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**OPTIMAL POWER GENERATION SCHEDULING FOR A  
SMALL HYDROPOWER PLANT**

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## INTRODUCTION

In the context of increasing energy demand, the requirement to reduce greenhouse gas emissions and shift to renewable energy sources is becoming an inevitable trend in modern power systems. Hydropower continues to play a crucial role due to its ability to directly convert flowing energy into electricity with high efficiency, fast response times, and the capacity to support power regulation for the electricity system. Besides large-scale hydropower projects, medium and small-scale hydropower plants are particularly significant for mountainous areas and dispersed river basins, where hydropower potential is insufficient for large-scale projects but can still be effectively exploited to supply electricity to the regional grid, contributing to local socio-economic development and increasing the level of renewable energy use.

Unlike renewable energy sources that depend directly on solar radiation or wind speed, hydropower has a certain degree of regulation thanks to the existence of reservoirs or water diversion structures. However, for small and medium-sized hydropower plants, the useful reservoir capacity is often not large, limiting long-term regulation capabilities, while the inflow of water into the reservoir varies greatly seasonally, daily, and according to weather patterns. This fluctuation makes plant operation more complex, especially during transitional periods between the dry and rainy seasons, or when extreme weather events occur. If not operated properly, the plant may encounter problems such as not fully utilizing the incoming water, having to release excess water leading to wasted water resources, operating the turbines in low-efficiency zones, or failing to maintain the reservoir water level within safe limits.

From a technical perspective, the power output of a hydroelectric plant depends simultaneously on the water flow through the turbines, the useful head, and the efficiency of the generating unit. These quantities all have a non-linear relationship with the reservoir state and operating mode. Therefore, determining the optimal power generation schedule cannot rely solely on simple operating experience, but needs to be modeled as an optimization problem that considers the physical, hydraulic, and engineering constraints of the plant. Among these, short-term hydro-scheduling is a crucial class of problems aimed at determining the flow rate, power output, reservoir water level, and operating state of the generating unit within each time interval to achieve the set optimal goal.

For small and medium-sized hydropower plants, the optimal goal may be to maximize total electricity generation, maximize revenue if time-series electricity price data is available, minimize spillway discharge, maintain reservoir water levels in a safe zone, or combine multiple goals in a multi-criteria optimization model. Within the scope of this report, the problem is approached by optimizing total electricity generation over a short operating cycle, based on a series of predicted reservoir inflows and the plant's technical constraints.

This report selects dynamic programming as the tool for constructing the operational optimization problem for the Thac Xang Hydropower Plant. Dynamic programming is suitable for sequential decision-making problems over time, where the current state of the system directly affects its operational capacity in subsequent time periods. In hydropower problems, reservoir capacity or water level can be considered a state variable, while power generation or total discharge is considered a decision variable. Through the water balance equation, power generation model, and reservoir-turbine characteristic relationships, the algorithm can find the optimal operating policy for the entire calculation cycle.

The objective of this report is to develop a theoretical framework and computational model for optimizing power generation schedules for small and medium-sized hydropower plants, focusing on the case study of the Thac Xang Hydropower Plant. The report includes: an overview of small and medium-sized hydropower; an analysis of operational issues and optimization problems; a presentation of the modeling basis for short-term power generation scheduling; the development of a dynamic programming model for the Thac Xang Hydropower Plant; and an analysis of simulation results to assess the applicability of the method in actual operation.

# **I. OVERVIEW OF SMALL AND MEDIUM-SIZED HYDROELECTRIC POWER PLANTS**

## **1.1. The role and importance of small hydropower plants**

Hydropower is one of the earliest and most widely exploited renewable energy sources in the power system. With its characteristics of rapid power output adjustment, long lifespan, and relatively low operating costs after initial investment, hydropower not only serves as a power generation source but can also participate in frequency regulation, power regulation, and support for system stability.

Small and medium-sized hydropower plants are particularly well-suited to medium- or small-scale river basins, especially in mountainous, remote, and isolated areas. These areas often have steep terrain, dispersed river networks, and relatively favorable hydropower potential, but lack the conditions for constructing large hydropower projects. Developing small and medium-sized hydropower allows for the utilization of local energy sources, reducing dependence on distant power transmission.

Besides their role in electricity generation, small and medium-sized hydropower plants can also contribute to water resource management at the basin level: supporting flow regulation, providing local water supply, partially reducing small flood discharges, and facilitating regional infrastructure development. However, due to the often limited reservoir size, small and medium-sized hydropower plants are also susceptible to fluctuations in natural flow. During the dry season, low inflow into the reservoir can reduce electricity generation; during the rainy season, rapidly increasing flow can pose a risk of overflow if the operating schedule is not properly planned.

Therefore, for small and medium-sized hydropower plants, the important issue is not only the design of the project but also optimal operation. Regulating water levels, distributing flow through the turbines, selecting the timing of power generation, and

maintaining the generating units within the high-efficiency zone are crucial factors determining the effectiveness of operation.

## 1.2. Basic structure of Hydropower Systems

Physically, a typical hydroelectric system comprises basic components such as: a catchment basin, a network of channels, a pond or reservoir, a spillway, penstocks, turbines, and generators.

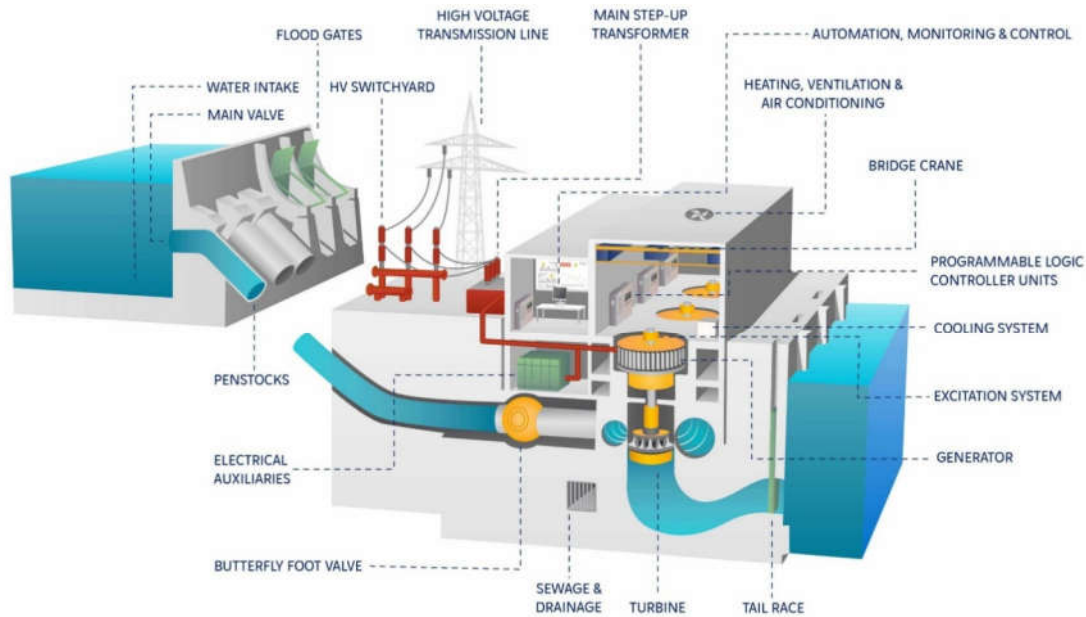


Figure 1. Structure of a hydroelectric power plant.

- Water catchment basin and reservoir: Rainwater from the basin is collected, stored in a reservoir, and distributed through a system of channels or pressurized pipelines.

- Electromechanical system: Includes the turbine, speed control system, control and monitoring system, and generator. Turbines come in various types (such as Kaplan, 5-blade propeller turbine - 5BPT, or counter-rotating centrifugal pump - PAT) and convert the potential and kinetic energy of the flow into mechanical energy to drive the generator. The generator converts this mechanical energy into electrical energy. The speed control system regulates the water flow through the turbine to maintain the required rotational speed and power output. The control and monitoring system collects operational data, monitors water level, flow rate, power output, unit status, and supports operational decision-making.

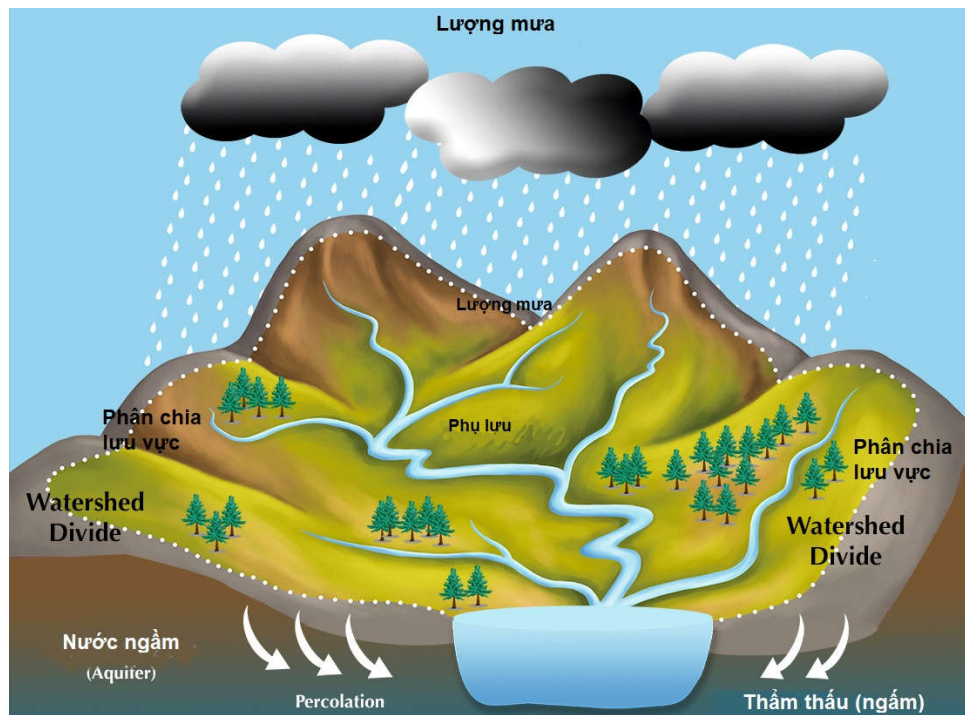


Figure 2. Reservoir catchment area

In terms of energy, the power generation process of a hydroelectric plant can be described as a series of transformations: water is collected or channeled from upstream, passes through the power line to the turbine, rotates the turbine and generator, and then the electrical energy is passed through a transformer system and connected to the power grid. In this series, the power output depends mainly on the flow rate through the turbine, the useful water head, and the combined efficiency of the turbine-generator. Therefore, any operational optimization problem needs to reflect the fundamental relationships between reservoir water level, reservoir capacity, flow rate, water head, and power output.

