir Operation by Stochastic Dynamic Programming for Moragolla Hydropower Project in Sri Lanka

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Development of a new hydropower project in an existing river management system sometimes impairs the original purpose of the system since it was not considered in the original design of the river system. It is ideal and imperative that the operation performance of existing facilities with planned new facilities are optimized together. However, this requires highly advanced computer computational and modeling tools.

In this article, the optimization study for the Moragolla hydropower project in Sri Lanka is introduced in detail. The project is a newly planned hydropower project in the Mahaweli river system where the project was not originally designed during the first planning of the river management. Therefore the optimization is done with the existing hydropower facility in the study. The method used for the optimization is multi-dimensional stochastic dynamic programming and outline of the multi-dimensional stochastic dynamic programming is introduced in the article.

*Keywords* : multidimensional optimization, reservoir operation, optimization, hydropower, stochastic dynamic programming

## 1. INTRODUCTION

Development of new hydropower project into an existing river management system sometimes impairs the original purpose of the existing system, especially when the new project was not considered in the original design of the river system<sup>3)</sup>. Prior to development of the hydropower project, (i.e. in the planning stage) improvement of operational efficiency of existing river management facilities should be optimized with planned facilities to maximize the benefit of the system with the new facility.

However, the countless numbers of river management facilities developed along the river makes it practically impossible to optimize the operation performance of the whole river management facilities. The difficulties mainly come from the fact that the number of the decision variables for optimization solver exceed the power and speed of the modern desktop computer. Studies of water resource management have attempted to cope with such multidimensional problem. The examples of the attempt, by limiting the search fields, use approximation method, or heuristic or metaheuristic method, etc.

In this article, attempt of optimization of several hydropower operation is explained as an example of limiting the number of multidimension problems. The optimization algorithm used for the problem is stochastic dynamic programming (SDP). The program algorithm of SDP is expanded for n-dimension problems and applied for a feasibility study of the planned hydropower project, namely Moragolla Hydropower Project. The feasibility study was conducted by a joint venture of Nippon Koei Co., Ltd.(NK) and Nippon Koei India (NK India) PVT. Ltd. under the contract with Ceylon Electricity Board of Sri Lanka<sup>5)</sup>. NK and NK India reviewed and updated the past feasibility study, and the reservoir optimization was conducted in the feasibility study.

# 2. OUTLINE OF MORAGOLLA HYDROPOWER PROJECT

The Moragolla hydropower project (the "Project") is a planned run-of-river hydropower aiming supply electricity



Fig.1 Location of Moragolla Hydropower Project<sup>5)</sup>

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for peaking load. The Project is located on the Mahaweli river close to Ulapane village in Kandy district of Central Province, which is about 130 km to the northeast of Colombo. The location of the Project is shown in the Fig.1.

The Project develops power output of 31.1 MW with a rated head of 69 m. A concrete gravity type dam is designed with 37 m height and 236 m crest length. The dam will create reservoir having capacity for daily peak power generation. Annual energy output is estimated at 81.65 GWh of which the firm energy is 66.12 GWh.

In the upstream reach of the Project, there is an existing hydropower station, named Kotmale. Kotmale is reservoir type hydropower project having a storage capacity for seasonal regulation of the Kotmale river stream flow. The Kotmale hydropower project is located along the Kotmale river, and the river joins to the Mahaweli river at the upstream of the planned Moragolla dam. The project



Photo taken by author Photo 1 Dam and Reservoir of Kotmale Hydropower

Item	Unit	Data
Catchment area	km <sup>2</sup>	249
Mean annual inflow	$m^{3}/s$	22.4
Type of hydropower		Run of River
Dam type		Concrete gravity
Dam height	m	37
Full supply level	EL.m	548.0
Minimum water level	EL.m	542.0
Available depth	m	6.0
Reservoir volume (effective)	million m <sup>3</sup>	1.98
Reservoir surface area	ha	38.47
Crest length	m	236
Length of water way	m	2,727
Planned installed capacity	MW	31.1
Number of unit		2
Type of turbine		Francis
Rated head	m	69.0
Annual Energy	GWh	97.6

Table 1 Project Features of Moragolla Hydropower Project<sup>5)</sup>

features of the Kotmale hydropower project are shown in  $\ensuremath{\mathsf{Table 2}}.$ 

The Kotmale hydropower station takes the water in at an intake near Kotmale dam, and conveys it to the powerhouse; the water is released downstream of the powerhouse of the Project's power station. The spilled water from the Kotmale dam flows to the Kotmale river and subsequently flows into the Moragolla reservoir. The river system of the Moragolla hydropower is shown in Fig.2. The Kotmale dam is also obliged to release irrigation water which is regarded as the first priority. Therefore, the water is first allocated to irrigation then hydropower follows.

