Journal of Mining and Earth Sciences

Website: http://jmes.humg.edu.vn

Real-time operating decision support system for reservoir operation using weather forecast and a hydrological model

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ARTICLE INFO

Article history:
Received 05th Feb. 2023
Accepted 29th May 2023
Available online 19th June 2023

Keywords:
Decision Support System,
Optimization,
Rainfall Forecast,
Simulation,
Small Hydropower.

ABSTRACT

This paper presents the application of a real-time decision support system (DSS) for power generation and flood control at the Thac Xang hydropower plant in Lang Son province, Vietnam. The DSS consists of three key components: real-time operation and visualization, forecast, and optimized decision modules. The real-time operation and visualization module provides operators with a graphical interface that displays real-time data on the plant's status, such as water levels, reservoir levels, and power output. The weather forecasting module provides information about future precipitation. This information is used as input data for the inflow forecasting model. The real-time computing module takes into account current conditions, such as the water level in the reservoir to compute relevant variables such as current inflow rate or outflow rates from the reservoir. The simulation module is used to test different operating scenarios taking current and future inflow rates into account. This helps the plant operators to understand the impact of their decisions on the plant's performance. The simulation module can also be used to identify potential problems and develop contingency plans. Therefore, a mathematical model is developed. Particularly, this model uses real-time information of dams. The main objective is to maximize economic value over the time horizon by producing electricity when it is most valuable. An approach of a simulated annealing algorithm is used to solve this model. We also present a decision support software tool for small hydropower systems that provide hydropower equipment operators with the information required to optimize the dam's performance in terms of power efficiency and effectiveness.

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DOI: 10.46326/JMES. 2023.64(3).05

1. Introduction

1.1. Extreme weather impacts on hydropower plants in Vietnam

In recent years, numerous studies have been undertaken to determine the scope and extent of predicted climate change threats in Viet Nam. The studies' key findings show Viet Nam's acute vulnerability to sea-level rise, temperature increases, precipitation changes, and extreme weather events (ADB, 2013).

Extreme weather events posed major challenges to hydropower plant operators in Vietnam. Over the last ten years, several severe incidents have occurred at hydropower plants in the Northern and Central regions of Vietnam.

The remarkable event in 2010 at Ho Ho hydropower plant (Figures 1 and 2), where flood water spilling over the top of the dam, when the plant operator failed to control the flood gates, was a serious warning to hydropower plant operators.

It was fortunate that the dam failure did not occur, but the powerhouse constructed on the downstream side of the dam was totally damaged by debris flow with a huge volume of driftwood falling from the top of the dam and jamming inside the powerhouse.

Another serious incident occurred in 2017 at Hoa Binh hydropower plant, the second largest plant in Vietnam. On October 11, Hoa Binh province declared a state of emergency for natural disaster due to heavy rain. On the same day, the Hoa Binh hydropower plant operator was forced to open 8 flood gates, for the first time since the plant was put into operation, in emergency discharge to protect the dam from a sudden surge of reservoir water level to a dangerous level.

During the recent heavy rain event in Central Vietnam in October 2020, the 15-day recorded rainfall, from 4 to 19 October, exceeded the haft of the total annual rainfall in many areas of Central Vietnam, especially in some places exceeded the annual rainfall such as Hue City, where rainfall reached a record high level of nearly 3000mm (Figures 3 and 4). The consequence of this event is great pressure on the flood control operation at hydropower plants in the affected regions. It caused severe flooding in the downstream area of dams.

Figure 1. Water spilling over top of Ho Ho dam due to uncontrollable flood.

Figure 2. Damage of Ho Ho powerhouse caused by debris flow and driftwood.

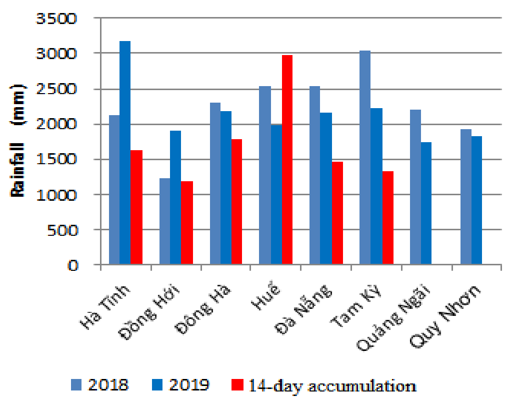

Figure 3. Rainfall records in Central Vietnam.