### 1.3. Operating characteristics of small and medium-sized hydropower plants

The water regulation capacity of small and medium-sized hydropower plants is generally more limited than that of large plants. Due to their small usable capacity, and even the fact that some are run-of-river or downstream hydropower plants with limited water storage capacity, electricity production is heavily dependent on the natural flow into the reservoir or the water intake. When the inflow changes, the plant's power generation mode must also change accordingly. Hydropower plant operation frequently faces non-linear and unstable conditions, especially changes in flow rate over time. In many semi-arid regions (such as the Elqui River basin, Chile), the system is under significant pressure

from prolonged droughts interspersed with extreme weather events. Major problems often encountered include:

- + Reservoir overflow: Occurs when there are sudden heavy rains after a dry period, with inflow exceeding the storage capacity and discharge limit of the system.

- + Turbine performance degradation: When water levels are insufficient, the flow rate through the turbine (such as a Kaplan turbine) drops below 40% of its rated capacity, leading to significant performance degradation.

- + Sensitivity to pressure fluctuations: Inexpensive devices like PATs are highly susceptible to instability when faced with constantly fluctuating flow rates and pressures.

#### **1.4. Optimization problems in the operation of small and medium-sized hydropower plants.**

Optimizing hydropower operation: This problem can be classified according to objectives, time frame, number of reservoirs, number of power plants, and level of model detail. For small and medium-sized hydropower plants, optimization problems often focus on short-term operation, efficient utilization of reservoir water resources, reduced spillway discharge, and maintaining generating units in the high-efficiency zone. The most important aspect is short-term power generation scheduling, aiming to determine the power generation regime at each time step, usually hourly or daily, based on forecasted reservoir water inflow.

Optimizing reservoir regulation: For power plants with regulating reservoirs, reservoir capacity is not only a structural parameter but also a source of energy reserves. Decisions to generate electricity at the present time will change the reservoir capacity at the next time. Therefore, the reservoir regulation problem needs to consider the intertemporal nature of operational decisions.

Optimizing power allocation among generating units: When a power plant has multiple generating units, the same total output can be achieved through various operating combinations. Each unit has its own performance characteristic curve, power limit, and operating conditions. Optimal power allocation helps increase overall efficiency and reduce energy losses. In simple models, this problem can be integrated into the plant's

overall efficiency relationship; in more detailed models, each generating unit needs to be modeled separately.

Optimizing the configuration and design of structures for small or micro-hydroelectric systems. In some studies, changes in reservoir configuration, channel placement, turbine location, or the number of regulating basins can significantly alter electricity production. The current file mentions a comparison of reservoir configurations such as single reservoir, parallel two reservoirs, series two reservoirs, and series two reservoirs with two independent catchments. However, in this report, that section should be presented as a general example of structural optimization, and should not be placed on par with the main problem of optimizing the operation of the Thac Xang Hydropower Plant using dynamic programming.

Multi-objective optimization: In practice, hydropower operation often does not follow a single objective. The plant may need to simultaneously maximize electricity generation, reduce spillway discharge, maintain end-of-cycle water levels, sustain environmental flow, reduce power fluctuations, and ensure reservoir safety. When these objectives conflict, a multi-objective optimization model or weighted objective function is necessary.

Optimization under uncertainty: Inflow to the reservoir, load demand, electricity prices, and meteorological conditions can all fluctuate compared to forecasts. Therefore, modern research approaches often combine forecasting models, machine learning, stochastic optimization, or reinforcement learning to improve the adaptability of the operating system.

### **1.5. Methods for solving hydropower optimization problems**

Hydropower optimization problems can be solved using various groups of methods, depending on model characteristics, number of variables, degree of nonlinearity, time range, and computational requirements. These groups include four main categories: traditional mathematical optimization methods, dynamic programming methods, metaheuristic algorithms, and data-driven methods.

The traditional mathematical optimization methods include linear programming, nonlinear programming, linear integer mixed programming, and nonlinear integer mixed

programming. These methods have the advantage of having a robust mathematical basis, being suitable for problems with clear structures, and being able to consider multiple constraints simultaneously. However, for hydropower problems, the relationship between power, flow rate, head, and efficiency is often nonlinear. If linearization is too strong, the model may lose accuracy; if nonlinearity is maintained, the problem may become difficult to solve or require significant computational time

Dynamic programming is a method particularly well-suited to sequential decision-making problems. The basic idea of dynamic programming is to divide the overall problem into time periods, at which point the system has a certain state and the operator chooses a control decision. This decision produces immediate benefits and causes the system to move to the next state. In the case of hydropower problems, the state is usually reservoir capacity or water level, and the decision is usually the output or discharge rate. This method allows for a clear examination of the dependence between time periods, meaning that the current power generation decision affects future power generation capacity.

The metaheuristic algorithm group includes genetic algorithms, swarm optimization, ant colony algorithms, tempering simulation, and many other variations. These methods have the advantage of being flexible and applicable to nonlinear, non-convex problems with many variables and complex constraints. However, the results often depend on algorithmic parameters, population size, number of iterations, and the method of encoding the solutions. Furthermore, these algorithms often do not guarantee finding a globally optimal solution in a strictly mathematical sense, but primarily aim to find a good solution within an acceptable timeframe.

Data-driven methods include machine learning and reinforcement learning. Machine learning is commonly used to predict flow, forecast power output, or estimate nonlinear relationships in a system. Reinforcement learning can be used to learn operational policies through interaction with a simulated environment. This is a research direction with great potential in the context of increasingly abundant operational data. However, these methods require sufficiently large, high-quality data and need to be carefully validated before being applied to actual operation.

Within the scope of this report, dynamic programming is chosen as the main method because it is suitable for the goal of building a short-term operational optimization problem for a specific hydropower plant. The problem has a sequential structure over time, the main state variable is reservoir capacity, the decision variable is flow rate, and the objective function is total power generation. This type of problem is suitable for clearly presenting the modeling basis, recurrence equations, and calculation procedures.

## **1.6. Objectives, scope, and direction of the report**

From the above analysis, it can be seen that the operation of small and medium-sized hydropower plants is an optimization problem with significant technical and economic implications. Due to reservoir capacity limitations, flow fluctuations, and the nonlinear relationship between flow rate, head, and efficiency, the construction of a rational power generation schedule plays a decisive role in the efficient exploitation of water resources. The main objective of this report is to build an optimal model for short-term power generation scheduling for small and medium-sized hydropower plants, focusing on dynamic programming methods and applying them to the case of the Thac Xang Hydropower Plant. The report aims to clarify how to determine state variables, decision variables, objective functions, state transition functions, and operational constraints of the hydropower problem.

The scope of this report is limited to the optimization problem of power generation in the short-term operating cycle. The model utilizes predicted inflow series to the reservoir, reservoir technical parameters, water level-capacity relationships, downstream water level-flow rate relationships, head characteristics, and turbine efficiency. At this stage, the report does not consider revenue optimization based on real-time electricity prices, does not fully account for the uncertainties of flow forecasts, and has not been extended to multi-cavitation reservoir systems.

## II. OPTIMIZATION MODEL FOR WATERFALL HYDROELECTRIC POWER PLANT

### 2.1. Overview of Thac Xang Hydropower Plant

The Thac Xang Hydropower Plant is a typical Class III hydropower project, designed to harness the potential of hydroelectric energy for electricity generation. Construction began in April 2008, restarted in September 2010, and was officially completed and connected to the grid in July 2016.

- The plant has an installed capacity of 20 MW, comprising two operating units.
- The plant's average annual electricity output supplied to the system is approximately 65.29 million kWh, with a firm capacity of 5.07 MW.



Figure 3. Thac Xang Hydroelectric Power Plant

## 2.2. Catchment Basin and Reservoir Specifications

To establish the optimal power generation problem, the physical parameters of the catchment area and reservoir serve as state variables and core constraints.

Receiving catchment area: The total catchment area is 2660 km<sup>2</sup>; the river length is 127 km and the catchment area is 92 km. This area has an average annual rainfall of 1350 mm, resulting in an average annual flow rate of 62.4 m<sup>3</sup>/s.

Reservoir: The total capacity of the Thac Xang reservoir is 43.89 million m<sup>3</sup>, of which the useful storage capacity for power generation regulation is 3.96 million m<sup>3</sup> and the dead storage capacity is 39.93 million m<sup>3</sup>.

Regarding water levels, the normal water level (NWL) and the design flood level are both at 183.00 m, while the dead water level (DWL) is set at 182.00 m.

Dam System: The main dam has a maximum height of 37 m, a crest width of 6 m, and a crest elevation of 185.5 m; the spillway has a crest elevation of 167 m.