# 3. OPTIMIZATION OF RESERVOIR OPERATION

# (1) PURPOSE OF THE OPTIMIZATION STUDY

The benefit of the project is assessed by the power supply capability of the new hydropower plant, and it is unknown whether the capability of the Moragolla hydropower plant is improved when the new plant and the existing Kotmale hydropower plant are considered as one system.

Table 2 Project Feature of Kotmale Hydropower Project<sup>2)</sup>

Item	Unit	Data
Catchment area	km <sup>2</sup>	565
Type of hydropower	-	Reservoir
Dam type	-	Concrete facing rock fill
Dam height	m	87
Full supply level	EL.m	703.0
Minimum water level	EL.m	665.0
Reservoir volume	million m <sup>3</sup>	172.6
Annual Energy	GWh	494
Installed Capacity	MW	201
Commission year	year	1984



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Fig.2 Flow Network of the Moragolla Project

As spilled water from the Kotmale dam will flow into the Moragolla reservoir, the operation of the Kotmale dam will influence the performance of the Project. Therefore, the study aims to find this influence of Kotmale dam operation to the Moragolla hydropower project and determine whether the operation of Kotmale hydropower station is significant to the Project.

## (2) DEFINITION OF TERMS

The definitions of technical terms used for reservoir operation optimization are as follows.

- Peak Period

The peak period is from 6:30 PM to 9:30 PM from Monday to Friday. The peak duration is three hours.

- Peak Power

The power generated during the peak period is considered as peak power. Power generated other than peak period is considered as "Off-Peak Power".

- Annual Energy

Annual energy is the average of annual energy produced by the power plant.

- Dependable Capacity

Dependable capacity is the amount of the capacity that the power plant can reliably contribute towards meeting system peak power demand<sup>7)</sup>. In this study, the dependable capacity is defined as the power output (MW) that the plant can produce with 90% probability of exceedance (POE) through the simulation duration (43 years).

# (3) RESERVOIRS CONSIDERED FOR OPTIMIZATION

Fig.3 shows the water resources management facilities along the Mahaweli River. As shown in the figure, the water resources of the Mahaweli River have been intensively developed for hydropower and irrigation.

The operation of the Project will directly or indirectly affect to the operation of downstream water resources management facilities. However, it is practically impossible to optimize the operation rule of all facilities due to complexity of modeling, and planning of new hydropower plant generally only studies the operation of the subject plant and downstream operation are considered as constraints. In this study, the operation of Kotmale and planned Moragolla hydropower plant directly affected, therefore, only these two reservoirs are considered.

## (4) OPTIMIZATION SCENARIOS

The optimization scenarios are as follows:

i) ["Independent operation" (which is solved by single



Ref: Feasibility Study Report of Moragahakanda development project<sup>4)</sup>

Fig.3 Existing Hydropower Plants along the Mahaweli River

reservoir optimization)] To find optimum reservoir operation rule of the Project without consideration of Kotmale hydropower operation. The Kotmale hydropower operation is also optimized independently.

ii) ["<u>Combined operation</u>" (which is solved by multireservoir optimization)] To find optimum reservoir operation rule of the Project in combination with Kotmale hydropower operation.

In the study, the results of single reservoir optimizations and multireservoir optimization are compared.

#### (5) OPTIMIZATION TOOL

The optimization tool used for the study is the generalized software developed by Nippon Koei Co., Ltd. (NK). The tool was developed incorporating extensive experiences in the study of NK's reservoir operation optimization<sup>6)</sup>. In the Project, the program code was customized for enhancement of multidimension SDP.

The program interface of the program is shown in Fig.4. The software can optimize the operation of more than 10 reservoir operations.

## (6) OPTIMIZATION FUNCTIONS OF THE TOOL

The optimization tool developed by NK has functions of dynamic programming(DP), stochastic dynamic programming(SDP) and multidimension SDP. The outline of each algorithm is as follows.

1) Dynamic Programming (DP)

DP was proposed by R.Bellman [1954] as a method to seek the optimum decision process in a given timeframe or in given multistage decision process<sup>1)</sup>. Hence, DP has been applied to problems of multistage decision processes which include the hydropower reservoir operation<sup>8)</sup>.

