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Optimum contributions of hydropower reservoirs to the minimum flow of Vu Gia – Thu Bon river basin

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Abstract

Upstream hydropower development has a great impact on downstream flows. According to the Regulation of Multi-reservoir Operation in Vu Gia – Thu Bon River Basin (Regulation 1537[1]), four large-scale upstream reservoirs must discharge certain flow during the dry season to increase water levels at downstream hydrological stations named Ai Nghia and Giao Thuy. These stations are used as the control points for the downstream water supply. An optimizing-simulation based model was developed that both maximizes total electricity production and ensures minimum flow downstream as required. A thousand combinations of the reservoir inflows were generated by Monte Carlo simulation, considering the correlation between tributaries. Then, the Scatter search algorithm available in the Optquest module of Crystal Ball was used to find the optimal release from the reservoirs. The results show that the current Regulation 1537 can be improved for more efficient water resources management.

Key words: minimum flow, Monte Carlo simulation, optimization, reservoir system operation

Highlights

- A link between up and down stream water uses in a river basin.
- A link between hydropower development and other socio-economic development in a river basin.
- A development of optimization – simulation based technique for integrated water resources management at the river basin scale.

INTRODUCTION

Operating upstream large-scale hydropower reservoirs is a complicated issue because of its close relation to different downstream water users that have different purposes. Although the amount of water loss due to most hydropower reservoirs is small, the changes in the downstream flow regimes are significant. These reservoirs store excess water during the flood season and release it in the dry season, to positively regulate the downstream flow. However, the reservoirs are operated intensively

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[1] Regulation of Multi-reservoir Operation in Vu Gia-Thu Bon river basin was issued together with Decision No. 1537/QD-TTg dated 07/9/2015 of the Prime Minister (for both flood and dry season). In the dry season, four reservoirs (A Vuong, Dak Mi 4, Song Bung 4 and Song Tranh 2) have to cooperate to release water (in a 10-day period) depending on the downstream water levels at Ai Nghia and Giao Thuy stations. The Regulations were designed to strengthen flood control and downstream water supply capacity, and are considered as legal documents that help managers to make effective water allocation decisions.

in the peak hours of the day, whereas the outflow is nearly zero during the low hours. As a result, the downstream flows, which are delivered to other water users, are influenced. Most large-scale reservoirs are multi-purpose. However, their basic functions are often contradictory. Therefore, it is necessary to research other methods to improve the performance of the reservoir, especially for multi-reservoir system operation in a river basin.

For many years, mathematical models have been used extensively for deriving operating policies for multi-reservoir systems to minimize conflicts between the objectives of the reservoirs. The simulation models, optimization models and models combining simulation and optimization are all widely used (Estalrich & Buras 1991; Babel *et al.* 2005; Loucks & van Beek 2005; Afzali *et al.* 2008; Long *et al.* 2008; Husain 2012; Fayaed *et al.* 2013; Ahmad *et al.* 2014).

The simulation models are often used to describe hydrological and hydraulic processes of water resources systems under various operating conditions of the system (Rani & Moreira 2010). The simulation models cannot create a direct optimal solution for reservoir system operation. However, running the simulation model multiple times with different scenarios will assist in finding a scenario that is close to best (Fayaed *et al.* 2013; Teegavarapu & Simonovic 2014). While simulation models can best describe the system, optimal models are often useful if the main purpose is to improve the performance of the system. Labadie (2004) summarized the optimization techniques used in allocation of water resources from single reservoir and multi-purpose reservoir systems, including Implicit Random Optimization methods and Explicit Stochastic Optimization methods. Models may also be able to simulate and optimize simultaneously (Mckinney *et al.* 1999).

Recently, a contradiction between water allocated for hydropower generation of the four major upstream reservoirs and water allocated for downstream domestic and irrigation uses has emerged in the Vu Gia – Thu Bon river basin. Regulation 1537 was ratified in 2015 by the Prime Minister in order to minimize this conflict. However, the process of building Regulation 1537 was mainly based on compromise between the parties involved without in-depth scientific research. For further verification of the Regulation, this study aimed to discover the most reasonable water contribution rates for the reservoirs to maintain the minimum flow downstream as required in Regulation 1537 and to maximize the total power generation of the hydropower plants. A simulation model of the reservoir system in the Vu Gia – Thu Bon river basin was developed in an Excel spreadsheet to simulate several scenarios for the contribution rate from the reservoirs. The random inflows of reservoirs were generated by Monte Carlo simulation considering the hydrological correlation between tributaries in the river system. After that, the Optquest module, which is available in Crystal Ball software with the scatter search algorithm, was used to find the best operational alternative such that the objective function is the largest total electrical production. The structure diagram for the optimum model is shown in Figure 1.