Table 1. Technical specifications of the Thac Xang hydroelectric power plant.

| No.       | Parameter                         | Symbol   | Unit              | Value           |
|-----------|-----------------------------------|----------|-------------------|-----------------|
| <b>I</b>  | <b>Catchment Basin Parameters</b> |          |                   |                 |
| 1         | Catchment Area                    | $F_{lv}$ | km <sup>2</sup>   | 2660            |
| 2         | River Length                      | $L_s$    | km                | 127             |
| 3         | Basin Length                      | $L_{lv}$ | km                | 92              |
| 4         | Average Basin Width               | $B_{lv}$ | km                | 29.4            |
| 5         | Annual Rainfall                   | $X_o$    | mm                | 1350            |
| 6         | Annual Mean Flow                  | $Q_o$    | m <sup>3</sup> /s | 62.4            |
| 7         | Total Annual Runoff               | $W_o$    | m <sup>3</sup>    | 10 <sup>6</sup> |
| 8         | Flood Discharge                   |          |                   |                 |
|           | - P = 0.2%                        |          | m <sup>3</sup> /s | 6320            |
|           | - P = 1.0%                        |          | m <sup>3</sup> /s | 4840            |
|           | - P = 5.0%                        |          | m <sup>3</sup> /s | 3359            |
|           | - P = 10%                         |          | m <sup>3</sup> /s | 2684            |
| <b>II</b> | <b>Reservoir</b>                  |          |                   |                 |
| 1         | Reservoir Surface Area            | $F_{mh}$ | km <sup>2</sup>   | 5.79            |

|            |                               |            |            |          |
|------------|-------------------------------|------------|------------|----------|
| 2          | Maximum Flood Level (Q2.0%)   | MNLKT      | m          | 185.07   |
| 3          | Design Flood Level (Q1.0%)    | MNLTK      | m          | 183.00   |
| 4          | Normal Water Level            | MND        | m          | 183.00   |
| 5          | Dead Water Level              | MNC        | m          | 182.00   |
| 6          | Total Storage Capacity        | $W_{tb}$   | $10^6 m^3$ | 43.89    |
| 7          | Useful Storage Capacity       | $W_{hi}$   | $10^6 m^3$ | 3.96     |
| 8          | Dead Storage Capacity         | $W_c$      | $10^6 m^3$ | 39.93    |
| <b>III</b> | <b>Discharge</b>              |            |            |          |
| 1          | Maximum Discharge             | $Q_{max}$  | $m^3/s$    | 90.14    |
| 2          | Average Discharge             | $Q_{tb}$   | $m^3/s$    | 12.11    |
| IV         | Hydraulic Head                |            |            |          |
| 1          | Maximum Head                  | $H_{max}$  | m          | 30       |
| 2          | Minimum Head                  | $H_{min}$  | m          | 25.8     |
| 3          | Rated Head                    | $H_{tt}$   | m          | 25.8     |
| <b>V</b>   | <b>Energy Parameters</b>      |            |            |          |
| 1          | Average Power Output          | $N_{tb}$   | MW         | 4.09     |
| 2          | Installed Capacity            | $N_{lm}$   | MW         | 20       |
| 3          | Annual Energy Generation      | $E_o$      | $10^6 kWh$ | 90.55    |
| 4          | Operating Hours               | $H_{cslm}$ | hours      | 4528     |
| <b>VI</b>  | <b>Project Specifications</b> |            |            |          |
|            | Project Grade                 |            |            | III      |
| 1          | Dam                           |            |            |          |
|            | Crest Elevation               |            | m          | 185.5    |
|            | Maximum Height                | H          | m          | 37       |
|            | Dam Crest Width               |            | m          | 6        |
|            | Downstream Slope              |            |            | 0.75     |
| 2          | Spillway                      |            |            |          |
|            | Crest Elevation               |            | m          | 167      |
| 3          | Intake Structure              |            |            | Concrete |
|            | Number of Gates               |            |            | 2        |
|            | Gate Dimensions               |            | m x m      | 3.80     |

|   |                    |     |    |         |
|---|--------------------|-----|----|---------|
| 4 | Powerhouse         |     |    | Outdoor |
|   | Number of Units    |     |    | 2       |
|   | Installed Capacity | Nlm | MW | 20      |
|   | Turbine Type       |     |    | Kaplan  |

### 2.3. Power transmission lines, turbines, and generators

The power plant's energy transmission system is responsible for channeling water from the reservoir through the intake, conduit, and turbine to generate electricity. The water flow through the turbine creates a mechanical torque that rotates the generator. The plant's power output depends primarily on three factors: the water flow through the turbine, the useful head, and the combined efficiency of the turbine-generator.

The Thac Xang hydropower plant has a maximum flow rate of 90.14 m<sup>3</sup>/s, an average flow rate of approximately 12.11 m<sup>3</sup>/s. The maximum head is 30 m, while the minimum and calculated head is 25.8 m. The plant uses two Kaplan turbine units with a total installed capacity of 20 MW.

In the operational optimization problem, the turbine efficiency characteristic plays a crucial role because it makes the relationship between flow rate and power output non-linear. Therefore, it cannot be simply assumed that generating electricity with more water will always result in a linear increase in efficiency. The optimization algorithm needs to determine the optimal flow rate to both utilize the inflow of water into the reservoir and maintain the turbine within a suitable operating range. Pump-actuated turbine (PAT): This solution utilizes counter-flow centrifugal pumps and has low investment costs. However, PAT lacks a guide mechanism to regulate flow rate, making it highly sensitive to pressure fluctuations and only truly effective under stable flow and head conditions.

Table 2. Power line and main unit parameters

| Parameter group | Quantity                             | Symbol            | Unit              | Value |
|-----------------|--------------------------------------|-------------------|-------------------|-------|
| Flow rate       | Maximum flow through the power plant | $(Q_{\max})$      | m <sup>3</sup> /s | 90,14 |
| Flow rate       | Average flow rate                    | $(Q_{\text{tb}})$ | m <sup>3</sup> /s | 12,11 |
| Head            | Maximum head                         | $(H_{\max})$      | m                 | 30    |

|                  |                              |              |               |        |
|------------------|------------------------------|--------------|---------------|--------|
| Head             | Minimum head                 | $(H_{\min})$ | m             | 25,8   |
| Head             | Design head                  | $(H_{tt})$   | m             | 25,8   |
| Energy           | Average power output         | $(N_{tb})$   | MW            | 4,09   |
| Energy           | Installed capacity           | $(N_{lm})$   | MW            | 20     |
| Energy           | Average annual energy output | $(E_0)$      | $10^6$<br>kWh | 90,55  |
| Generating units | Number of generating units   | —            | tổ            | 2      |
| Generating units | Turbine type                 | —            | —             | Kaplan |

#### 2.4. Operational optimization requirements for the Thac Xang hydroelectric power plant.

In practical operation, hydropower plants need to simultaneously ensure several requirements: efficient utilization of reservoir water inflow, maintaining water levels within permissible limits, operating turbines within suitable efficiency zones, and limiting spillway discharge. For Thac Xang Hydropower Plant, these requirements are even more pronounced due to the reservoir's useful capacity of only about 3.96 million m<sup>3</sup>, while inflow can vary significantly over time.

+ The requirement to maximize electricity generation during the operating cycle: With the same series of inflows to the reservoir, different power generation schedules will produce different electricity outputs due to changes in reservoir head and turbine efficiency.

+ The requirement to maintain reservoir water levels within safe limits: In the calculation model, the upstream water level needs to be between the dead water level and the normal water level. For Thac Xang, this range corresponds to 182.00 m to 183.00 m. Violating the lower limit can affect power generation capacity and the operational safety of the power line; while violating the upper limit can increase the risk of spillway discharge or affect reservoir safety.

+ Requirement to limit spillway discharge: The optimization problem needs to allocate the generation flow to maximize the utilization of the inflow into the reservoir without exceeding the water level limit.

+ Requirement to ensure the operating limits of the generating units: The total generating capacity must not exceed the installed capacity of 20 MW. At the same time, the capacity of each generating unit must be within the permissible operating range. For a plant with two generating units, the optimization algorithm needs to indirectly or directly determine the generating unit dispatching mode corresponding to the total generation flow and the plant's generating capacity.

Based on the above requirements, the Thac Xang Hydropower Plant operation optimization problem can be considered a sequential decision-making problem over time. At each time period, the amount of water used for power generation must be decided, thereby determining the generating capacity and reservoir status in the next time period. Decisions made at the present time directly affect future power generation capacity through changes in reservoir volume and water level.

## 2.5. Mô hình Toán học cơ sở (Basic Mathematical Modeling)

### 2.5.1. Reservoir water balance model

The Short-Term Generation Scheduling (STHS) problem requires tight constraints through two basic mathematical models of reservoirs and generators.

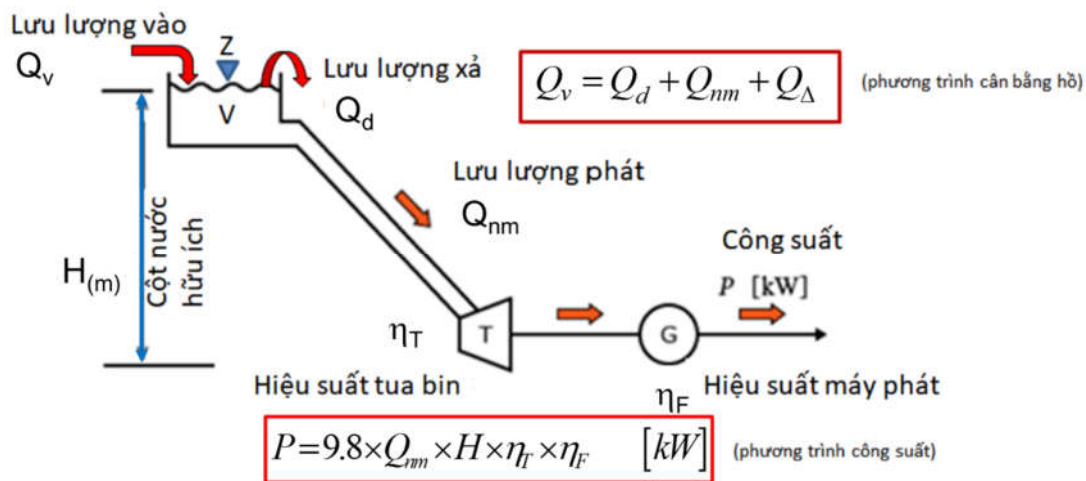


Figure 4. Flow diagram of the plant

Reservoir Balance Equation:

$$Q_v = Q_d + Q_{nm} + Q_{\Delta}$$

Where:  $Q_v$  is the inflow rate;  $Q_d$  is the outflow rate through the spillway;  $Q_{nm}$  is the power generation flow rate (flowing through the turbine); and  $Q_{\Delta}$  is the amount of water loss or difference.

