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Optimal Management of Dam Reservoirs: The Case of the Zongo II Dam on the Inkisi River (DRC)

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Abstract: This research addresses the optimal management of the Zongo II hydroelectric dam reservoir, located on the Inkisi River in the Democratic Republic of Congo. Faced with the persistent energy deficit in the city of Kinshasa, the main objective is to define a sequence of optimal decisions aimed at maximizing energy production during the dry season. The study is based on hydrological and hydraulic modeling of the site, taking into account the topography, geology, and hydrological characteristics of the river. From these elements, a mathematical model of the management system was developed and then optimized through dynamic programming. The results make it possible to formulate rules for the daily management of reservoir levels, ensuring stable turbine operation while reducing water losses. This work illustrates the importance of rational and dynamic planning in the management of hydraulic infrastructures, especially in tropical contexts subject to strong seasonal variability. The developed approach can serve as a reference for integrated water resources management and other hydroelectric projects in the DRC.

Keywords: *Optimal Management, Retention, Dam, ZongoII, Hydroelectric*.

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I. INTRODUCTION

Electricity production in the Democratic Republic of Congo remains insufficient to meet national demand, especially in Kinshasa, where the electrification rate does not exceed 45%.

The main sources of production are the Inga I and II hydroelectric power plants, which are interconnected to the Zongo I hydroelectric power plant. However, their output is limited, and power outages are common during the dry season (May to September).

In this context, the Zongo II hydroelectric dam, currently under construction on the Inkisi River in Kongo Central Province, represents a strategic opportunity to increase production capacity.

The objective of this research is to define an optimal management method for the Zongo II reservoir to ensure stable energy production throughout the year, particularly during low-water periods.

The Zongo II dam is located in Kongo Central Province in the Democratic Republic of Congo. It is located between 4 ° 46'16" ~ 4 ° 46'46" South latitude and 14 ° 52'02" ~ 14 ° 53'40" East longitude, 70 km (as the crow flies or 165 km by road) southwest of the capital Kinshasa, near and downstream

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of the ZONGO I hydroelectric power station. It is built on the Inkisi River, 4.4 km before its confluence with the Congo River, to supply a hydroelectric power station located on the beach on the left bank of the Congo River, 1.7 km downstream of the confluence, in order to produce electricity.