DP computes a sequence of optimal return functions  $F_T(\mathbf{x})$ ,  $F_{T-1}(\mathbf{x})$ , ....,  $F_0(\mathbf{x})$  using the following the recursive equation.

$$F_{t}(\mathbf{x}) = \max \{ ft(\mathbf{x}t, \mathbf{x}_{t+1}, u_{t}) + F_{t+1}(f_{t+1}(\mathbf{x}_{t+1}, \mathbf{x}_{t+2}, u_{t+1})) \}$$
(1)

Equation "(1)" forms a recursive function and is called Bellman equation. The function " $f_t(x_t, x_{t+1}, u_t)$ " is an objective function to be optimized, such as maximizing electricity production or maximizing income by selling electricity. DP seeks the optimum path of decision process by finding the path which produces maximum aggregated value of  $F_t(x)$ . The concept of optimum path finding by DP is shown in Fig.5. 2) Stochastic Dynamic Programming (SDP)

If the future inflow is perfectly predictable, DP solves the problem by considering the inflow as deterministic variable. This type of DP is called Deterministic DP. Deterministic DP directly uses historical series data such as inflow into the reservoir. However, as it is not possible to perfectly predict the future inflow for long term planning horizon, the estimation of power production by deterministic DP sometimes overestimates the actual power generation.

SDP assumes the future inflow as an unknown variable, but assumes that the probability distribution of inflow is steady from present to future. The outline of SDP and its application to water resources is well described by J.Labadie<sup>3)</sup>. The concept of the inflow with probability is as shown in Fig.6.

The inflow with probability is treated as one of inputs to DP, and as the inflow is considered with probabilities, the Bellman equation changes its form to recursive function of expected value of objective function as shown in the equation b.

$$F_{t}(x) = \max\{E(f_{t}(x_{t}, x_{t+1}, u_{t}, p)) + F_{t+1}(f_{t} + 1(x_{t+1}, x_{t+2}, u_{t+1}))\}$$
(2)

"E()" in the equation "(2)" is an operator of expectation of the objective function of  $f_t(x_{t,}x_{t+1},u_{t,}p)$ . SDP also gives

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Fig.5 Concept of Finding Optimum Path of the Reservoir by Dynamic Programming



the reservoir operation table that is used for the power generation simulation.

3) SDP for Multireservoir Case

The optimization of the combined operation of Kotmale reservoir and Moragolla reservoir is considered as DP for multireservoir system. This type of problem is a stateof-the-art problem as dealing multireservoir system in DP may still cause the explosion of computer time. The concept of the DP model for multireservoir system is shown in Fig.7.

#### 4) Reservoir Operation Rule Table

The uniqueness of the multidimensional dynamic programming is the output. Dynamic programming for one reservoir operation optimization gives target reservoir volume for discretized reservoir volume for the next time step. Fig.8 shows the concept of operation rule table given by DP.

For the multidimension DP, the dimension of the table is increased with the number of decision variables, i.e. the number of reservoirs to be considered. For example, in case of optimization for two reservoirs, the output of DP is 3-dimension of t, Vol<sub>I</sub>, and Vol<sub>I</sub>, where Vol<sub>I</sub> and Vol<sub>II</sub> is



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## Fig.7 Concept of DP Model for Multireservoir System (case: N=3)

Discrete	Time Step (Daily)									
Reservoir Volume	1	2	3	•	•	t	•	•	364	365
V <sub>1</sub>	$\rightarrow$	Ы	Ы			-			$\rightarrow$	$\rightarrow$
V <sub>2</sub>	$\rightarrow$	Ы	Ы			-			7	7
V <sub>3</sub>	$\rightarrow$	$\rightarrow$	Ы			-			7	7
•										
Vi										
•										
V <sub>N</sub>	$\rightarrow$	$\rightarrow$	$\rightarrow$			-			7	7
→ Reservori volume does not change										
Increase reservoir volume										
Decrease reservoir volume										
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Fig.8 Concept of Output for 1-Dimension DP

target reservoir volume of reservoir I and II, respectively. The concept of the output of 2-dimension DP is shown in Fig.9.

5) Simulation after Optimization

The program gives the reservoir operation rule as the output of multidimension SDP. In this case, the program gives reservoir operation rule given by two-dimensional SDP. In order to calculate the electrical energy and power output, the tool carries out simulation of power generation. The result of the simulation is summarized to enumerate the annual electrical energy, and dependable capacity. The flow of the calculation is shown in Fig.10.



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Fig.9 Concept of Output for 2-Dimension DP



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Fig.10 Study Flow of Optimization and Simulation

## (7) SELECTION OF THE OBJECTIVE RETURN FUNCTION

The Project is designed for the power supply during peaking electricity load, and the benefit of such project generally is measured by the dependable capacity of the plant. The dependable capacity is used for project economic evaluation. Therefore, the objective return function is selected to maximize the dependable capacity of the plant. The equation of objective function forms as shown below.