### 2.5.2. Useful water column model

The useful head is a quantity that determines the ability of a water flow to convert energy into power generation. The useful head is determined by the difference between the upstream and downstream water levels, after subtracting head losses along the power transmission line.

At time  $t$ , the useful head is determined by the formula:

$$H_{hi,t} = Z_{tl,t} - Z_{hl,t} - h_{tt,t}$$

Where:

- $H_{hi,t}$  is a useful water column
- $Z_{tl,t}$  is the upstream water level;
- $Z_{hl,t}$  is the downstream water level;
- $h_{tt,t}$  is the head loss on the power line.

### 2.5.3. Power output model

Power Equation:

The flow of water through the plant, passing through the turbine that rotates the generator, will produce electrical power according to the formula:

$$P = \eta(Q, H) \times \rho \times g \times Q_{nm} \times H_{hi}$$

Where:  $\eta(Q, H)$  is the efficiency of the entire generating unit, including the turbine and generator, at the respective flow rate and head;  $\rho$  density of water,  $g$ , acceleration due to gravity,  $Q_{nm}$  useful flow rate and pressure head  $H_{hi}$ .

The useful head is determined by the difference in upstream water levels ( $H_u$ ) with downstream water level ( $H_{hl}$ ) and head loss ( $H_{tt}$ ):

$$H_{hi} = H_{ul} - H_{hl} - H_{tt}$$

In this case: the upstream water level is a function of the water volume (V) in the lake.

$H_{ul} = f(V)$  The downstream water level is a function of the discharge flow rate.

$H_{hl} = f(Q_{nm} + Q_{dp})$ ; Head loss depends on the flow rate through the plant.

$H_{tt} = f(Q_{nm})$

The optimization problem for the hydroelectric power plant presented in this paper will be the total electrical energy (E) obtained based on the inflow into the reservoir and the plant's technical constraints. Further development will be undertaken to optimize it economically when market electricity price forecasts become available. The non-linear relationship between water level (Z), volume (V), and downstream flow rate (Q) are crucial inputs for optimization algorithms (such as Dynamic Programming - DP, Genetic Algorithm - GA) to find the best water discharge trajectory to maximize electrical energy output without violating dam safety constraints.

## KẾT LUẬN

The above content presents the research subject, mathematical model, optimization problem formulation, dynamic programming algorithm, and simulation results for the Thac Xang Hydropower Plant. Based on the technical parameters of the catchment area, reservoir, power line, and generating units, the short-term power generation scheduling optimization problem was formulated with the objective function of maximizing the total power generated in a 168-hour cycle.

The mathematical model is built based on the water balance equation, the useful head model, and the power generation formula. Relationships such as water level - reservoir capacity, downstream water level - flow rate, head loss, and turbine efficiency are used to reflect the actual operating conditions of the plant.

Dynamic programming is applied with reservoir capacity as the state variable and power generation flow rate as the decision variable. The algorithm consists of two phases: inverse computation to determine the optimal policy and forward simulation to create an optimal operating schedule over time. Simulation results show that the algorithm is capable of efficiently utilizing the reservoir's water inflow, maintaining the water level within

permissible limits, avoiding spillway discharge in the scenario considered, and achieving a total power output of approximately 1683–1684 MWh

The results of the discretization density survey show that as the number of state levels increases, the optimal energy output increases but gradually saturates. This confirms the need to choose a reasonable discretization density to balance accuracy and computational load. The content of this chapter serves as a basis for making observations, conclusions, and directions for developing optimal hydropower operation models in subsequent studies

### **III. DEVELOPING A DYNAMIC PROGRAMMING PROBLEM FOR THAC XANG HYDROELECTRIC POWER PLANT**

To effectively manage a small-scale hydropower plant in the face of varying inflow, data analysis and the establishment of optimization strategies are crucial requirements. The System for Scheduling and Reservoir Regulation (STHS) problem is addressed through various layers of algorithms, ranging from traditional to artificial intelligence applications.

#### **3.1. Short-Term Hydro Scheduling - STHS**

The STHS problem aims to maximize economic benefits or electricity production over a short period (usually daily or weekly). The modeling process includes:

Objective function: Maximizing power generation based on available hydraulic parameters.

State variables and control variables: Discharge flow ( $Q$ ) is used as the control variable, while reservoir water level ( $Z$ ) and volume ( $V$ ) act as state variables.

Constraints: Based on two core models: the reservoir model (flow balance equation  $Q_v = Q_d + Q_{nm} + Q_{\Delta}$ ) and the generator model (maximum/minimum power limit, useful head).

#### **3.2. Optimization Strategy using Dynamic Programming (DP) for Thac Xang Hydropower Plants**

Among traditional methods, Dynamic Programming (DP) and Mixed Linear Programming (MILP) are fundamental tools. To apply DP, we need to define the problem through four core elements:

##### **a. Stages**

These are the time steps at which we need to make decisions. In the hydropower plant problem, each hour in the operating cycle is defined as a stage ( $t=1,2,\dots,T$ , where  $T$  is the total number of hours in the forecast series).

##### **b. States**

States are considered variables that describe the "condition" of the system at each stage. They contain enough information to allow us to make decisions for the next stage without knowing the past. For a hydropower plant, the most important state variable is the water

volume in the reservoir  $V_t$  (Reservoir volume at the beginning of stage  $t$ ). The reservoir water volume is a continuous variable; for DP to work effectively, a finite number of states are needed. Therefore,  $V_t$  needs to be discretized.

In the operating volume range  $[V_{\min}, V_{\max}]$ , the water volume in the reservoir is discretized into  $N$  different state levels:  $V(1), V(2), \dots, V(N)$ . These are the possible states that the reservoir can be in at each stage.

### c. Decisions

The decision here is the plant's operational activity performed at each stage. In this problem, the decision is the total downstream discharge flow  $Q_{\text{discharge},t}$  (Total discharge flow in stage  $t$  includes power generation flow and spillway discharge flow).

Similar to the state variable, the decision variable also needs to be discretized. The discharge flow range  $[0, Q_{\text{discharge},\max}]$  is divided into  $M$  different levels:  $Q(1), Q(2), \dots, Q(M)$ .

### d. State Transition Function and Profit Function

State transition function: This is a function to determine what the next state will be based on the current state and the chosen decision. In a hydroelectric plant, this is the water balance equation:

$$V_{t+1} = V_t + (Q_{\text{vao},t} - Q_{\text{xa},t}) \cdot \Delta t$$

Where  $Q_{\text{vao},t}$  is the predicted inflow to the reservoir during period  $t$ .

**Profit function:** Calculates the benefit obtained at a given period  $t$  when in a certain state and making a certain decision. In this paper, profit is defined as energy ( $E$ ).

$$E_t(V_t, Q_{\text{xa},t}) = P(V_t, Q_{\text{xa},t}) \cdot \Delta t$$

In which the power function  $P(V_t, Q_{\text{xa},t})$  is a complex nonlinear function

$$P = \eta(Q, H) \times \rho \times g \times Q \times H$$

## 2.3. Calculation steps of the DP algorithm

The DP algorithm for reservoir operation is developed in two phases: Inverse calculation and Forward simulation.

## Phase 1: Backtracking

Backtracking is performed from the last stage ( $t=T$ ) back to the first stage ( $t=1$ ).

### Step 1: Initialization at the last stage ( $t = T$ )

Create a storage table  $J_T(V_T)$ : Optimal profit at the final stage  $T$  for each volume state  $V_T$ .

For each possible volume state  $V_T^{(i)}$  (với  $i=1\dots N$ ):

- Try all possible discharge decisions  $Q_{xa,T}^{(j)}$  (với  $j=1\dots M$ ).
- Calculate immediate profit:  $E_T(V_T^{(i)}, Q_{xa,T}^{(j)})$ .
- *Assumption:* At the end of period  $T$ , there are no further future benefits. Therefore,  $J_T(V_T^{(i)})$  is the greatest profit that can be achieved.

$$J_T(V_T) = \max_{Q_{xa,T}} \{E_T(V_T, Q_{xa,T})\}$$

- Save the decision  $Q_{xa,t}^{(i)}$  has generated this maximum profit.

### Step 2: Regression loop ( $t = T-1, T-2, \dots, 1$ )

For each stage  $t$  under consideration:

- Create a table  $J_t(V_t)$  and an optimal decision table  $Q_{xa,t}^*$ .
- For each possible volume state:  $V_t^{(i)}$
- For each possible discharge decision:  $Q_{xa,t}^{(j)}$ :
- Calculate immediate profit:  $E_t(V_t, Q_{xa,t}) = P(V_t, Q_{xa,t}) \cdot \Delta t$
- Calculate the next state:  $V_{t+1} = V_t + (Q_{vao,t} - Q_{xa,t}) \cdot \Delta t$
- Determine the optimal future profit: Find the value  $J_{t+1}(V_{t+1})$  from the table calculated in the previous step (period  $t+1$ ). If  $V_{t+1}$  does not fall on discrete points, perform linear interpolation between the two nearest points.
- From the table calculated in the previous step (stage  $t+1$ ). If it does not fall exactly on discrete points, perform linear interpolation between the two nearest points.