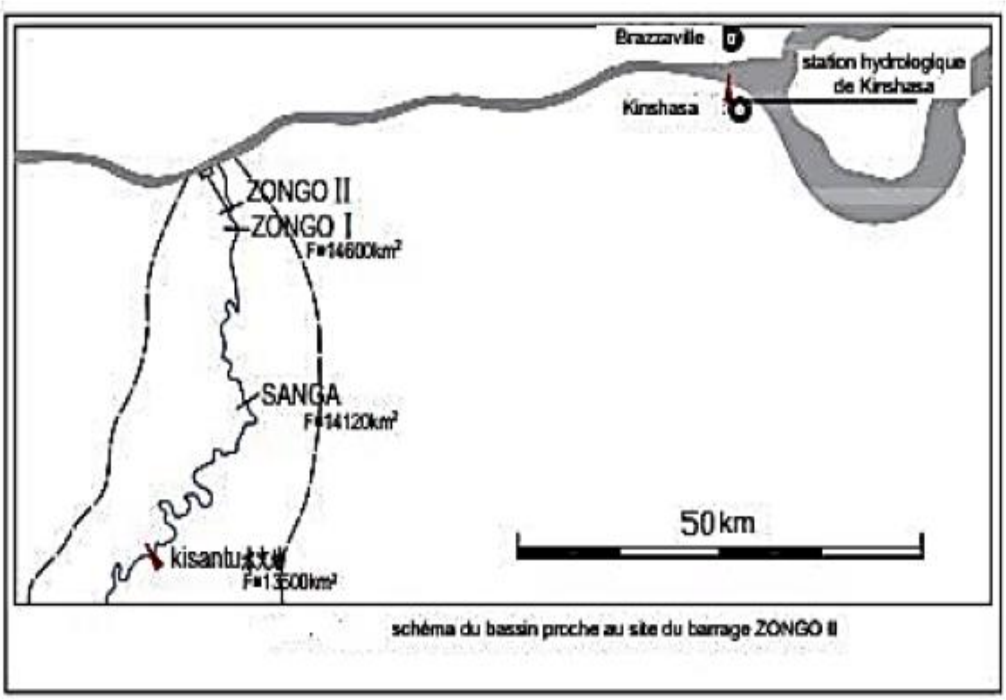

Fig.1 Geographical Location of the Zongo II Dam

The Inkisi River is a Class I tributary of the Congo River, originating in northern Angola. It flows into the Democratic Republic of Congo from south to north. The watershed of the Inkisi River is narrow and long, the upstream level in Angola is between 800~1200m, the downstream level in the Democratic Republic of Congo is between 300～800m. At the dam, the watershed area is 14600 km2, the cross-section of the river is “V”, the two banks are steep, the water current is fast, the channel width is about 200m, with an overall slope of about 13‰. Upstream of the dam there are already two hydroelectric power plants: ZONGO I (maximum installed power: 75 MW) and SANGA (maximum installed power: 12 MW).

- A dam is a structure built across a watercourse and intended to regulate the flow of the watercourse and/or to store water for various uses. The structure creates either3:
- A constant level reservoir called a body of water: in this category we find diversion or water intake dams, dams for raising or raising the body of water and retention dams.
- A variable level reservoir called a reservoir: in this category we find accumulation or storage dams. Depending on whether the capacity of the reservoir helps to adapt the flow of the river to demand or to regulate the river regime (reduce flood flows and reinforce low flow rates), we speak of a supply reservoir or a regulating reservoir..

The surface at which the structure rests on the bed and banks of the watercourse is called the foundation, and the surfaces that limit the structure upstream and downstream are the facings.

The morphology of the area covered by the reservoir is the basin. The volume of water contained in a reservoir is called the reserve.

A distinction is made between the usable reserve, up to the minimum operating level; the drainable reserve, up to the threshold of the lowest drainage; the dead zone below this threshold; and the flood overfill zone, between the normal reservoir (or normal reservoir level) and the maximum level. This is shown schematically in Figure 2;

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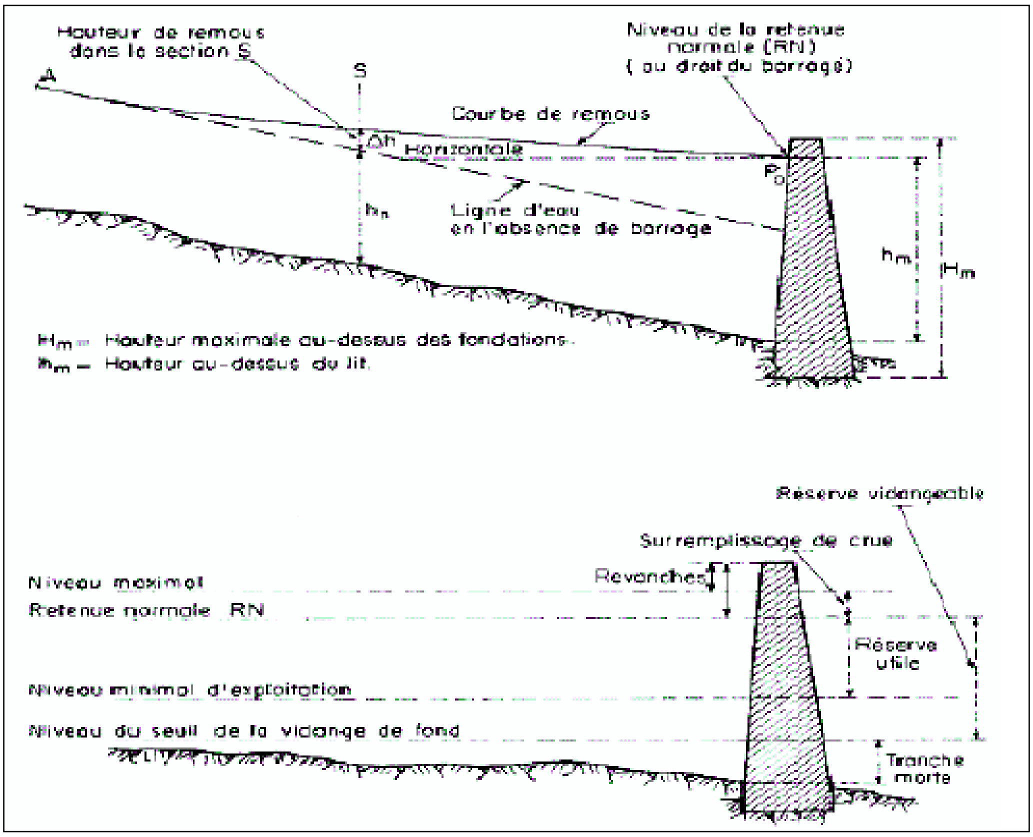