The serious events mentioned above, are all characterized by unusually concentrated heavy rainfall. If not controlable, they will cause damage to the power generation system or threaten the safety of dams.

Vietnam is a country that still depends on hydropower with a high proportion of this power source to total grid capacity.

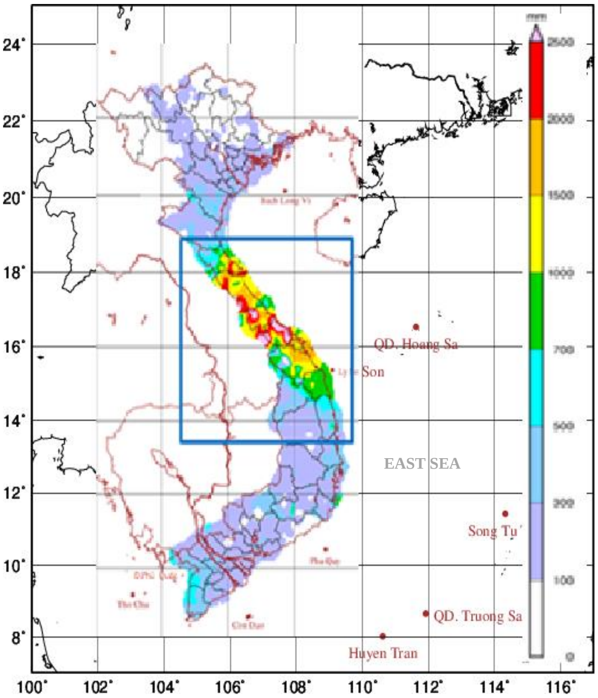

Figure 4. 15-day accumulated rainfall recorded using analysis method from weather radar.

Facing climate change, it is necessary to have safe and effective solutions to protect this power source, as well as human life and property in the affected areas of hydropower projects.

1.2. Application of real-time operating decision support system to reservoir operation

One solution to this problem is to build a real-time operating decision support system (DSS) to manage hydropower plant reservoir operation and control floods.

A DSS is a computer-based tool having interactive, graphical and modeling characteristics to address specific problems and assist individuals in their study and search for a solution to their management problems (Loucks & da Costa, 1991). The purpose of DSS is not to replace but rather to improve human decision-making in making informed choices to achieve a predefined objective (Ahmad & Simonovic, 2006).

The main objective of the present study is to propose an operating DSS system for hydropower plants to empower the stakeholder agencies with the advancement of current weather forecast capability, hydrological modeling, and optimization technique.

A DSS for hydropower plant operation typically has three modules: real-time operation, weather forecasting, and optimization modules. The weather forecasting module provides information about future precipitation. This information is used as input data for the inflow forecasting model. The real-time computing module takes into account current conditions, such as the water level in the reservoir to compute relevant variables such as current inflow rate or outflow rates from the reservoir. The simulation module is used to test different operating scenarios taking current and future inflow rates into account. This helps the plant operators to understand the impact of their decisions on the plant's performance. The simulation module can also be used to identify potential problems and develop contingency plans.

One important feature of our DSS is the ability to predict stream inflow into the reservoir using rainfalls forecasted by Numerical Weather Prediction (NWP) model. With the ability to reliably predict the flow into a reservoir, flood control will be safer.

When reservoir inflow can be predicted with sufficient accuracy hydro generation scheduling can be effectively created through the use of a simulator, a sophisticated software program that is built to help the operator to study various operation scenarios to find the most optimal one.

2. Study site and parameters

2.1. Thac Xang hydropower plant

Thac Xang hydropower complex is located at Hung Viet commune, Trang Dinh district., Lang Son province of Vietnam.

For the operationalization of the DSS conceptualized in this study, Thac Xang dam in Lang Son province of Vietnam was chosen based on its hydrologic characteristics and long record of the observed data. The storage dam, operated primarily for hydropower generation and flood control, forms Thac Xang Lake over the Bac Giang.

River, the grade I branch of Ky Cung River, with a reservoir storage capacity of 43.89 million cubic meters. The storage capacity to annual inflow ratio is around 0.028, which makes the short-term forecasts meaningful for optimizing reservoir operations (Anghileri et al., 2016).