- Calculate total profit: Total = Immediate profit + Optimal future profit.
  - Find the decision  $Q_{xa,t}^{(j)}$  that yields the greatest total profit
  - Store that greatest total profit in  $J_t(V_t^{(i)})$
  - Store the corresponding optimal decision in  $Q_{xa,t}^*(V_t^{(i)})$ .

After the loop finishes at  $t=1$ , a set of "optimal operating policy" tables is generated  $Q_{xa,t}^*$  for all states and all stages.

## Phase 2: Forward Simulation

The forward simulation process will find a single optimal path (set of discharge values as  $t$  approaches 1). Starting at the initial stage ( $t=1$ ): Knowing the initial state of the reservoir is  $V_{start}$ .

### Simulation progressing over time ( $t = 1, 2, \dots, T$ ):

- At stage  $t$ , the current state is  $V_t$ .
- Look up the policy table calculated in Phase 1 to find the optimal decision
- $Q_{oiuu,t} = Q_{xa,t}^*(V_t)$ . (Use interpolation if  $V_t$  does not fall into a discrete point).
- Record this decision.
- Determine the state for the next phase:  $V_{t+1} = V_t + (Q_{vao,t} - Q_{xa,t}) \cdot \Delta t$

Repeat until the end of the cycle.

The final result of Phase 2 is a single optimal operating schedule for the entire cycle.

At the Thac Xang Hydropower Plant, DP is directly applied to review the optimal water discharge trajectory over each time step. This strategy is particularly dependent on analyzing data from the system's nonlinear characteristic curves:

Water level-capacity relationship (Q-Z relation): Models the change in reservoir storage space as the water level fluctuates from Dead Water Level (DWL - 182.00m) to Normal Water Level (NWL - 183.00m)

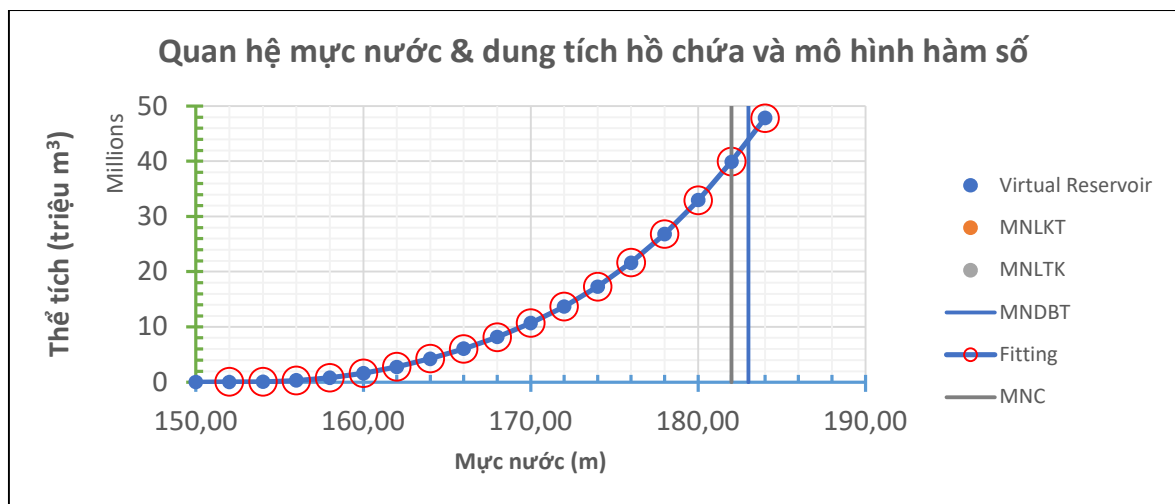


Figure 5. Relationship between water level and hydropower capacity of Thac Xang

Downstream water level - flow rate relationship (Zt-Q relation): Determines the accurate useful head (H) for the power calculation formula

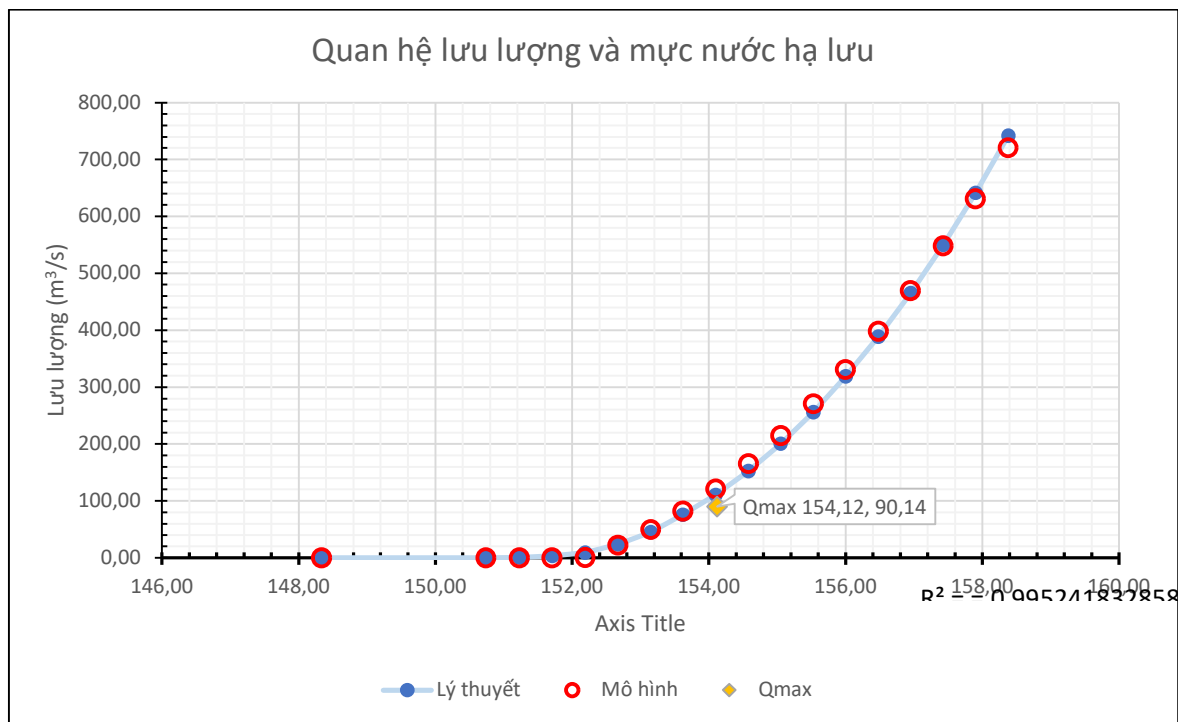


Figure 6. Relationship between downstream water level and flow rate

Turbine Efficiency Curve: Kaplan turbine data analysis shows that efficiency ( $\eta_T$ ) varies significantly with discharge rate ( $Q/Q_{max}$ ). For optimal performance, the DP will seek to maintain discharge flow rate close to the rated point, where turbine efficiency peaks at approximately 90%.

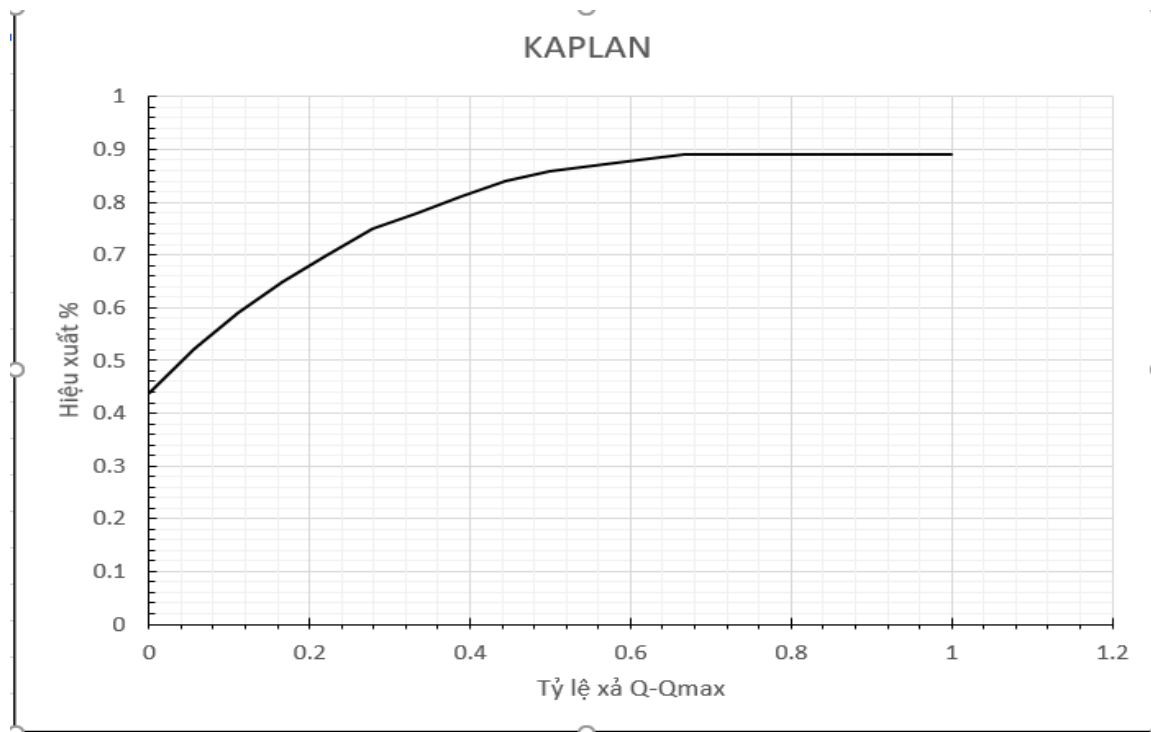


Figure 7. Turbine performance curve

### 3.3. Genetic Algorithms - GA

For small hydropower systems with unstable flow, Genetic Algorithm (GA), PSO, and ACO demonstrate superior advantages.