Fig. 2 Different Levels at the Right of a Dam

II. METHODOLOGY

The approach adopted includes five main steps:

- Data collection and processing: compilation of topographic, hydrological and meteorological information of the Inkisi River basin.
- Physical modeling of the system: representation of the dam, the reservoir and the power station using AutoCAD Civil 3D, HEC-RAS and Excel software.
- Mathematical formulation: the system is governed by the following continuity equation:
- St+1=St+(Qt−Lt)ΔtS_{t+1} = S_t + (Q_t - L_t)\Delta tSt+1=St+(Qt−Lt)Δt
- where StS_tSt is the stock at time ttt, QtQ_tQt the natural input, and LtL_tLt the release (including turbine and ecological flow).
- Optimization: Application of dynamic programming to determine the sequence of optimal decisions in two scenarios:
  - Certain future: known contributions;
  - Uncertain future: random contributions with probability of occurrence.
- Validation and analysis: comparison of simulated results with actual or estimated production values.

- *Management of Dam Retention*

The essential role of a dam is to regulate hydrological inflows by absorbing their variability: in one way or another, it transfers water withdrawn during a period when it is abundant, or even excessive, to a period when it has a greater use value.

The random nature of hydrological phenomena clearly dominates management problems: the aim is to find the most economical management rule possible, that is, one that achieves a compromise between the costs of protection against exceptional events and the average results expected following the structure's normal "cruising" operation.

In other words, the primary purpose of a management rule is to dampen the variability of inflows to produce a sequence of releases that is as regular as possible.

So for a management rule to be more effective, it is useful to predict as best as possible the evolution of future inputs and needs. Just as we drive poorly in the fog, we manage ineffectively in uncertainty, as we said previously. Managing is planning. It is also knowing how to take risks to balance the uncertain costs of protection against exceptional failures and the uncertain benefits in the more or less long term. Managing a reservoir consists of storing and then releasing water at different times of the year, so as to best satisfy the uses considered. The daily choice of the volume of water to be stored or released by the manager of a resource system depends on three main components1:

- The physical system, composed of the various watercourses and constructed structures (dams, diversion structures, regulation structures) and the physical constraints of these structures (minimum and maximum capacity of reservoirs, production capacities, head heights, distances between structures).
- The desired uses of the water resource, i.e., the objectives of the physical system management.

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- The management strategy adopted to best meet the desired uses and objectives for which the physical system developments were designed.

➢ *Optimization Models*

- *The Objective Filling Curve Method1*

This is an empirical management method that takes into account the manager's common-sense practical rules. First, continuous observation of the levels in the reservoir and the river is carried out to assess the situation at a given moment.

The reservoir, as well as the river, is divided into four zones: an inactive zone (dead zone for reservoir siltation), a low-flow zone (alert zone or buffer zone between normal operation and shutdown), a normal operating zone (operation at full capacity), and a flood control zone (flood reduction zone), beyond which the water overflows the structure.

The reservoir's level (or stock) objective curve evolves throughout the year. The thickness of the reservoir's operating zones and control points fluctuate in the same way, which makes it possible to model weaker buffer effects during critical periods. The manager's objective is to stick as closely as possible to this ideal objective curve. The only variable to adjust is the level in the reservoir. As long as we are within the normal operating zone, the structure operates routinely and we rely on the dam operator's experience. As soon as we leave this zone, exceptional measures must be implemented.