The Vu Gia – Thu Bon river system

The Vu Gia – Thu Bon river system is the largest river system in the Central part of Vietnam, with an annual water volume of 20 billion cubic meters. The entire catchment area located on the eastern slope of the Truong Son range with a basin area of 10,350 square km, of which the area located in Kon Tum province is 560.5 square km, the rest being mainly in Quang Nam and Da Nang provinces. The river originates from the province of Kon Tum, which flows through Quang Nam, Da Nang city, to the East Sea at Cua Dai and Cua Han.

In the Vu Gia – Thu Bon basin, there are currently four large hydropower reservoirs in operation, namely A Vuong, Song Bung 4, Dak Mi 4, and Song Tranh 2 (Figure 2). Several parameters of these reservoirs are given in Table 1. The operation of these reservoirs had made the situation of water resources management in the river basin more complicated. The contradiction between the water use goals becomes profound, especially in the dry season, which requires a compromise between

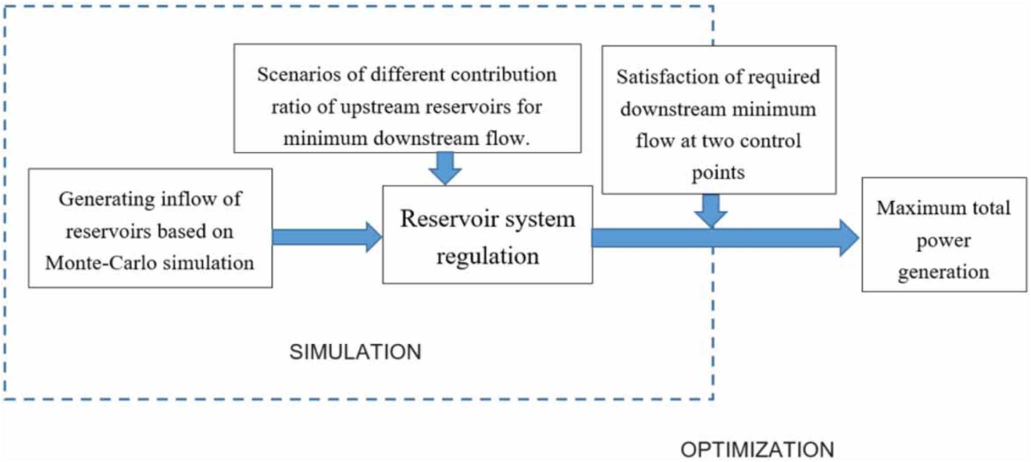

Figure 1 | Structure of the optimization – simulation based model of the reservoir system in Vu Gia – Thu Bon river basin.

Table: Hydropower Information of the VGTB (Large and Medium HPP)

No	Name	Storage Capacity ($10^6 m^3$)	Installed capacity (MW)	Energy Production (Mil. kWh)	Comment
1	Avuong	343.55	210	815	Existing HPP
2	Song Tranh 2	733.40	190	679	
3	Dak Mi 4 A	310.32	148	589	
4	Song Con 2 (B1 & B2)	30.39	63	207.86	
5	Song Bung 5	20.14	57	223.78	
6	Dak Mi 4 B	2.57	42	163.8	
7	ZaHung	NA	30	122.7	
8	Song Bung 6	3.22	29	120.52	
9	Dak Mi 4C	2.67	18	69.1	Proposed HPP
10	Song Bung 4	510.8	156	623.8	
11	Song Bung 2	94.3	100	419	
12	Dak Mi 2	0.919	98	458.85	
13	Sông Tranh 3	34.1	62	230.7	
14	Dak Mi 3	3.4	54	220.5	
15	Song Bung 4A	10.6	49	199.1	
16	Song Tranh 4	20.08	48	188.4	

Figure 2 | Map of Vu Gia- Thu Bon river basin.

objectives to improve the efficiency of water allocation in the river basin. According to Regulation 1537, the water supply requirement in the downstream of the Vu Gia – Thu Bon river basin is controlled at the hydrological stations Ai Nghia (on the Vu Gia river) and Giao Thuy (on the Thu Bon

Table 1 | Specification of A Vuong, Song Tranh 2, Song Bung 4 and Dak Mi 4

No.	Data	Unit	A Vuong	Tranh River 2	Bung River 4	Dak Mi 4
I	Parameter of reservoir					
1	Basin area F_{lv}	km^2	682	1,100	1,448	1,125
2	Annual flow	m^3/s	39.8	110.5	73.7	67.80
4	Normal water level	M	380	175	222.5	258
5	Dead water level	M	340	140	205.0	240
6	Total volume W_{tb}	10^6 m^3	343.55	729.20	510.8	312.38
7	Effective volume W_{hi}	10^6 m^3	266.48	521.10	233.99	158.26
II	Hydroelectric power plants					
1	Maximum flow (Q_{max})	m^3/s	78.4	245.52	166.0	128
5	Installed capacity (N_{lm})	MW	210	190	156	74
6	Annual energy (E_0)	10^6kWh	815	679.6	586.2	
7	Number of turbines	set	2	2	2	2

Source: Regulation 1537.

river). The four hydropower reservoirs are required to release flow to maintain the water levels at these stations of not less then 2.67 m and 1.02 m, respectively.