Mechanism of operation: The GA algorithm is used to control the schedule of the upstream pumping station. It continuously collects and evaluates three input parameters: reservoir water level, inlet flow rate, and electricity tariff.

The predicted average inflow ( $m^3/s$ ) data for the Thac Xang hydropower plant reservoir over 7 days is given in Table 3.

Table 3. 7-day average water flow data

| Ngày +                   | 1    | 2    | 3  | 4    | 5    | 6  | 7    |
|--------------------------|------|------|----|------|------|----|------|
| Lưu lượng<br>( $m^3/s$ ) | 15.8 | 14.3 | 24 | 59.2 | 54.7 | 64 | 54.2 |

The average water inflow data for the reservoir, as shown in Table 3, is divided into 24 time steps/day. Assuming the initial water level is the dead water level (39,930,000  $m^3$ ), the results obtained after optimization with 50 volume levels and 30 flow rate levels are shown in Figure 8. The main parameters are as follows

Optimal number of phases: 168 hours

Number of level/volume states: 50

Number of flow rate levels: 30

Tối ưu hóa vận hành thủy điện - Thuật toán DP

File

Cài đặt tham số | Dữ liệu đầu vào | Đồ thị kết quả

Tải dữ liệu đầu vào

Tải file CSV dòng chảy | Đã tải dữ liệu dự báo: 7 ngày

Tham số tối ưu DP

Số trạng thái thể tích: 50

Số trạng thái lưu lượng: 30

Chức năng

Giải bài toán DP | Xuất dữ liệu kết quả

Kết quả và trạng thái

Đã tải dữ liệu dự báo dòng chảy từ file CSV: 7 ngày  
Đang giải bài toán DP... Vui lòng đợi.

===== KẾT QUẢ TỐI ƯU DP =====

Tổng năng lượng sản xuất : 1683.42 MWh  
Thể tích cuối kỳ : 39940985 m³  
Số giai đoạn tối ưu : 168 giờ  
Số trạng thái mức/thể tích : 50  
Số mức lưu lượng phát : 30

=====

Chi tiết vận hành (10 bước đầu):  
Thời điểm 0: Thể tích = 39930000 m³, Xả = 0.00 m³/s, Công suất = 0.00 MW  
Turbine 1(OFF: 0.0MW, 0.0m³/s), Turbine 2(OFF: 0.0MW, 0.0m³/s)

Figure 8. Results of the DP optimization problem

Benefits: Based on these parameters, GA will automatically decide the optimal pump activation time. This helps the system ensure that pumps only run when necessary (avoiding excessive starting that wastes electricity), maintain water levels at a safe level to proactively prevent reservoir overflow, and minimize overall energy costs.

In particular, the program calculated and utilized most of the reservoir water (end-of-cycle volume 39,940,985 m³) and generated 1683.42 MWh of electricity.

Variations in reservoir water volume, water level, flow rate, status, and power output of each generator unit.

Figure 9 shows the group of flow rate graphs of the power plant during the optimal operation. Because the reservoir water volume was at a sufficient level, the optimization

program utilized the entire the inflow to the reservoir is used for power generation. The spillway discharge is zero. The total flow through the plant is planned to closely follow the inflow to the reservoir, ensuring full utilization of the water. Therefore, the reservoir water volume at the end of the period is approximately the same as at the beginning of the period (3,993,000 m<sup>3</sup> at the beginning compared to 39,940,985 m<sup>3</sup> at the end of the period).

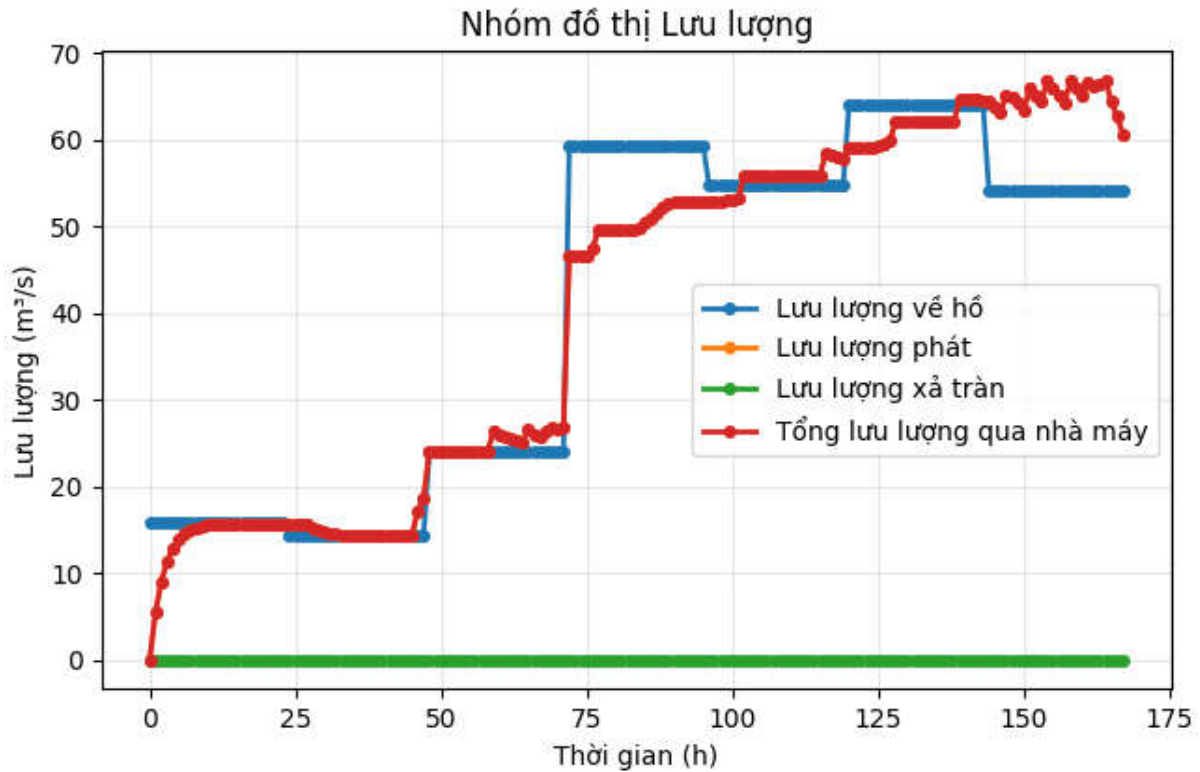


Figure 9. Flow components

Corresponding to the operating water flow rates during the optimal time, the upstream, downstream water levels and head of the plant are shown in Figure 11.

In which the upstream water level is optimally maintained between the dead water level and the storm level (182.0m to 182.45m), the downstream water level varies between 148.25m and 150.75m.