The powerhouse contains two Kaplan turbine units with a hydraulic capacity of 80 m^3/s and a combined nameplate capacity of 20 megawatts (MW). The dam is operated by Su Pan 1 Hydropower JSC (Su Pan 1), a private owner of the Thac Xang hydropower plant.

2.2. Basin features

Although classified as small hydropower according to Vietnamese standards, Thac Xang dam has a considerably large drainage basin of 2660 km^2 (Figure 5). Local planning authority issued a general plan for energy development in the basin, where a cascade of 6 hydropower plants is expected to be built. However, only Thac Xang hydropower plant is currently in operation. So hydrological model, in this case, is calibrated to predict natural stream inflow with no influence of any other reservoir activities upstream of the dam.

The rain monitoring network in Vietnam is generally poor. Recently there have been attempts to develop automatic weather station (AWS) on reservoir basins. To implement the DSS system, Su Pan 1 has installed 6 AWS in the reservoir basin. This observation density is far from satisfactory for capturing the spatial distribution of rainfall. To improve accuracy, analytical rainfall using radar signal analysis technology is applied to the basin to increase the ability of real-time rainfall monitoring with better reliability. This significantly increased the input quality for the hydrological model from the time rain has fallen until the stream reached the reservoir. Taking advantage of stream flow travel times of about 20 hours the reservoir flow is predicted with high accuracy by hydrological model.

Figure 5. Thac Xang reservoir drainage basin and stream network.

2.3. Plant's data and parameters

Plant's data and parameters are integrated in real-time into the DSS by two methods, live data feed, and analytical method. For example, turbine discharge data is fed into the system through a data logger, whereas discharge via spillway can only be indirectly fed to the system using the parametric function of spillway capacity. The parametric function, in this case, is the mathematical relationship between forebay water level, gate opening, and release rate.

The main parameter of our DSS system includes the forebay and tailrace curve, head loss curve, turbine hill curve, and floodgate capacity curve. The forebay curve, also referred to as the reservoir capacity curve, was constructed using a topographic map (scale 1:2000) covering the entire reservoir. The map is created from topographic survey data during the feasibility study of the site. The curve is then modeled by a fitting technique using the polynomial function to available series of data.

The tailrace is the water immediately downstream of a dam into which the spillway and turbines discharge. The tailrace elevation directly affects the hydraulic head, which in turn affects the power generated in the turbines. Hence, accurately modeling power generation necessitates accurately modeling the tailrace elevation. After the plant is put into operation, observed data is available that allows us to properly calibrate the relationship between tailrace water level and discharge. Nonlinear optimization techniques were used to model this relationship using polynomial functions of turbine discharge.

Head losses are due to the frictional resistance of the water conveyance system, which has a nonlinear relationship with turbine discharge. The same technique of optimization using polynomial functions was applied to model this system parameter.

The turbine hill curve provided by the equipment manufacturer is also integrated into the system. Turbine performance is monitored using the curve and actual turbine discharge data obtained from the flow sensor attached to penstock at the location before water flow enters the guide valve.

The floodgate capacity curve (Figure 6) was constructed from the actual spillway cross section and the geometry of floodgates (Figure 7). Thac Xang dam has 3 radial gates with a geometric size of 14.5 m wide and 16.5 m high, which is considerably large of its kind. Gate discharge is a function of the forebay water level and the gate's opening, which is derived from intensive studies using hydraulic models to define the discharge coefficient for different configurations of spillway and gate structure (U. S. Bureau of Reclamation, 1960). Equation (1) is used to compute gate discharge within our DSS.

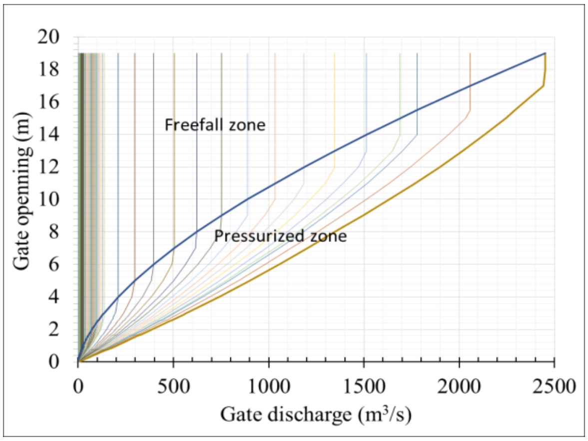

Figure 6. Capacity curve of floodgate installed at Thac Xang dam.