METHODOLOGY

Simulating inflows of reservoirs

At first, the 30-year inflow time series were collected from reservoir design documents, which had been approved by the competent authorities. The design consultants for these reservoirs are Power Engineering Consulting Joint Stock Company 1 (PECC1) and Power Engineering Consulting Joint Stock Company 2 (PECC2). They had applied common rainfall-runoff models such as MIKE NAM and TANK models to calculate the runoff time series to the reservoirs (PECC2 2003, 2007; PECC1 2006, 2010). Since the four reservoirs are located on four different tributaries of the same river system, the correlations were analyzed for each pair of time series. In general, the monthly correlation coefficients between the three reservoir inflows of A Vuong, Dak Mi 4 and Song Bung 4 are rather good. However, the relationship between the flow to the Song Tranh 2 reservoir and the rest of the reservoirs is quite loose. There were six pairs of reservoir inflows analyzed for correlation, including: A Vuong – Song Tranh 2, A Vuong – Song Bung 4, A Vuong – Dak Mi 4, Song Bung 4 - Dak Mi 4, Song Tranh 2 - Dak Mi 4, Song Tranh 2 - Song Bung 4. With the monthly data, there were a total of 72 correlation coefficients between reservoir inflows (Table 2).

High correlation coefficients were included as constraints for the Monte Carlo simulation model when generating random inflow values of each reservoir.

Secondly, the most fitted probability distribution based on 30-year data time series of each reservoir was determined. Several standard goodness-of-fit tests are available in Crystal Ball to judge the quality, or goodness, of each fit. The different distributions were sorted in order of their fit tests using a comparison chart that showed the fitted distributions superimposed over the data. A summary table can show some or all of the goodness-of-fit statistics, including *P*-values of certain distributions. Each goodness-of-fit test is calculated for every distribution, but only the selected test determines how the distributions are ranked. The Chi-Square test is selected for discrete distributions, and the default for continuous distributions is the Anderson-Darling test.

Table 2 | Correlation coefficients of reservoir inflows in pairs

Reservoirs	Jan	Feb	Mar	Apr	May	Jun
AV-ST2	0.118	0.126	0.031	0.027	0.080	0.215
AV-SB4	0.740	0.449	0.498	0.725	0.621	0.565
AV-DM4	0.969	0.923	0.892	0.905	0.803	0.889
SB4-DM4	0.752	0.527	0.584	0.746	0.786	0.673
ST2-DM4	0.162	0.105	0.058	0.039	0.174	0.149
ST2-SB4	0.243	0.159	0.161	0.093	0.013	0.023

Reservoirs	Jul	Aug	Sep	Oct	Nov	Dec
AV-ST2	0.153	0.248	0.041	0.777	0.885	0.798
AV-SB4	0.274	0.598	0.668	0.863	0.966	0.872
AV-DM4	0.635	0.702	0.686	0.784	0.574	0.718
SB4-DM4	0.561	0.776	0.742	0.758	0.681	0.594
ST2-DM4	0.133	0.250	0.175	0.797	0.603	0.763
ST2-SB4	0.019	0.123	0.027	0.730	0.889	0.750

AV: A Vuong; ST2: Song Tranh 2; SB4: Song Bung 4; DM4: DakMi4.

Then the Monte Carlo simulation method was applied to randomly generate the inflow time series of the four reservoirs in the Vu Gia – Thu Bon basin.

Checking the correlation matrix (Figure 3) showed that the generated inflow correlation coefficients were close to the desired actual correlation coefficients. For example, the generated inflows of A Vuong and Dak Mi 4 reservoirs had a correlation coefficient of 0.816, whereas the actual correlation coefficient was 0.803.

The statistical parameters of generated and actual time series were also compared (Table 3). Difference in average Q value is changing from 0% (A Vuong & Song Tranh 2) to 0.47% (Dak Mi 4 & Song Bung 4). Deviation to the median is from 0% (A Vuong) to 0.39% (Dak Mi 4). Deviation of standard deviation is from 0.1% (Song Tranh 2) to 1.97% (Song Bung 4). To conclude, the generated random values can be used as input for simulation-optimization for the four reservoirs in the Vu Gia – Thu Bon river basin.