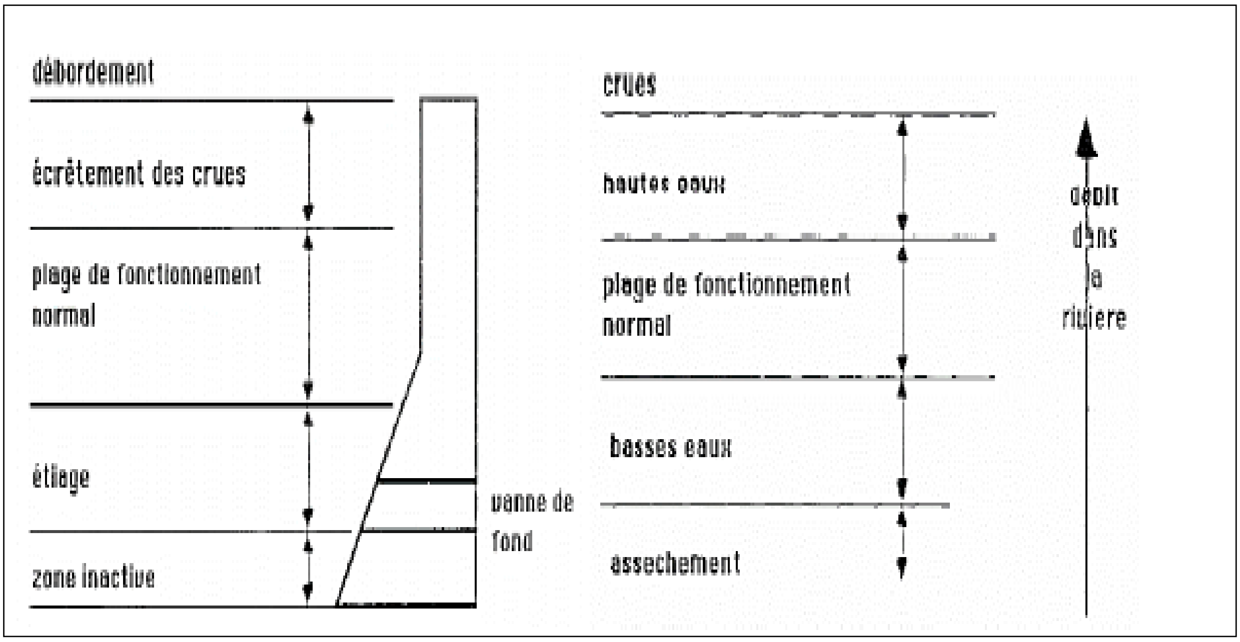

Fig.3 Cutting of the Reservoir (River) for Management in Objective Curve

➢ *Optimization by Dynamic Programming*

The objective of optimization algorithms is to determine the values of a set of decision variables that maximize or minimize a constrained objective function. In the case of a hydraulic reservoir, the sequence of decision variables is generally defined by the sequence of water releases Rt that maximizes or minimizes an objective function denoted fobj. The objective function is the heart of optimization.

The form of this function generally depends on the case study considered and can therefore take different forms. For example, it could be expressed in terms of economic revenues (maximizing revenues from hydroelectricity, minimizing production costs, minimizing costs related to flood damage), in terms of utility (minimizing restrictions on energy supply, maximizing hydroelectric production over a period) or in terms of water reliability or availability (minimizing spills, minimizing the frequency of restriction episodes, maximizing minimum flows). According to the definition of the objective function fobj, the optimization problem over a period [t0, tf] consists of solving the equation:

$$\boldsymbol{Max}_{\boldsymbol{Rt}}\{\boldsymbol{E}[\textstyle\sum_{\boldsymbol{t}=\boldsymbol{t}0}^{\boldsymbol{tf}} \boldsymbol{fobj}(.)]\}$$

$$\boldsymbol{Min}_{\boldsymbol{Rt}}\{\boldsymbol{E}[\textstyle\sum_{\boldsymbol{t}=\boldsymbol{t}0}^{\boldsymbol{tf}} \boldsymbol{fobj}(.)]\}$$

For these two equations, the symbol **E**[.] represents the mathematical expectation. The mathematical expectation used here results from the fact that the optimization of hydraulic structures management is most often carried out in a context of uncertain future. Such optimization can therefore only guarantee a maximization (or minimization) of the expected sum of the values of the objective function at each date $\boldsymbol{t}$

At a given date t, the value of fobj is partly conditioned by the decision taken Rt. However, it can depend on elements external to the system. For example, if fobj corresponds to economic revenues linked to energy production, fobj depends a fortiori on the selling price of energy on the market. This is why the notation fobj (•) is currently adopted, as it does not restrict the objective function to a dependence on the decision variable $\boldsymbol{R}$. The constraints applied to the management of a hydraulic dam are expressed in the general case by the following equations:

$$\boldsymbol{Rtmin} \leq \boldsymbol{Rt} \leq \boldsymbol{Rtmax}$$

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$$\boldsymbol{Stmin} \leq \boldsymbol{St} \leq \boldsymbol{Stmax}$$

$$\boldsymbol{St}+\Delta \boldsymbol{t}=\boldsymbol{St}+(\boldsymbol{Qt}-\boldsymbol{Rt})\times\Delta \boldsymbol{t}$$