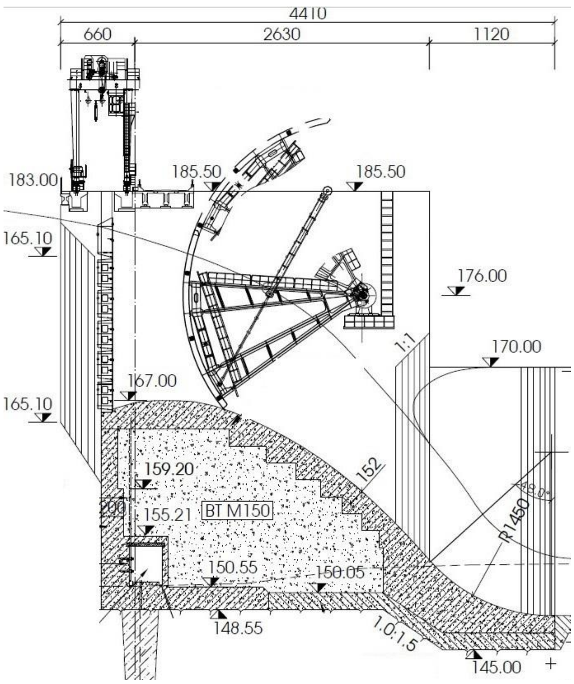

Figure 7. Spillway cross section of Thac Xang dam.

$$Q = \frac{2}{3}\sqrt{2g}\mu B\left(H_1^{3/2} - H_2^{3/2}\right) \qquad (1)$$

Where, Q - gate discharge (m^3/s; μ-discharge coefficient; B-gate width(m); H_1 - water head when the gate is fully opened; H_2 - Total head based on the spillway crest when the gate is fully closed.

3. Real-time operation module

Plant operators depend on the current system status of the reservoir. Therefore the most current state of the reservoir should be assimilated for simulating the reservoir operations model to generate future optimal releases. The system should also stream the actual operations. The real-time operation module in our DSS is designed for that purpose.

Real-time reservoir inflow is computed to help the operator optimize the plan for release policy over the forecast horizon of 48 hours. Actual flood control requires computing temporal resolution as short as 10 minutes to provide operator inflow value at each step so gate opening can be decided to balance with the outflow. Reservoir operation rules for hydropower plants require that no artificial flood be caused during flood discharge. To do this, the operator must balance the discharge volume with the flow into the reservoir. When a major flood is coming, the 10-minute extreme short-term forecast is calculated based on the evolution of the discharge curve into the reservoir by calculating the tangent slope angle of the final discharge point. When the approximate flow into the reservoir is known, after 10 minutes, the flood gates will be operated to discharge that flow so that the total amount in and out of the reservoir is balanced. For floods of a medium or low peak, this time may be longer than 20 or 30 minutes.

$$q_{in}(t) = \sum q_r(t) + \frac{\Delta V(t)}{\Delta t} \qquad (2)$$

Where, q_{in}-reservoir inflow at time t; q_r-release from different channels, i.e. spillway, turbine or other channels like irrigation and minimum required release; ΔV reservoir volume change between two consecutive steps; Δt-time difference between two consecutive steps.

Spillway release is computed using equation (1), while turbine release data is live feed at each step of computation of the system to obtain reservoir inflow value from equation (2). These time series are then visualized in a hydrograph showing the rate of flow versus the time past section of the dam where water is released from the reservoir.

4. Forecast module

4. 1. Rainfall forecast model

Output from regional NWP at a lead time of 48 hours is integrated into the DSS to facilitate the rainfall-runoff model to generate reservoir inflow prediction. The skill of this NWP was confirmed by several pilot studies for a reservoir in Vietnam to more than 60% which indicates a useful forecast. A longer lead time forecast of 10 days, with high uncertainty and lower skill, is used as a reference source of information for operators in the DSS. The NWP model has a resolution of 5 × 5 km providing hourly forecast.