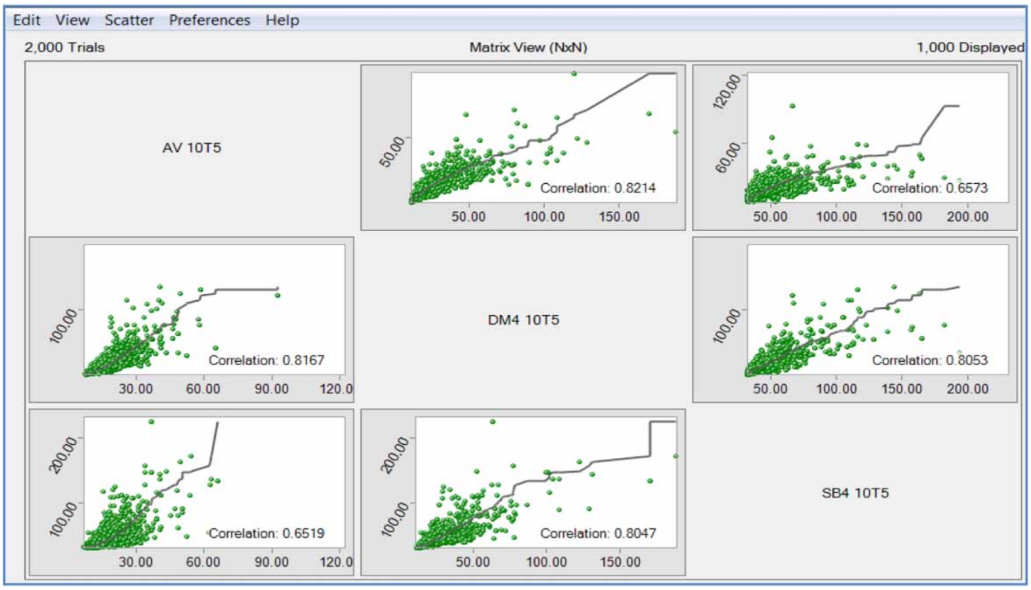

Figure 3 | Matrix view of correlations between generated reservoir inflows in first 10 days of May.

Table 3 | Generated and time-series inflow statistical parameters

Reservoirs		Q average	Median	Standard deviation	Cv
A Vuong	Random	21.56	20.46	6.66	1.11
	Actual	21.56	20.46	6.69	1.14
	Error	0.00	0.00	0.03	0.03
	%	0.00	0.00	0.45	2.63
Song Tranh 2	Random	38.92	36.66	13.77	1.19
	Actual	38.92	36.64	13.87	1.14
	Error	0.00	0.02	0.10	0.05
	%	0.00	0.05	0.72	4.39
Dak Mi 4	Random	97.98	99.76	32.26	−0.24
	Actual	98.28	100.15	32.35	−0.25
	Error	0.30	0.39	0.09	0.01
	%	0.31	0.39	0.28	4.77
Song Bung 4	Random	159.69	145.17	79.03	1.32
	Actual	158.95	144.94	77.50	1.28
	Error	0.74	0.23	1.53	0.04
	%	0.47	0.16	1.97	3.13

Building An optimizing – simulation based model

The main task of the four reservoirs, A Vuong, Song Bung 4, Dak Mi 4 and Song Tranh 2, is generating electricity. However, according to Regulation 1537, the reservoirs have the responsibility to discharge flow to contribute to the maintenance of minimum water levels at Ai Nghia and Giao Thuy stations. The later task was considered as a constraint in the model. At this time, the only goal of the system was to generate as much electricity as possible for the four hydropower plants, A Vuong, Song Bung 4, Dak Mi 4 and Song Tranh 2.

Objective function:

$$F = \text{Max}\left(\frac{1}{n}\sum_{i=1}^{4}\sum_{j=1}^{n}\sum_{t=1}^{25} 9,81 * \beta_{i,j} * Q_{i,j,t} * H_{i,j,t} * \Delta t\right) \tag{1}$$

where:

F: Total electricity production of the four hydropower plants A Vuong, Song Bung 4, Dak Mi 4 and Song Tranh 2.

$Q_{i,j,t}$: Average flow through turbines of plant i, year j, at time period t

$H_{i,j,t}$: Average water column for power generation of plant i, year j, at time period t

$\beta_{i,j}$: The total efficiency of the turbine and generator of the plant i in year j

Δt: Time step (10 days)

n: Number of simulated years (10,000 years)

i: Index of hydropower plants.

The constraints:

(a) Constraints on reservoirs and hydropower plants: constraints on water balance at reservoir nodes; constraints on water balance at flow nodes; constraints on the minimum and maximum stored volume of the reservoirs; constraints on maximum flow through turbines; constraints on power generation capacity; constraints on reservoir topography; constraints on rating curves at downstream cross sections.

(b) Constraints on downstream water supply requirements: Ensure the flow (or water level) at the control points of $Q_{AiNghia} \geq 70\ m^3/s$ (or $H_{AiNghia} \geq 2.67$ m), $Q_{Giao\ Thuy} \geq 48\ m^3/s$ (or $H_{Giao\ Thuy} \geq 1.02$ m).