With $\boldsymbol{St}$ the water stock of the reservoir (m3), $\boldsymbol{Stmin}$ and $\boldsymbol{Stmax}$ the minimum and maximum possible stocks of the reserve, $\boldsymbol{Rt}$ the flow rate of withdrawals for the turbine on the reserve (m3/s); $\boldsymbol{Rtmin}$ and $\boldsymbol{Rtmax}$ the minimum and maximum turbines that can be ensured by the reservoir and $\boldsymbol{Qt}$ the contributions to the reservoir at a date $\boldsymbol{t}$. $\boldsymbol{\Delta t}$ is the time interval during which $\boldsymbol{Qt}$ and $\boldsymbol{Rt}$ are assumed to be constant.

As indicated in the equations above, the constraints of a management system can vary over time, which is generally the case. A common example is to limit the stock $\boldsymbol{Stmax}$ of a reservoir to certain periods of the year, considered high risk, to maintain sufficient storage capacity to cope with possible future floods.

III. RESULTS AND DISCUSSION

Analysis of the hydrological series revealed significant seasonal variability, with a minimum average flow of 14 m³/s during the dry season and a maximum of 95 m³/s during the rainy season. Simulations determined the optimal useful volume of the reservoir to ensure minimal turbine use during the dry season. Dynamic programming led to the development of an optimal management plan for turbine flows, ensuring a balance between energy production and environmental protection. The results indicated that maintaining a high reservoir level at the end of the rainy season increases energy production by 12 to 18% during the dry season compared to traditional management.

Fig.4 Aerial View of the Zongo II Dam Site with the Development Plan

The ZONGO II hydroelectric power plant development consists primarily of the following structures:

- Retention structure: concrete gravity dam (with rubble masonry blocks) with water intake, spillway, and flush (or silt) sluices.
- Water supply structure: intake gallery (2,525 m long and 7.5 to 9.24 m in diameter) with surge chimney (69 m high and 18 m in diameter) and penstocks (470 m long and 6.6 to 4 m in diameter).
- Special structures: the plant equipped with three generators (50 MW each), valves, etc.

A. Description of the Physical System

The Zongo II hydroelectric power plant consists of a gravity dam, a feeder gallery and a plant with 3 groups of 50 MW each. In this section, we describe the elements necessary for managing the power plant.

➢ *The dam*

Type: concrete weight, triangular shape of downstream fruit 80%, the facing is vertical over 5 m and continues with a slope of 20%. See plan in appendix

- *Features*

Hmax: 22.76 m (from the foundation), which corresponds to the level of 362.5 m. Hret_normal: 15.5 m, which corresponds to the level of 356 m. Length at the crown: 205 m

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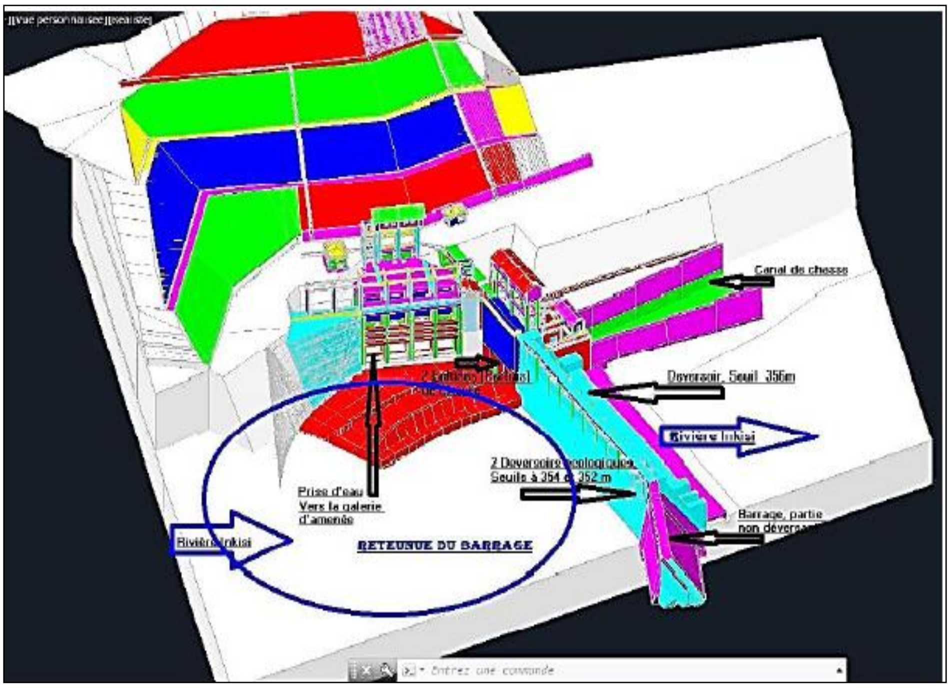

Fig.5 Perspective View of the Zongo II Dam

➢ *Restraint*

The normal reservoir level is 354, the minimum operating level is 354 m. Here is the reservoir filling curve.