4. 2. Rainfall-runoff model

The Tank model (Sugawara et al., 1984) is built in, as a rainfall-runoff model, for our DSS. A tank model is a simple concept that uses one or more tanks illustrated as reservoirs in a watershed that consider rainfall as the input and generate the output as the surface runoff, subsurface flow, intermediate flow, subbase flow, and base flow as output, as well as the phenomenon of infiltration, percolation, deep percolation and water storages in the tank, can be explained by the model. The improvement of performances of the tank model was conducted by trial and error or automatically by comparing the historical discharge (observed discharges) with simulated discharge resulting from the model (Sugawara, 1979)

To further improve model performance a modified version from the original Tank proposed by Sugawara was applied (Figure 8). The top 3 tanks have 3, instead of 2 in the original version, side outlets. The bottom tank is different from Sugawara proposal. It has an infiltration outlet. These configurations allow the model to describe the runoff curve much better without the need for evaporation data, which is not available during real-time operation.

For the large catchment of Thac Xang dam, the multi-tank model (Figure 8) is designed to capture spatial and temporal rainfall. The catchment is divided into 3 sub-basin (Figure 9) each has its own tank model to predict runoff. Reservoir inflow is a summation of these 3 sub-basin runoffs taking time travel from each

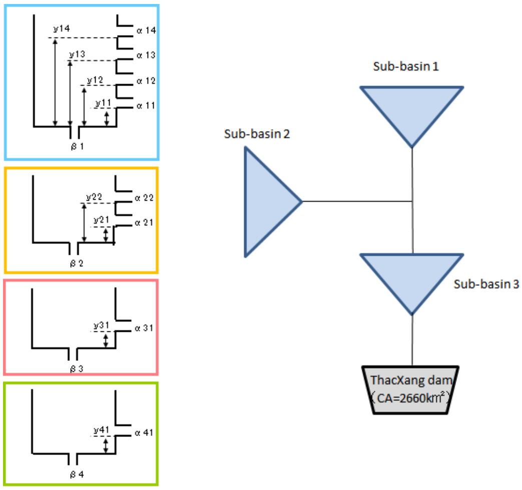

Figure 8. Multi-tank catchment model.

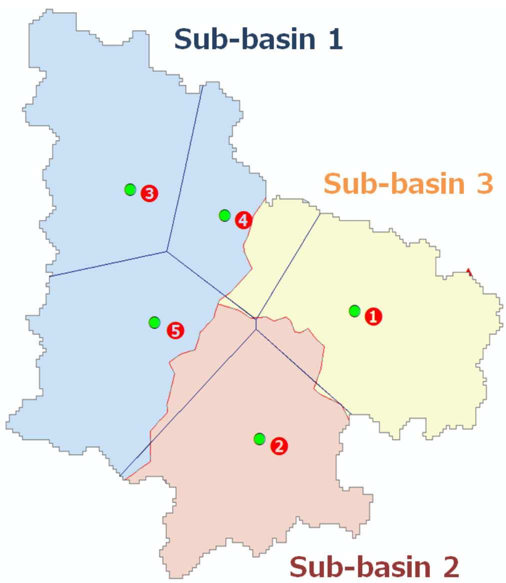

Figure 9. Catchment division in rainfall-runoff modelling.

sub-basin to the reservoir into account. Calibration of this model was done by trial and error until the required performance level is satisfied (Sugawara, 1979). Table 1 shows a set of model parameters used in our DSS. Hourly rainfall data is fed into the Tank model so that the model runs automatically to generate runoff for a 48-hour time horizon. This time series is visually shown in a hydrograph to provide operator knowledge of the 48-hour predicted reservoir inflow.

Table 1. Tank model parameters.

Block	Sub-basin 1	Sub-basin 2	Sub-basin 3
CA（km²）	1284. 6	681.9	693.6
Travel time(h)	18	9	1
α14	0.040	0.040	0.040
α13	0.030	0.030	0.030
α12	0.020	0.020	0.020
α11	0.010	0.010	0.010
β1	0.040	0.040	0.040
y14	160	160	160
y13	100	100	80
y12	40	40	30
y11	10	10	10
α22	0.040	0.040	0.040
α21	0.020	0.020	0.020
β2	0.020	0.020	0.020
y22	50	50	50
y21	25	25	25
α31	0.010	0.010	0.010
β3	0.040	0.040	0.040
y31	20	20	20
α41	0.001	0.001	0.001
β4	0.000	0.000	0.000
y41	0	0	0

5. Optimization module

Based on the forecast inflow, the optimization model runs in a plant simulator, a computer program, which works as a virtual hydropower plant, built in the DSS, an optimized set of releases to be made from the reservoir based on the current reservoir storage and future inflow. The operator also has the option to visualize the corresponding forebay elevations of the reservoir and hydroelectric energy that could be produced (in MWh) by following the optimized release policy. This provides a real-time prospect to the dam operator in assessing the advisory to be followed.