- Objective function

$$f_{t} = \left(\frac{P_{\max} - P_{\text{primary}}(t)}{P_{\max} - P_{\min}}\right)^{2}$$
(3)

 $P_{max}$  :Maximum power output of Kanan hydropower plant (MW)

 $P_{primary}(t)$ : Primary power output of day "t" (MW)

P<sub>min</sub> :Minimum power output of Kanan hydropower plant (MW)
\* The function forms as quadratic equation as this form of equation empirically fits to maximization of dependable capacity.

The constraints of the optimization are: reservoir capacity, maximum/minimum plant discharge, and spillway capacity. The irrigation supply is also considered as constraints for release from the Kotmale dam, since the irrigation supply is the first priority of water supply of the Kotmale dam.

# (8) DAILY STOCHASTIC DISCHARGE FOR STOCHASTIC OPTIMIZATION

The stochastic data set for the Project and the Kotmale hydropower station was prepared for the calendar days from January 1<sup>st</sup> to December 31<sup>st</sup>. The discharge with probability prepared for the optimization study is shown in Fig.11.

#### (9) DAILY DISCHARGE FOR POWER GENERATION SIMULATION

- Moragolla Reservoir

The daily discharge at the Moragolla dam site was estimated for the power simulation on the basis of available rainfall data in the hydrological study of the revised feasibility study of the Project<sup>5)</sup>. The Moragolla river discharge is estimated from 1968 to 2010. The estimated daily discharge is used for power generation simulation.

## - Kotmale Reservoir

The daily discharge at the Kotmale dam site was estimated using the stream flow data of the Kotmale dam and at Morape which was located at the Kotmale reservoir before the construction of Kotmale dam. The Kotmale river





discharge is estimated from 1968 to 2010 for the use of power generation simulation.

# 4. RESULT OF MORAGOLLA AND KOTMALE RESERVOIR OPERATION OPTIMIZATION (COMBINED OPERATION)

The reservoir operation of the two reservoirs is optimized by SDP, and the power generation simulation is performed using the estimated stream flow data from 1968 to 2010. The result of the simulation is discussed in this section.

1) Water Level

The daily average water level of the simulation for Moragolla and Kotmale reservoir is shown in Fig.12.

The black lines in the graph are the reservoir water level of combined operation, whereas the brown lines are those of the independent reservoir operation optimization result. As shown in the graphs, the water level of the Moragolla reservoir of combined operation is slightly lower (around 0.1 m) than that of independent reservoir operation case.

For Kotmale reservoir, the reservoir water level of combined operation is greater for 6 m at maximum. This indicates that the combined operation of Moragolla and Kotmale reservoirs may make the Kotmale reservoir water level higher than the independent reservoir operation.

It is noted that the water level of the Kotmale reservoir is much lower than the Full Supply Level (FSL) of 703



Fig.12 Daily Average Reservoir Water Level of Moragolla and Kotmale Reservoir<sup>5)</sup>

m ASL. This is caused by the release for irrigation requirement at Kotmale dam which inhibits the Kotmale reservoir to keep the water level close to FSL.

2) Electrical Energy (unit: GWh)

The monthly electrical energy supplied by Kotmale and Moragolla hydropower plants for combined and independent operation are shown in Fig.13.

As shown in the figure, the differences between independent operation and combined operation of Moragolla hydropower plant are almost the same, while there are some differences between the two modes of operation in Kotmale reservoir operation.

It is noted that the monthly energy during the dry period from January to May increases while the monthly energy decreases during the period from October to December. This increment of energy in dry season is around 10%. As increase in electrical energy production in dry season leads to increase in dependable capacity, it implies that the optimization model is able to make Kotmale hydropower station to generate more electricity of the combined operation than that of independent operation in dry season.





Fig.13 Monthly Energy for Combined Operation and Independent Operation  $^{5)}$ 



Fig.14 Monthly Average Peak Power for Combined Operation and Independent Operation<sup>5)</sup>

#### 3) Power Output (unit : MW)

The monthly average of power output during peak load is shown in Fig.14. The tendency of the power output of Moragolla hydropower and Kotmale hydropower plants are similar to the monthly energy discussed in item<sup>2)</sup>. The differences between the two modes are negligible for Moragolla hydropower plant operation, and around 10% increase during dry period for Kotmale hydropower. This indicates that the combined operation helps to increase the dependable power of Kotmale hydropower.