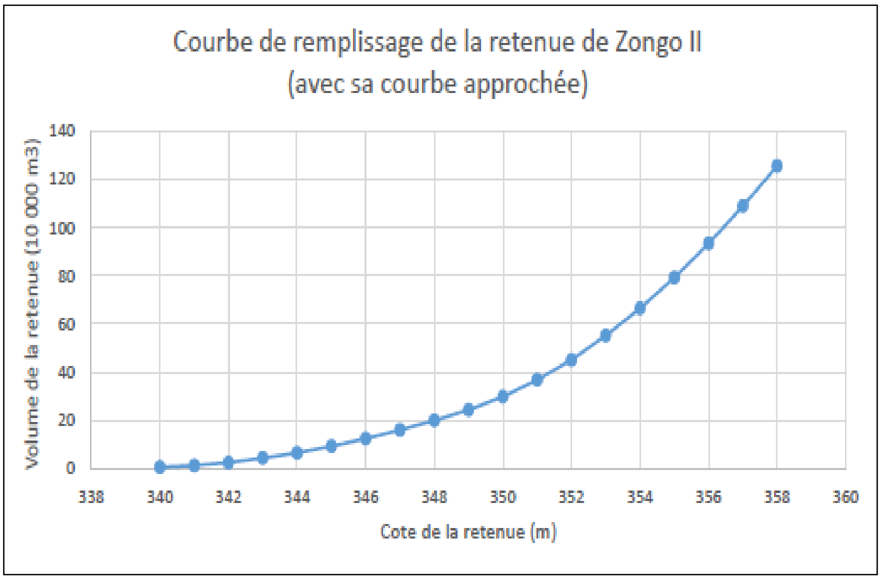

Fig.6 Filling Curve of the Zongo II Dam Reservoir

➢ *La Courbe De Remous :*

We have seen that our reservoir is located downstream from the Zongo I power plant. The water level of the Zongo II reservoir must be adjusted so as not to submerge or significantly reduce the net height due to backwaters.

The modeling was performed using HEC-RAS software.

HEC-RAS is a hydraulic software program developed by the U.S. Army Corps of Engineers in 1995 to model the steady and unsteady flows of canals and rivers. It allows us to calculate the hydraulic axis, the energy line, the rating curve, and sediment transport, and can assist in modeling flows in structures: bridges, culverts, dams, spillways, sluices, natural or artificial reservoirs, etc.

Thus, it uses several hydraulic equations: continuity, quantity of movement, conservation of energy, Barret de Saint Venant, etc.

In our case, with the topographic data of our site, we have:

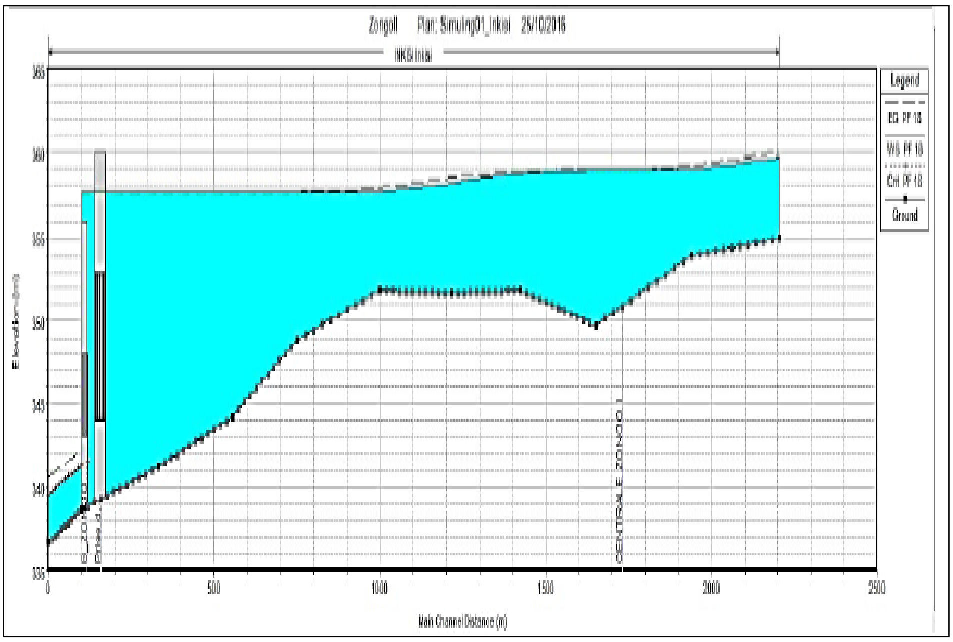

Fig.7 Profile of the Eddy Curve for the Flow Rate of 585 m3/s

- The use of the model also contributed to a better understanding of the system's sensitivity to variations in inputs.
- In an uncertain future scenario, the model anticipates production fluctuations limited to ±5%, demonstrating the system's robustness.

This method provides an effective decision-making tool for dam managers and energy planners in the Democratic Republic of Congo.

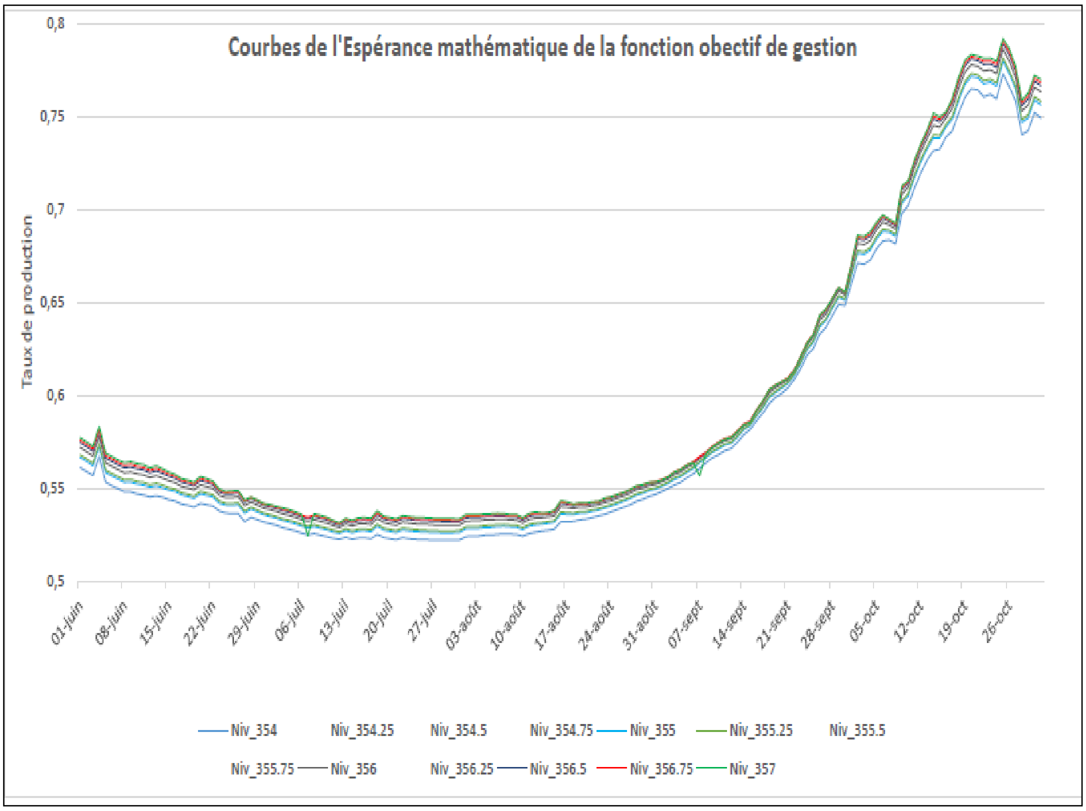

Fig.8 Curves of Mathematical Expectation at Different Levels of Retention

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➢ *Management Optimization*

We previously stated that we will use the dynamic programming method to optimize our management model. As a reminder, optimizing a management model involves maximizing (minimizing) the cost (benefit) of an objective function, a function that encompasses all the operating objectives of a hydraulic development.