Optimization requires representing two key inputs in addition to plant characteristics: reservoir inflow and energy prices. The latter is fixed by the avoided cost scheme applied for the Thac Xang hydropower plant. The simulator work based on the hydropower production function (HPF) and optimization technique.

The HPF is a nonlinear function, which expresses the amount of gross electrical power extracted from a hydro turbine generator, unit efficiency, turbine discharge, and hydraulic head.

$$P(t) = g\eta H(t)Q(t) \tag{3}$$

Where, P(t)-is the gross electrical power (kW); g-is gravitational acceleration (m/s^2); H(t)-water head (m); and Q(t)- flow through turbines (m^3/s)

Integrating power over time, t (hour), in a given period, ΔT, yields generation (kWh)

$$E = \int_0^T g\eta H(t)Q(t)dt \tag{4}$$

Multiplying generation with energy price, *r(t)* (VND/kWh) results in hydropower revenue (VND):

$$R = \int_0^T g\eta H(t)Q(t)r(t)dt \tag{5}$$

The simulator algorithm solves dynamic optimization problems. Given the amount of water available for release and the given price of electricity over a particular time horizon (T), the plant operator must decide how much water to release for generation in each period (t) to maximize the economic value of the electricity produced. That is to maximize:

$$\sum_0^T P(t)\, r(t) Q(t) \tag{6}$$

Subject to the following constraints:

a) Total amount of water for release W can not be exceeded:

$$\sum_{0}^{T} Q(t) \leq W \qquad (7)$$

b) Gross electrical power, or generation capacity at a time must be in a range from minimum to maximum generation level

$$p_{min} \leq P(t) \leq p_{max} \qquad (8)$$

c) Discharge must respect the minimum and maximum release levels. In this case, the maximum is the total discharge of all units at installed capacity and the minimum is the required release by environmental law.

$$q_{min} \leq Q(t) \leq q_{max} \qquad (9)$$

Using the built-in virtual plant simulator, the operator attempts to maximize economic value over the time horizon by producing electricity when it is most valuable. In the case of avoided cost scheme applied to Thac Xang hydropower plant, the price is highest during the on-peak hours of the dry season. During off-peak hours the strategy is to keep the water head as high as possible but quickly lower the reservoir water level once there is a forecast of high flow coming in.

6. Programming of the DSS

As one of the widely used heuristic approaches (including genetic algorithm and local search) to solve combinatorial problems, simulated annealing (SA) can produce a good though not necessarily global optimal solution within a reasonable computing time. Simulated annealing is a Monte Carlo simulation-based search algorithm. The term "simulated annealing" is derived from a process of heating and then cooling a substance slowly to finally arrive at a solid state. In this simulation, a minimum of the cost function corresponds to the ground state of the substance. The whole search algorithm simply mimics the physical process as below. In the early stages of the execution, the temperature is high, which results in a higher probability for jumping to occur more frequently. In this case, the frequent jumping, which occurs as a way of avoiding local minima, may produce a higher probability of a poor solution. In another way, simulated annealing selects the next point randomly. If a lower-cost solution is found, it is selected. If a higher-cost solution is found, it has a nonzero selection probability. The function that governs the behaviour of the acceptance probability is called the cooling schedule. As the execution time elapses, the temperature decreases, and the cooling schedule reduces the frequency of jumping.

The simulation process terminates after several successive executions with no improvements and returns the best solution found. The following code illustrates the SA algorithm in pseudo-code (Eglese, 1990):

Select an initial state $i \in S$

Select an initial temperature $T > 0$

Set temperature change counter $t = 0$

Repeat

Set repetition counter $n = 0$ (number of iterations to be performed at each temperature)

Repeat

Generate state j

a neighbour of i

Calculate $\delta = f(j) - f(i)$

if $\delta = 0$ then $i = j$

Else *if* random (0, 1) < $exp(-\delta/T)$ then $i = j$

$n+=1$

Until $n = N(t)$

$t+=1$

$T = T(t)$

Until the stopping criteria are true.