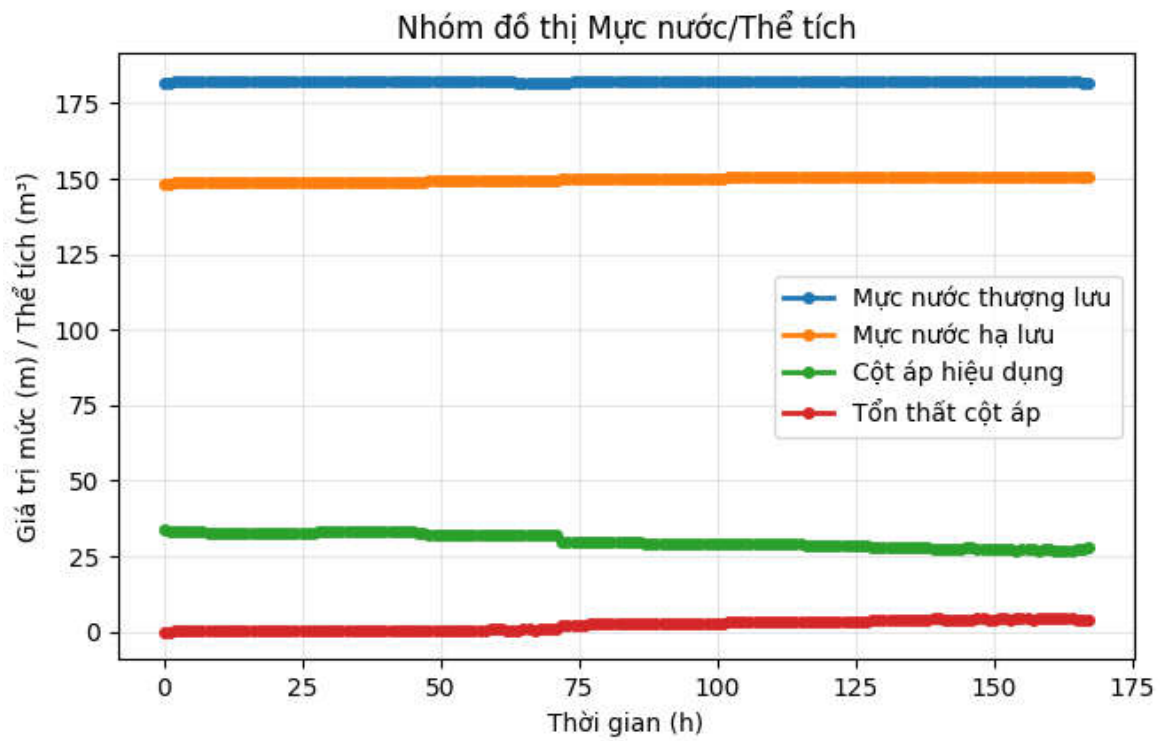


Figure 10. Water level components

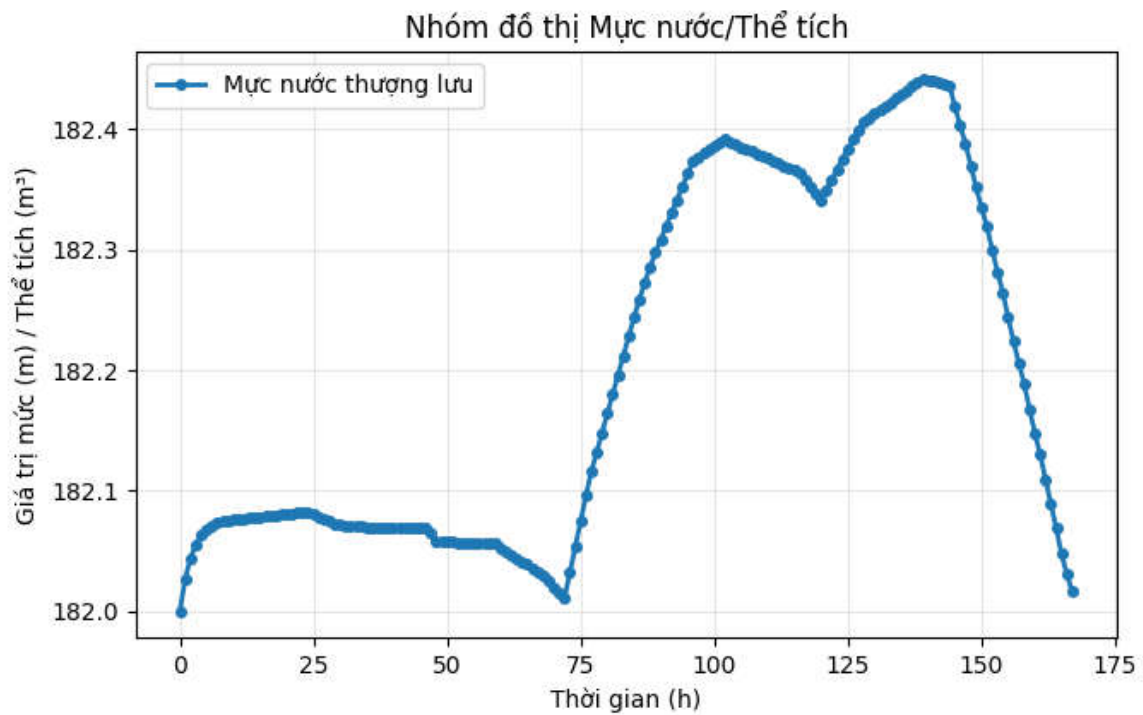


Figure 11. Upstream water level

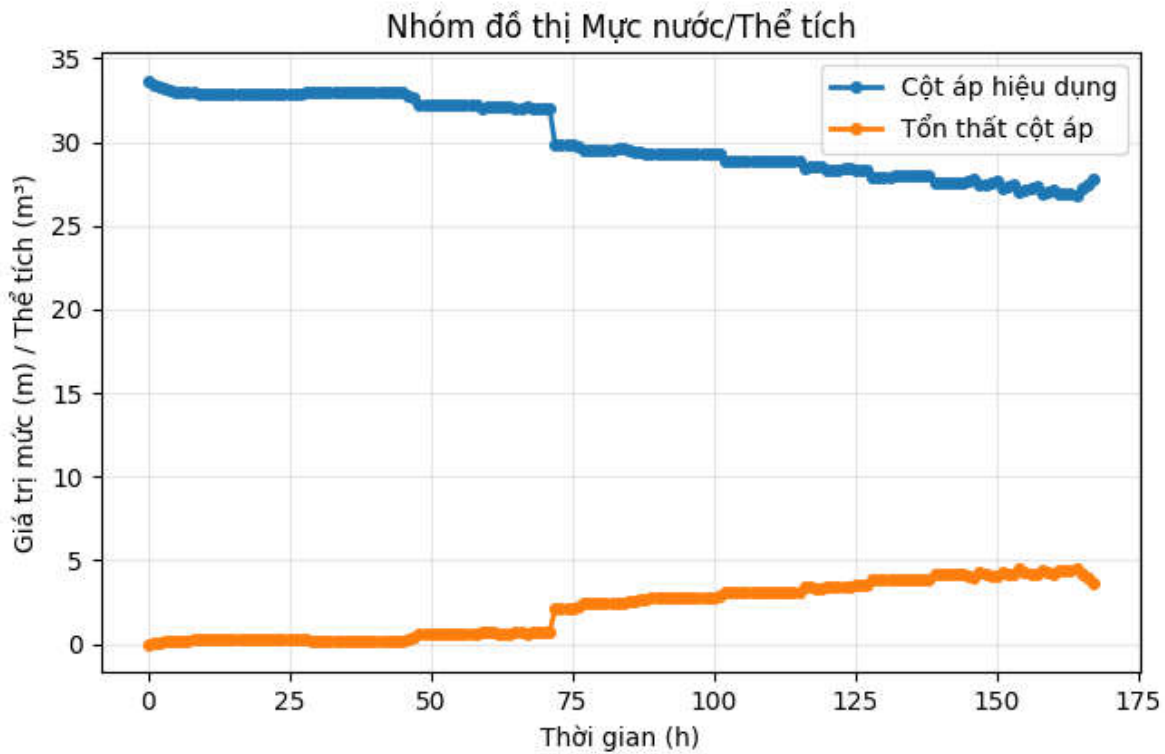


Figure 12. Useful head and head loss

The useful (effective) head (Figure 12) is maintained between 27m and 33.5m, ensuring the operating head of the turbine generator of the power plant.

The simulation results of the power plant's power generation operation are shown in Figure 13. According to the results of the optimal dynamic programming run, in the first 72 hours only unit 1 operates with a power generation capacity of approximately 4Mw and 6Mw. From the 72nd hour, both units are planned to be put into operation with unit 1 operating at maximum capacity (11Mw), and unit 2 gradually increasing its power generation capacity to 6Mw.

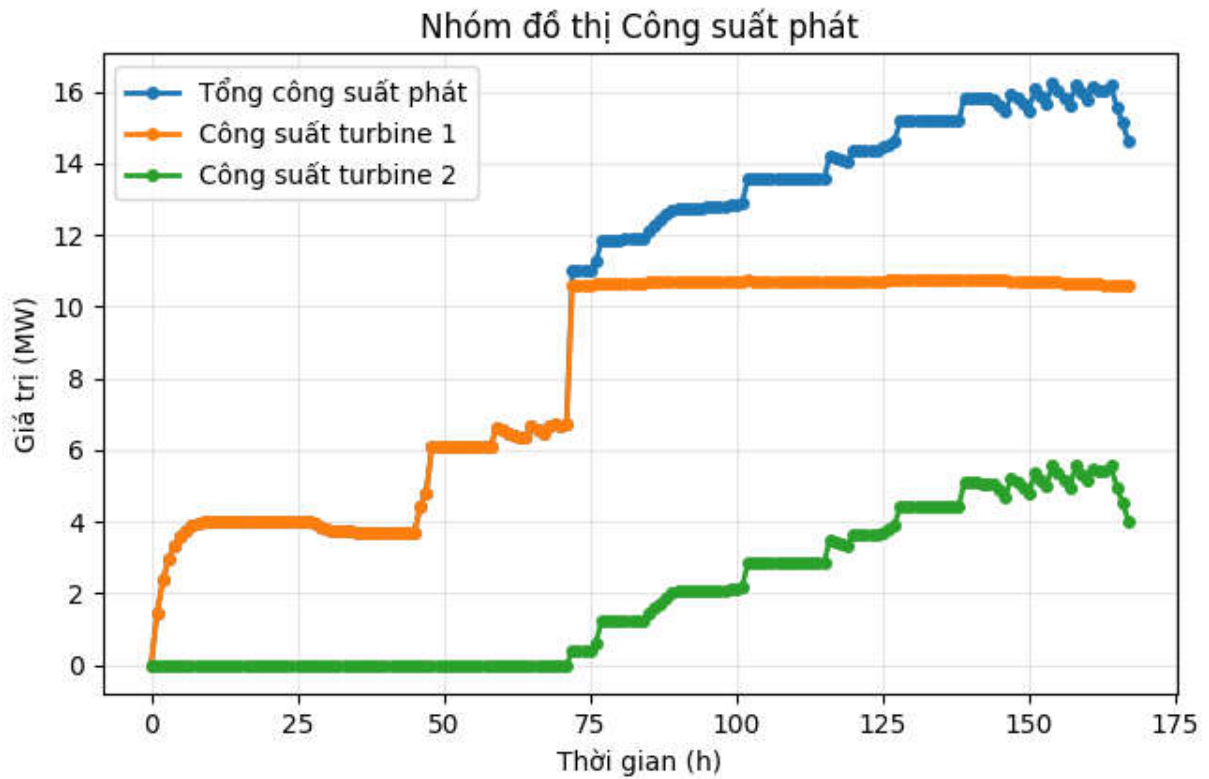


Figure 13. Power Components

To investigate the effect of discrete grid density, the author performed optimization runs with different densities. The number of optimal densities run with the number of level states x number of flow densities was changed from 10x10 to 80x80. The results obtained are the total energy produced and the final reservoir water volume, shown in Table 4 and Figure 14.