For our development, we modeled two objectives: the production of electrical energy and the guarantee of an ecological flow downstream of the Zongo II dam. As indicated in the dynamic programming optimization diagram, the solution will be carried out in two stages:

- First, using the deterministic approach, assuming all management parameters are fully known: daily input rates throughout the dry season, the requested production rate (in our case, since we are producing for a city with an energy deficit, the requested production is the maximum amount that natural inputs can provide), etc. In this case, we will refer to management in the Certain Future.
- Next, we will proceed with the implicit stochastic approach, which takes into account the random nature of inputs (the requested production always remaining at the maximum level). In this case, we will refer to management in the Uncertain Future.

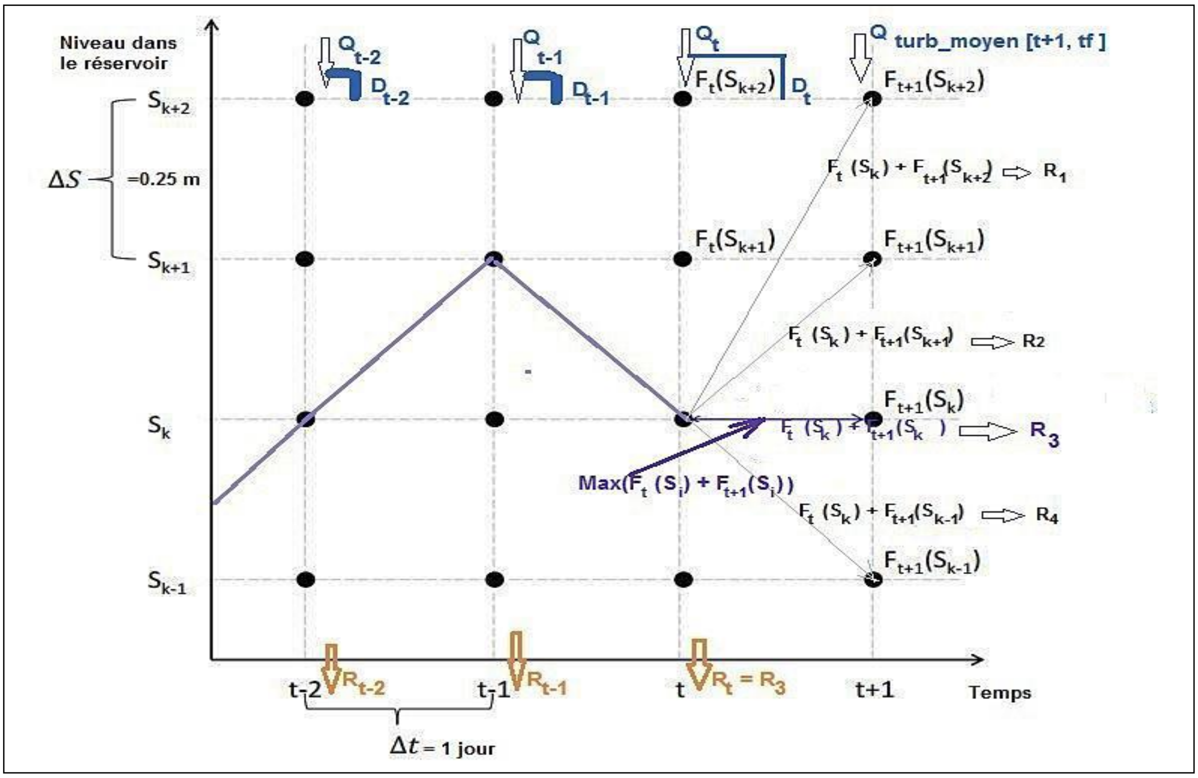

Fig. 9 Schematic of Optimization in Discretized Space

IV. RECOMMENDATIONS

- Implement integrated water resource management in the Inkisi basin, encompassing domestic and agricultural uses.
- Develop continuing education programs for hydraulic engineers on modeling and optimization tools.
- Incorporate long-term climate scenarios into dam management policies.
- Promote applied research and collaboration between universities, businesses, and public institutions.
- Extend the optimal management model to other dams in the DRC to harmonize production strategies.

V. CONCLUSION

This research validates the importance of dynamic programming for optimal management of the Zongo II dam reservoir. The implemented strategy guarantees stable energy production during the dry season, while ensuring a minimum ecological flow and preserving the sustainability of the system. The developed model could be used in other hydroelectric power plants in the country to improve energy planning and strengthen hydraulic security.

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