All of the objective functions and constraints were built in an Excel spreadsheet. Then, the OptQuesttool was applied to find the optimal solution. OptQuest is an optimization tool that runs with Crystal Ball. It acts as an add-in in Crystal Ball, and enhances the simulation model by finding the optimal solution. At a basic level, OptQuest selects a value for each decision variable, imports values into an Excel spreadsheet, runs a Monte Carlo simulation, records the results, and repeats the process. The calculation can be done manually, but as the number of variables decides to increase, the number of variable combinations becomes difficult to use. At an advanced level, OptQuest use a variety of search methodologies, including Tabu search and Scatter search to help find a global optimal solution. While running solutions, OptQuest also checks for compliance with the constraints and requirements. (Oracle Coporation 2008).

The optimization process was applied as follows:

- The inflow time-series of each reservoir was randomly generated according to the Monte Carlo simulation. In order to ensure the homogeneous characteristic of flow regime in the same river system, the generated inflow values still complied with predetermined correlations between tributaries. Each random event is called a trial in Crystal Ball.
- The flow through the turbines of each hydropower plants at each period (25 periods × 4 hydropower plants = 100 variables) was a decision variable. For each set of values for the flow through the turbines, the simulation of the reservoir will be performed to determine the power production at each period. Each such activity is called a simulation. The developed model includes the decision variables of flow through turbines of four hydropower plants at each stage (25 periods × 4 hydropower plants = 100 variables).
- The objective function is to maximize the total power production, which is calculated by the Equation (1). Depending on the calculation scenarios, the total electricity production of one reservoir, two reservoirs or all four reservoirs in the dry season or the whole year can be calculated.
- An optimal search (based on 5,000 of simulations and 2,000 trials) to determine the optimal decision procedure for power production in the dry season of the system.

RESULTS AND DISCUSSION

With the optimizing-simulation based model established above, various scenarios were calculated with different discharge ratios for the four reservoirs: A Vuong, Song Bung 4, Dak Mi 4 and Song Tranh 2, in order to determine the best scenario in terms of electricity generation and ensuring the minimum water level at Ai Nghia and Giao Thuy stations. Ten scenarios were divided into 03 categories as follows:

Category 01: scenario was following the regulation 1537

Baseline scenario (BS): Minimum discharging rates of A Vuong, Song Bung 4 and Dak Mi 4 reservoirs were chosen strictly complying with regulations in Regulation 1537. In the Regulation 1537, the dry season is divided to normal water use period (from 11 June to 31 August and from 16 December to 10 May in the following year) and high season-water use period (from 11 May to 10 June).

Category 02: scenarios were determined according to reservoir characteristics

Scenario 1: The discharge rates of A Vuong, Song Bung 4 and Dak Mi 4 reservoirs were proportionate to the catchment areas of reservoirs in the system ($Q_{A\ Vuong} = 10.2\ m^3/s$; $Q_{SongBung4} = 21.7\ m^3/s$, $Q_{Dakmi4} = 16.8\ m^3/s$).

Scenario 2: The discharge rate of A Vuong reservoir is equal to that of Song Bung 4 reservoir (50%–50%). The discharge rate of Dak Mi 4 reservoir is 8 m^3/s during the normal water use period and is 12.5 m^3/s during the increasing water use period according to Operational Rule 1537.

Scenario 3: The discharge rates of A Vuong, Song Bung 4 and DakMi 4 reservoirs were proportionate to the annual reservoir inflows ($Q_{A\ Vuong} = 11.4\ m^3/s$; $Q_{Song\ Bung\ 4} = 19.1\ m^3/s$, $Q_{Dakmi4} = 18.2\ m^3/s$)

Scenario 4: The discharge rates of A Vuong, Song Bung 4 and Dak Mi 4 reservoirs were proportinate to the reservoir inflow rates in the dry season ($Q_{A\ Vuong} = 9.8\ m^3/s$; $Q_{Song\ Bung\ 4} = 20.2\ m^3/s$, $Q_{Dakmi4} = 18.7\ m^3/s$)

Scenario 5: The discharge rates of A Vuong, Song Bung 4 and DakMi 4 reservoirs were proportionate to active volumes of 4 reservoirs ($Q_{A\ Vuong} = 19.7\ m^3/s$; $Q_{Song\ Bung\ 4} = 17.3\ m^3/s$, $Q_{Dakmi4} = 11.7\ m^3/s$).

Category 03: scenarios were determined according to reservoir characteristics but the discharge rate of Dak Mi 4 reservoir in accordance with regulation 1537

The Dak Mi 4 is the only reservoir to transfer water from Vu Gia river to Thu Bon river for power generation, it cannot reuse the water through turbine to discharge downstream of the Vu Gia river. While other reservoirs can take advantage of the water through turbine to contribute to the downstream minimum flow, the Dak Mi 4 has to reserve a portion of volume for this purpose. The following scenarios to keep the Dak Mi 4 a constant minimum release after the Regulation 1537:

Scenario 6: The discharge rates of A Vuong, Song Bung 4 reservoirs were proportionate to the catchment areas, the discharge rate of DakMi 4 reservoir complies with Operational Rule 1537 ($Q_{A\ Vuong} = 13.03\ m^3/s$; $Q_{Song\ Bung\ 4} = 27.67\ m^3/s$, $Q_{Dakmi4} = 8\ m^3/s$)