Simulation results show that as the detail of the discrete grid increases, the total energy produced gradually increases, demonstrating that the algorithm is converging towards a global optimal solution. However, the computational efficiency decreases. The largest increase in output occurs in the initial steps, then decreases significantly as the grid becomes finer. This result shows that the solution is close to optimal, and further increasing detail will no longer be efficient while the number of calculations and computation time increase significantly. Furthermore, the final reservoir volume is very close to the initial volume, confirming that the operating plan has optimized water usage, maximizing water utilization for power generation without waste.

Table 4. Optimization by Number of States

| Số trạng thái (Mức/Lưu lượng) | Tổng năng lượng sản xuất (MWh) | Thể tích cuối kỳ (m <sup>3</sup> ) |
|-------------------------------|--------------------------------|------------------------------------|
| 10 x 10                       | 1670.68                        | 40,093,594                         |
| 20 x 20                       | 1678.12                        | 39,981,797                         |
| 30 x 30                       | 1681.41                        | 39,957,145                         |
| 40 x 40                       | 1682.44                        | 39,946,858                         |
| 50 x 50                       | 1682.97                        | 39,939,737                         |
| 60 x 60                       | 1684.08                        | 39,933,611                         |
| 70 x 70                       | 1684.18                        | 39,933,411                         |
| 80 x 80                       | 1684.43                        | 39,931,119                         |

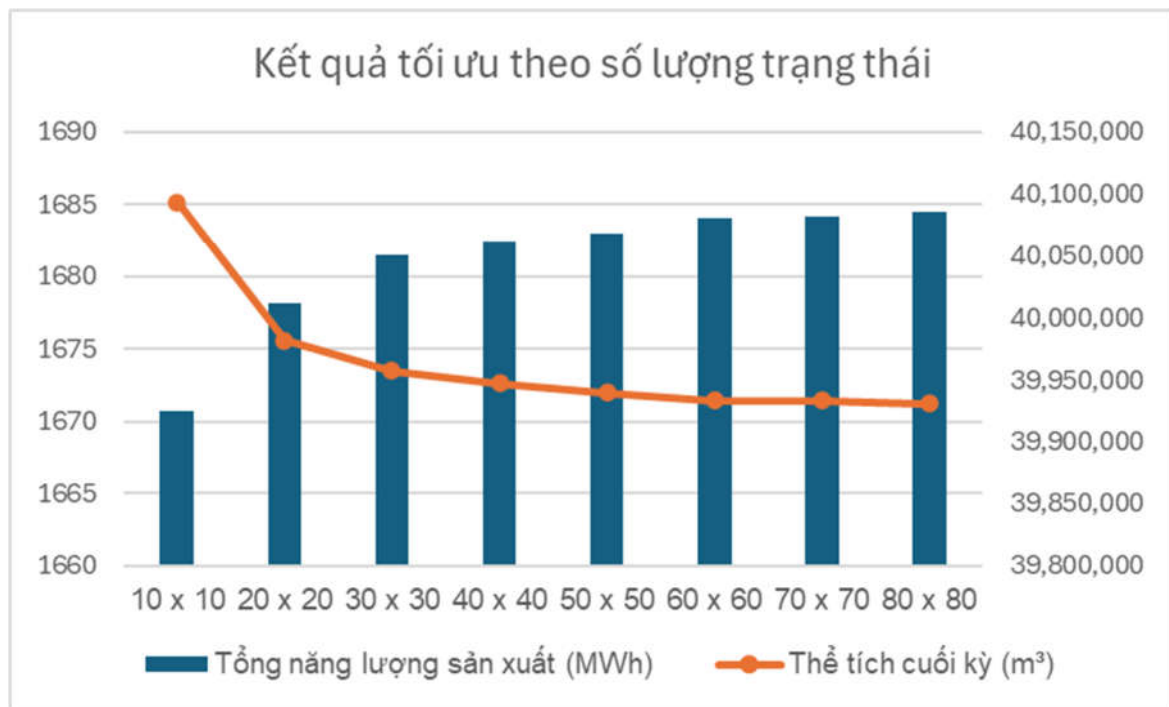


Figure 14. Optimization based on the number of states

Based on the results obtained, the software has successfully constructed an optimal discharge flow scenario using a dynamic programming algorithm. The resulting data shows that the plant's operating parameters are ensured within the set limit conditions. As the number of state grids increases, the optimal results will be better, but this requires a large amount of computation, and the optimal results will approach saturation. In actual operation, plants do not operate with overly detailed discharge levels

The results of the optimization problem solved using dynamic programming show that the algorithm has developed a reasonable operating schedule for the Thac Xang Hydropower Plant within a 168-hour calculation cycle. With the 7-day inflow series of water into the reservoir, the model determined the optimal power generation trajectory over time, while ensuring key operating constraints such as reservoir water level limits, plant flow limits, turbine capacity limits, and water balance conditions.

According to the calculation results, the total electricity generated reached approximately 1683.42 MWh in the 7-day cycle. The reservoir volume at the end of the cycle reached approximately 39,940,985 m<sup>3</sup>, approximately the initial capacity at the dead water level. This result shows that the algorithm has utilized almost all of the reservoir's inflow for power generation while maintaining a safe reservoir state at the end of the cycle. In other words, the model not only maximizes electricity generation in the short term but also avoids depleting the reservoir or over-accumulating water after the calculation cycle ends. The near-zero discharge reflects the algorithm's efficiency in allocating the generation flow over time. Instead of allowing too much water to accumulate in the reservoir and having to release it when the inflow increases, the algorithm proactively increases the generation flow at appropriate times, thereby utilizing the water resources for electricity generation.

The dynamic programming method effectively solved the short-term power generation scheduling problem for the Thac Xang Hydropower Plant. The algorithm determined a suitable flow trajectory for power generation based on the inflow series into the reservoir, ensuring no spillway discharge occurred in the scenario considered, while maintaining the reservoir water level within safe operating limits.

Results on water level and head pressure show that the model accurately reflects the relationship between reservoir state, power generation, and the plant's hydraulic conditions. Results on power generation show that the algorithm is capable of adjusting the unit dispatching mode according to water source conditions: operating one unit when the flow is low and dispatching both units when the flow increases.

A survey of discretization density demonstrates that the quality of the solution depends on the detail of the state grid and decision. Increasing the discretization density increases the total power generation and the final volume approaches the desired value. However,

since the improvement efficiency diminishes as the mesh becomes too fine, a suitable discrete density must be selected to ensure a balance between accuracy and computational efficiency.

Thus, the results obtained have demonstrated the feasibility of applying dynamic programming in optimizing the operation of small and medium-sized hydropower plants. In the case of the Thac Xang Hydropower Plant, this method allows for the construction of a quantitatively based power generation schedule, effectively utilizing the reservoir's water inflow and ensuring technical constraints are met in the short-term operating cycle

### **3.4. Aquifer Infiltration**

For semi-arid regions, which are under pressure from prolonged droughts interspersed with extreme heavy rainfall (such as the Elqui River basin, Chile), conventional reservoir configurations are unlikely to be sufficient.

Integrated Strategy: To address the overflow problem, an alternative regulation strategy is applied: Aquifer infiltration. Instead of discharging excess surface water during rapid floods, a portion of the flow is actively diverted into the groundwater system.

Resource Optimization: This approach helps restore depleted aquifers, ensuring long-term sustainability without affecting the "Desmarque" index (the proportion of essential surface water that people are allowed to exploit during the dry season). This is a strategy to optimize system operation combined with ecological resource conservation.

### **3.5. Machine Learning & Reinforcement Learning**

To address the lag of traditional mathematical models, data analysis is gradually shifting towards Machine Learning (ML) and Reinforcement Learning (RL) techniques.

Machine Learning (ML): Regression neural network architectures such as LSTM (Long Short-Term Memory) or regression trees are proposed for use in predicting highly accurate inflow and outflow power in the near future.

Reinforcement Learning (RL): Modern algorithms such as DQN (Deep Q-Network), DDPG, or SAC are applied to enable the system to automatically "learn" optimal water discharge control policies through continuous interaction with a simulated reservoir environment

## IV. CONCLUSION

The problem of optimizing power generation schedules and regulating water levels for small-scale hydropower plants (typically the Thac Xang project) provides a valuable empirical and theoretical foundation in the context of increasingly volatile flow and weather conditions. Reliance on traditional reservoir operation methods often reduces overall efficiency or creates dam overflow risks when rainfall changes erratically.

From data analysis and simulation setups, the report draws the following key conclusions:

### 1. Optimization of physical structure and technology selection

- Reservoir configuration: A system consisting of two reservoirs in series with two independent catchments has been proven to be the most optimal configuration. Thanks to the optimal distribution of inflow (each basin contributing 50% of the flow) combined with optimized reservoir and channel size design, this configuration effectively manages the inflow without overflowing, resulting in a peak total power output of 293.81 MWh (a 50.5% increase compared to the initial configuration).

### 2. Algorithm Management and Control Strategy

- Flood Prevention and Resource Protection: The Aquifer Infiltration strategy serves as a sustainable risk management solution. By diverting excess surface runoff underground during heavy rainfall, the system not only completely prevents dam overflow but also supports the recovery of depleted aquifers without affecting the essential water supply index (Desmarque).

- Algorithm Application: Integrating Genetic Algorithms (GA) into the system to control upstream pumping stations yields significant results in automating input regulation, optimizing pump run times to maintain safe water levels, and saving energy costs. Simultaneously, traditional methods such as Dynamic Programming (DP) remain a solid foundation for building short-run generation (STHS) trajectories.

### 3. Future Development Directions

Based on the foundation of this report, further development directions could focus on designing automated data processing pipelines and multi-domain feature extraction. In particular, combining optimization tools with Machine Learning (ML) models such as

LSTM, regression trees for flow prediction, or Reinforcement Learning (RL) algorithms such as DQN, DDPG, and SAC will enable hydropower systems to learn water release policies and regulate automatically in real time, responding flexibly to all changing environmental scenarios.

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