The duration curves of the peak power of Kotmale and Moragolla hydropower plants for combined and independent operation are shown in Fig.15.

As shown in the figure, the peak power of combined operation is increased from that of independent operation. The increment of power of combined operation is 3%. This increase is mainly due to increase of peak power during the dry period, which will result in increase in dependable capacity. The allocation of peak power output of Kotmale and Moragolla hydropower plants are shown in the duration curves in Fig.16.

As shown in the figure, Moragolla hydropower plant contributes as base power in peak power supply for both scenarios, and the peak power supply by Kotmale is high variation from 190 MW to 12 MW for both cases.

#### (2) SUMMARY AND CONCLUSION FOR COMBINED OPERATION

The results of the combined operation and independent operation are summarized as shown in Table 3.

The table shows that the combined operation of Kotmale and Moragolla hydropower plants will improve the output of annual power, dependable power and average power. But effect of improvement is limited since the dependable





power is increased just 1.3%. This means that even if the Moragolla hydropower plant operation is closely tied with Kotmale hydropower plant, improvement of the economical benefit of the Project is not significant; in addition, optimization and developing operation rule of combined operation is complicated.

Therefore, in the feasibility study of the Project, the combined operation of Kotmale and Moragolla hydropower plants are not considered to determine the dependable capacity of the Project, and the dependable capacity of independent operation is adopted for economic evaluation.



Fig.16 Duration Curve of Peak Power Output of Kotmale and Moragolla Hydropower Plants for Combined Operation<sup>5)</sup>

Table 3	Summary of Result for Reservoir Operation
	Optimization for Combined Operation of
	Kotmale and Moragolla Hydropower Plants <sup>5)</sup>

Items		Annual Energy (GWh)	Dependable Capacity (MW)	Average Power (MW)	
Independent Operation	Total	456.9	29.9	156.7	
Combined Operation	Total	459.9	30.3	161.7	
Increment	Value	3	0.4	5	
	%	0.70%	1.30%	3.20%	

## 5. CONCLUSION

According to the result of optimum reservoir operation of the planned Moragolla hydropower and the existing Kotmale hydropower project, the production of electrical energy is certainly increased when the operation of two hydropower stations optimized together.

However the result of the study also shows that such improvement of the optimization of operational performance of the two hydropower stations is limited. One of the possible reasons of the small improvement of the performance is that the Moragolla hydropower is runof-river type project and the reservoir capacity is limited to regulate the flow regime of the river.

In the feasibility study of the Project, further study for combined operation by multidimension DP was not conducted. But it is recommended conducting optimization study involving relating water resources facilities when the project is implemented.

Challenges for application of the multidimension DP is to express the operation output table when the number of dimension is more than three. The dimension of output table is corresponding to the number of dimension. The 3-dimension DP needs 4-dimension table which may be difficult to express. One of the possible countermeasures is to establish the artificial neural network (ANN) model by determining the network coefficients by learning the DP output table data. But of course it needs some studies to prove the effectiveness of application of ANN.

#### References

- Bellman, R., "The Theory of Dynamic Programming" the Rand Corporation, July 1954.
- Electric Power Development Co., Ltd., Nippon Koei Co., Ltd. "Study of Hydropower Optimization in Sri Lanka, Final Report" Japan International Cooperation Agency, Ceylon Electricity Board, February 2004.
- Labadie, J., "Optimal operation of multireservoir systems, Journal of water resources planning and management, State-ofthe-Art Review", March/April 2004, pp.93-111, ASCE.
- 4) Lahmeyer International in association with Central Engineering Consultancy Bureau in Sri Lanka, United Consulting Group in Kuwait, and Chuo Kaihatsu Corporation in Japan, "Feasibility Study of Moragahakanda Development Project" Mahaweli Authority of Sri Lanka, Ministry of Mahaweli Development, Sri Lanka, 2001.
- 5) Nippon Koei in Joint Venture with Nippon Koei India PVT. LTD., "Moragolla Hydropower Project, Review of Feasibility Study and Preparation of Detailed Design and Bidding Documents", Ministry of Energy, Ceylon Electricity Board, Sri Lanka, May 2013.
- Uematsu, S., "Reservoir Operation Study for the Nam Ngum River Basin," Koei Forum No.19, pp.53-62, March 2011.
- US Army Corps of Engineers, "Engineer Manual No.1110-2-1701, engineering and Design, Hydropower." 1985, USA.
- Yakowitz, S., "Dynamic Programming in Water Resources," Water Resources Research, Vol. 18, No.4, pp.673-696, August 1982.