Scenario 7: The discharge rates of A Vuong, Song Bung 4 reservoirs were proportionate to annual reservoir inflows, the discharge rate of Dak Mi 4 reservoir complies with Operational Rule 1537 ($Q_{AVuong} = 19.86\ m^3/s$; $Q_{Song\ Bung\ 4} = 20.84\ m^3/s$, $Q_{Dakmi4} = 8\ m^3/s$)

Scenario 8: The discharge rates of A Vuong and Song Bung 4 were proportionate to inflows in the dry season, the discharge rate of DakMi 4 complies with Operational Rule 1537 ($Q_{A\ Vuong} = 19.56\ m^3/s$; $Q_{Song\ Bung\ 4} = 21.14\ m^3/s$, $Q_{Dakmi4} = 8\ m^3/s$)

Scenario 9: The discharge rates of A Vuong, Song Bung 4 were proportionate to reservoir capacities, the discharge rate of DakMi 4 complies with Operational Rule 1537 ($Q_{A\ Vuong} = 16.42\ m^3/s$; $Q_{Song\ Bung\ 4} = 24.28\ m^3/s$, $Q_{Dakmi4} = 8\ m^3/s$)

Actual electricity productions of A Vuong, Song Bung 4, Dak Mi 4 and Song Tranh 2 hydropower plants were collected to compare with the electricity production calculated by each scenario. The data was provided by National Load Dispatch Centre (Table 4).

DISCUSSION

All scenarios have an average value of total electricity production in the dry season (from four reservoirs) larger than the actual electricity production in 2015 and 2016. The largest electricity production was determined in Scenario 5, reaching 1,570.0 million kWh, 10.2 million kWh (0.6%) higher than the Baseline Scenario; 88 million kWh (5.9%) and 170.1 million kWh (12.1%) respectively higher than the actual electricity production of reservoirs in 2015 and 2016.The smallest electricity production is determined in Scenario 4, reaching 1498.3 million kWh.The production of electricity according to Scenario 5 and Scenario 8 is higher than that of the baseline scenario. The production of electricity in the Baseline Scenario (1,559.8 million kWh) is not much different from Scenario 2 (1,555.5 million kWh), Scenario 6 (1,554.8 million kWh) and Scenario 7 (1,553, 1 million kWh). In terms of electricity production, Scenario 5 was proposed to be the optimal scenario (Table 5 and Figure 4).

Table 4 | Actual electricity production during the period of 2014–2016 from reservoirs

		Month												
No.	**Reservoir**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Sum**
Year 2014														
1	A Vu‘o’ng	56.95	45.84	61.55	41.52	74.89	63.8	42.48	63.79	31.78	57.28	18.33	31.66	**589.87**
2	Dak Mi 4	50.13	45.46	55.67	24.6	49.05	35.91	43.53	44.83	28.58	83.88	89.7	118.5	**669.84**
3	Song Tranh 2	34.32	26.69	29.35	21.13	35.94	32.82	21.13	12.84	18.93	57	57.75	104.65	**452.56**
4	Song Bung 4	–	–	–	–	–	–	–	–	–	48.06	30.85	13.25	**92.16**
Year 2015														
1	A Vu‘o’ng	17.46	20	55.19	31.83	69.44	67.28	56.21	52.47	48.36	69.53	59.31	16.41	**563.5**
2	Dak Mi 4	121.9	52.72	52.38	64.21	44.62	44.35	35.36	36.89	67.29	60.93	109.7	87.18	**777.53**
3	Song Tranh 2	72.31	40.15	37.82	44.05	64.22	34.99	18.71	21.03	20.32	20.44	102.19	48.72	**524.94**
4	Song Bung 4	38.44	22.47	46.17	26.56	34.99	31.17	20.73	25.2	24.33	50.59	29.9	10.5	**361.04**
Year 2016														
1	A Vu‘o’ng	2.5	1.37	2.66	31.01	47.1	53.54	77.84	67.34	67.19	60.87	63.38	128.29	**603.08**
2	Dak Mi 4	59.29	38.12	37.76	34.08	50.43	44.03	50.73	57.53	84.87	70.67	149.13	154.69	**831.31**
3	Song Tranh 2	48.16	32.02	26.28	29.11	57.55	40.79	41.4	33.07	49.51	40.25	108.83	140.25	**647.22**
4	Song Bung 4	19.94	19.18	29.95	21.42	23.63	17.3	19.69	30.19	36.98	54.46	76.42	86.53	**435.7**

Source: National Load Dispatch Centre.