As can be seen, the annealing schedule consists of:

the initial value of T

a cooling functions

the number of iterations N(t) to be performed at each temperature

a stopping criterion to terminate the algorithm.

In SA, the algorithm attempts to avoid entrapment in a local optimum by sometimes accepting a neighborhood movement, which increases the value of the objective function. The acceptance or rejection of an uphill move is determined by a sequence of random numbers but with a controlled probability. The probability of accepting a move, which causes an increase δ in f is called the acceptance function and is normally set to $exp(-\delta/T)$ where T is a control parameter, which is analogous to temperate in physical annealing.

In this paper, for the model described in section 5, the algorithm was coded in Visual C# 2017 and implemented on an Intel(R) Core (TM) i7-4790 with 3. 6GHz CPU.

Simulation results

Consider a small hydropower system at Lang Son in Vietnam

- Factory name: Thac Petrol Hydroelectric Plant
- Location: Hung Viet Commune, Trang Dinh Dist., T. Lang Son
- Name of the river: Bac Giang
- Factory type: After the dam
- Number of units: 02
- Capacity: 20MW
- Useful reservoir capacity: 13. 91 million m^3
- Basin area: 2660 km^2

The application of the solution given by our SA is illustrated in Figure 10.

The results of using the SA algorithm for the problem applied in Thac xang hydropower have brought high economic efficiency compared to before the use of the application of decision support tools in Figure 11.

7. Result and discussion

Figure 10 is the hydrograph of the actual operation recorded at Thac Xang Hydropower. Our DSS has successfully supported the operator to achieve safety during flood control and efficient power generation. Reservoir inflow prediction enabled an operator to lower the water level before the floods come, while real-time computation of inflow support “balanced release” so the water level was kept stable during flood regulation. The stable water level indicates the flood regulation is implemented according to the rules and no artificial flood was caused.

Plant electricity sales robustly improved during 3 years from 2017 to 2019 since the introduction of the system. Figure 11 shows that power release increased even though the total inflow decreased, this indicates effective use of water for power generation. Unnecessary spills decreased over time also indicates the good performance of the operator.

8. Conclusion

In this paper, we present a real-time operating DSS and study the case of Thac Xang hydropower plant. The application of the system leads to more realistic and reliable information for the plant’s operator to make decisions during flood control as well as power generation planning. Robust improvement of operation safety and power sale is recorded after the introduction of the system.

Contribution of authors

Thuy Van Ha - conceived of the presented idea, developed the theory, and performed the computations; Tuan Ngoc Ha - verified the analytical methods; Khoat Duc Nguyen - supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

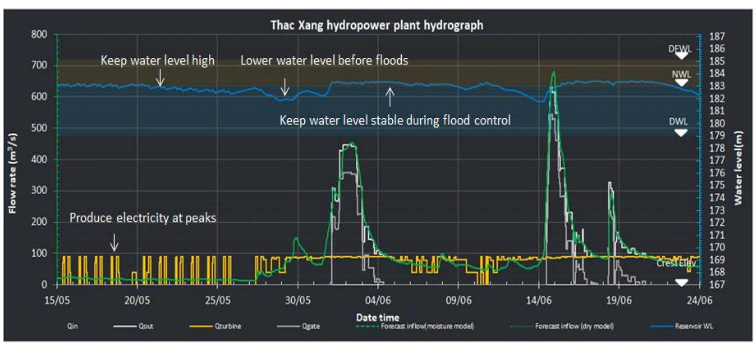

Figure 10. Hydrograph of the real-time DSS for Thac Xang hydropower plant.

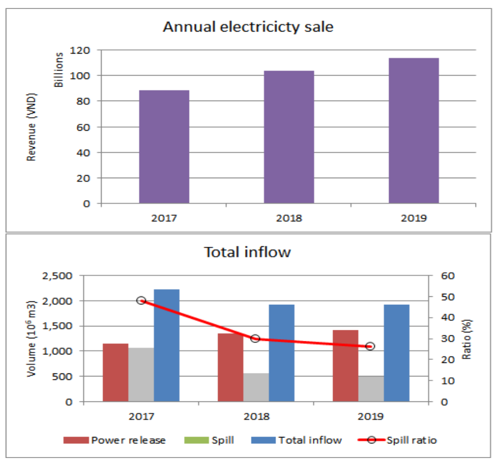

Figure 11. Revenue and water usages.

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