Table 5 | Total electricity production in the dry season according to scenarios

Reservoirs	Baseline scenario	Sce.1	Sce. 2	Sce. 3	Sce. 4	Sce. 5	Sce. 6	Sce. 7	Sce. 8	Sce. 9
A Vuong	582.09	563.25	580.39	575.92	562.75	574.80	568.51	565.25	577.5	565.25
Song Tranh 2	303.35	307.84	306.36	306.30	297.81	306.80	304.45	311.62	302.01	304.29
Song Bung 4	384.85	390.72	382.34	388.38	375.82	385.60	381	383.04	387.55	387.17
DakMi 4	289.53	249.27	286.44	242.01	261.96	302.85	300.88	293.18	296.96	291.08
Total electricity production in the dry season	1,559.82	1,511.08	1,555.54	1,512.61	1,498.34	1,570.05	1,554.84	1,553.09	1,564.02	1,549.27

Million kWh.

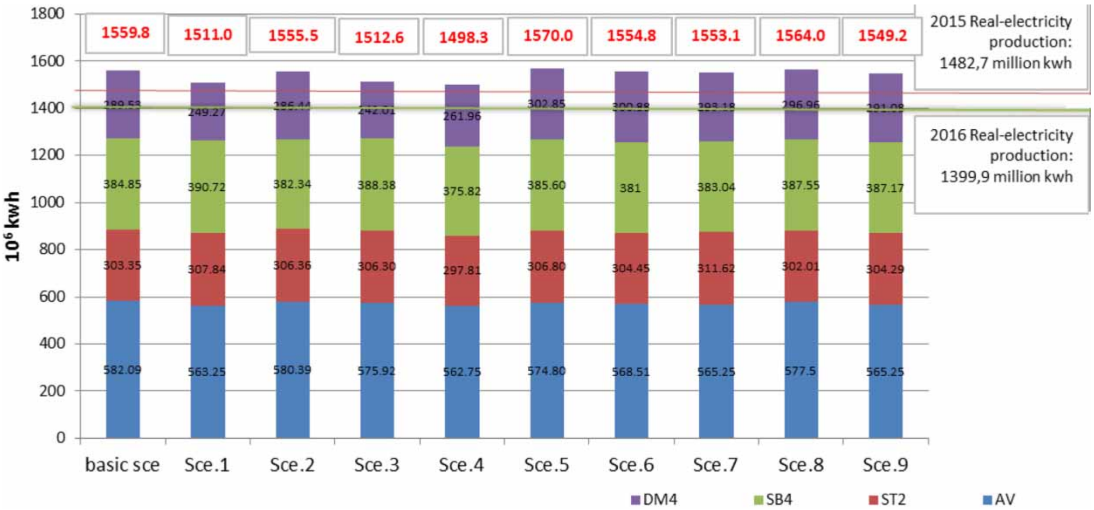

Figure 4 | The total electricity production according to scenarios.

Most of the operational curves of 04 reservoirs violate the current Lower Limit Guide Curve (LLGC) in the Regulation 1537 (dashed lines - Figure 5). The operational curves of reservoirs are lower than the LLGC in June, July, and August. At the end of the dry season, in order to meet the requirement of minimum flow for downstream, all the reservoirs have to discharge significantly. Operation curves of reservoirs in Scenario 5 have the least violation with the LLGC, the violation only occurred in A Vuong and Song Bung 4 reservoirs during one to two weeks in July. Thus, the operational curves of reservoirs in Scenario 5 were proposed to be chosen for improving water use efficiency. The optimal discharge rates of reservoirs in the Scenario 5 are shown in Table 6.

CONCLUSIONS

An optimization model combined with a reservoir operation simulation model has been developed with the objective function, which maximizes the electricity production from hydropower plants while ensuring the required water supply for economic, service sectors and domestic use in the dry

Table 6 | The minimum discharge calculated in each period in the dry season of reservoirs in scenario 5 (optimal scenario)

Period of water supply	A Vuong	Song Bung 4	Dak Mi 4	Period of water supply	A Vuong	Song Bung 4	Dak Mi 4
20 Dec	0	0.00	0.00	30 Apr	6.820741	5.98	4.04
30 Dec	0	0.00	0.00	10 May	15.18019	13.31	9.00
10 Jan	0	0.00	0.00	20 May	13.28	11.64	7.87
20 Jan	9.371005	8.21	5.55	30 May	17.18045	15.06	10.18
30 Jan	0	0.00	0.00	10 Jun	14.76258	12.94	8.75
10 Feb	0	0.00	0.00	20 Jun	20.3595	17.85	12.06
20 Feb	5.108986	4.48	3.03	30 Jun	10.25398	8.99	6.08
30 Feb	17.23082	15.10	10.21	10 Jul	13.01071	11.40	7.71
10 Mar	17.87443	15.67	10.59	20 Jul	13.91461	12.20	8.25
20 Mar	8.319986	7.29	4.93	30 Jul	16.10559	14.12	9.54
30 Mar	21.00961	18.42	12.45	10 Aug	5.584454	4.90	3.31
10 Apr	18.98927	16.64	11.25	20 Aug	11.37033	9.97	6.74
20 Apr	18.68001	16.37	11.07	30 Aug	18.54635	16.26	10.99

Unit: m^3/s.

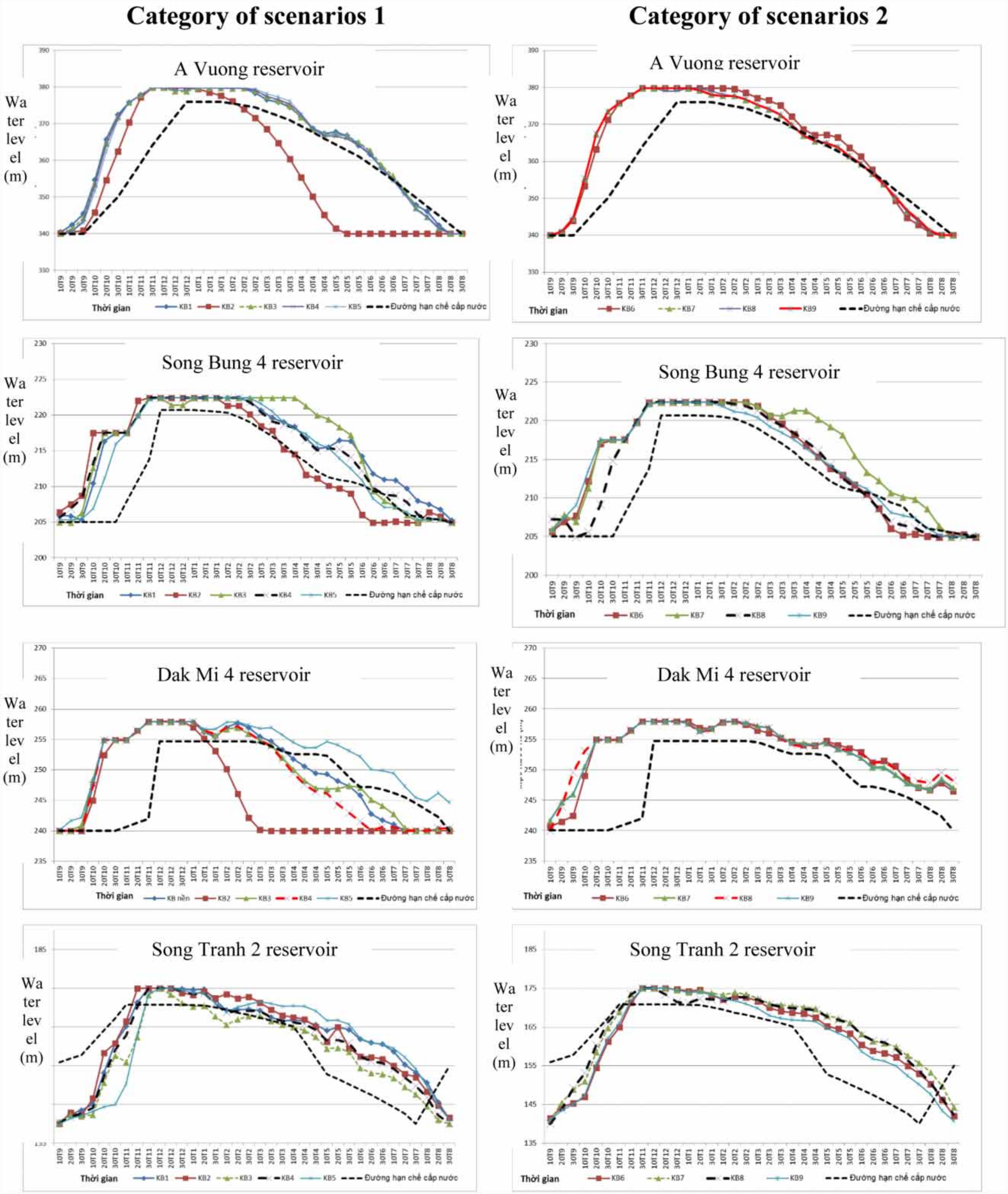

Figure 5 | The optimal operation curve of scenarios (the Low Limit Guide Curve is the dashed line).

season in the Vu Gia – Thu Bon river basin. This study shows that the selection of minimum discharging flow should be proportional to the active capacity of the reservoirs. With the optimal minimum discharge rates ((QA Vuong = 19.7 m^3/s; QSong Bung 4 = 17.3 m^3/s, QDakmi4 = 11.7 m^3/s), the average electricity production of the four reservoirs reached 1,570.0 million kWh, 10.2 million kWh (0.6%) higher than the current scenario according to Regulation 1537. Besides that, the discharge rate ensures the water levels at control points in Ai Nghia and Giao Thuy stations as required. The results of the calculation and analysis have indicated that the new operational guide curve proposed in this study is better than that in the Regulation 1537. However, the study is still limited in the calculation time step of 10 days. To be more practical, further research on how to regulate reservoir systems and evaluate the water supply capacity downstream with short time steps is needed.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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