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Research Paper

# Impacts of Climate Change and the Need to Define an Efficient Operating Methodology for Nangbéto Dam

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## ABSTRACT

Climate change is a major threat to industrial development because of its adverse effects on the energy sector, especially hydroelectric power plants.

This paper focuses on the analysis of the impact of climate change on the Mono River basin and the implications for the electricity production of Nangbéto Hydroelectric Power Plant. The approach consisted of combining historical hydrological data and physical, technical, and economic information to analyze the extent to which variations in average rainfall and global warming impacted the operation of the Nangbéto Hydroelectric Power plant.

Based on the curves obtained, the impacts of climate change on the Mono River and on the operation of the Nangbéto Power Plant were recorded. Also, the management of the Nangbéto dam water retainer by the current operator was analyzed to highlight the strengths relating to the optimization of electricity production and the economic profitability of the plant.

***Keywords:*** Climate change, hydropower plant, optimization, hydrological data.

## INTRODUCTION

Climate change is one of the great challenges of the 21st century [1]. Hydroelectric power generation makes a substantial contribution to meeting the growing global electricity demand [2]. In 2009, hydropower accounted for around 16% (around 3,551 TWh / y) of total world electricity production and reached 26% of the total installed capacity of electricity production [3].

It is now established that climate change will affect water resources. The situation is worrying for the hydroelectric power generation sector since water is its raw material. It is important to adapt the management rules and/or the water systems installations, to minimize the negative impacts and/or to capitalize on the positive effects that climate change could bring [4].

Climate is defined as the distribution of different meteorological variables over a defined period. Climate change thus refers to a lasting change of the average and the variability of climate properties. The ongoing climate change is characterized by an increase in the average surface temperature of land and oceans [5].

In addition to the warming of the atmosphere, climate change is characterized by other structural changes such as changes in precipitation levels or humidity levels, with large geographic disparities. The increase in the frequency and in the intensity of extreme weather events: storms (cyclones, typhoons, etc.), floods, droughts, heatwaves, cold spells, etc. is another important component of climate change.

With an installed capacity of 65.6 MW, Nangbéto power plant is built on the Mono river, precisely in Togo (West Africa). It is operated by the ECB (Electric Community of Benin), which is an international company in charge of power transmission and electricity production in Togo and Benin. This power plant produces an average of 150 GWh of energy per year and today represents 13% of the energy needs in Togo and Benin [6, 7].

Nangbéto power plant is not immune to the adverse effects of climate change [8].

This work proposes a review and analysis of the existing literature on the quantification and qualification of the impacts of climate change on the electricity production of Nangbéto power plant.

The analysis focuses on the history of: (i) water inputs, (ii) daily evaporations, (iii) volumes of water evacuated or discharged, (iv) volumes turbined, etc., and will be used to highlight the effects of climate change on the Mono basin and to analyze and redefine the operation and management program of Nangbéto power plant.

## DATA AND METHODOLOGY

The methodology used consists in analyzing, first the hydrological dynamics of the Mono basin and the distribution of incoming floods to Nangbéto dam, to assess the impacts of climate change over several years, and secondly, the water retention management plan and the annual energies produced according to the incoming flood to assess the efficiency of operating programs and to propose an optimal management method for this power plant.

To this end, the data used, which mainly come from the recordings made by the operator of the Nangbéto power plant, cover the period from 1989 to 2020. These data are among others: (i) the daily flows of the Mono river in Nangbéto, (ii) the daily evaporation, (iii) the level of the water retention, (iv) the precipitation in Nangbéto, (v) the total turbined volume, (vi) the total energy produced, (vii) the total volume discharged, (viii) the daily volume of water released by the Nangbéto power plant, etc.

After the description of the functional characteristics of Nangbéto power plant, the hydrological data curves are represented for analysis and discussions on the results obtained are carried out to assess the current management and operation method of Nangbéto dam.

## NANGBETO HYDRO POWER PLANT

**Table 1 : Characteristics of Nangbéto groups**

| Equipment | Parameter | Value | Unity |
|---|---|---|---|
| Turbine | Manufacturer | Escher WISS | - |
| | Rated mechanical power | 32,8 | MW |
| | Rated speed | 166,7 | Rev/mn |
| | Nominal flow | 120 | $m^3/s$ |
| | Pipe diameter | 5,2 | m |
| | Model and manifacturer of speed and power regulator | ETR21 -Escher WISS | - |
| Alternator | Manufacturer | SIEMENS | |
| | Active power | 32,8 | MW |
| | Apparente power | 35,5 | MVA |
| | Power factor | 0,9 | - |
| | Model and manifacturer of excitation system | Thyripol -SIEMENS | - |
| Dam | Upstream level | 144,5 | m.o.s |
| | Downstream level | 110 | m.o.s |
| | Medium drop | 30 | m |
| | Main dike length | 500 | m |
| | Side dike length on the left bank | 2,6 | km |
| | Side dike length on the right bank | 2,8 | km |

*m.o.s.: Meter Over Sea*

The Nangbéto dam is an embankment dam built on the Mono river in the Plateaux region of Togo (Coordinates 7 ° 25 ′ 25 ″ N, 1 ° 26 ′ 25 ″ E). It was built between 1984 and 1987 with the aim of supplying hydroelectric power to Togo and Benin as well as creating fisheries and providing water for irrigation. The first spin took place on June 5, 1987 [7]. The project was financed by the World Bank and the African Development Bank at a total cost of $ 98.22 million [9].

The Nangbéto power station is equipped with two groups driven by Kaplan turbines with vertical axis, each coupled to an alternator. The characteristics of turbines and alternators are summarized in table 1 [10,11,12].

The sectional view of the turbine-alternator assembly is shown in Figure 1 below.

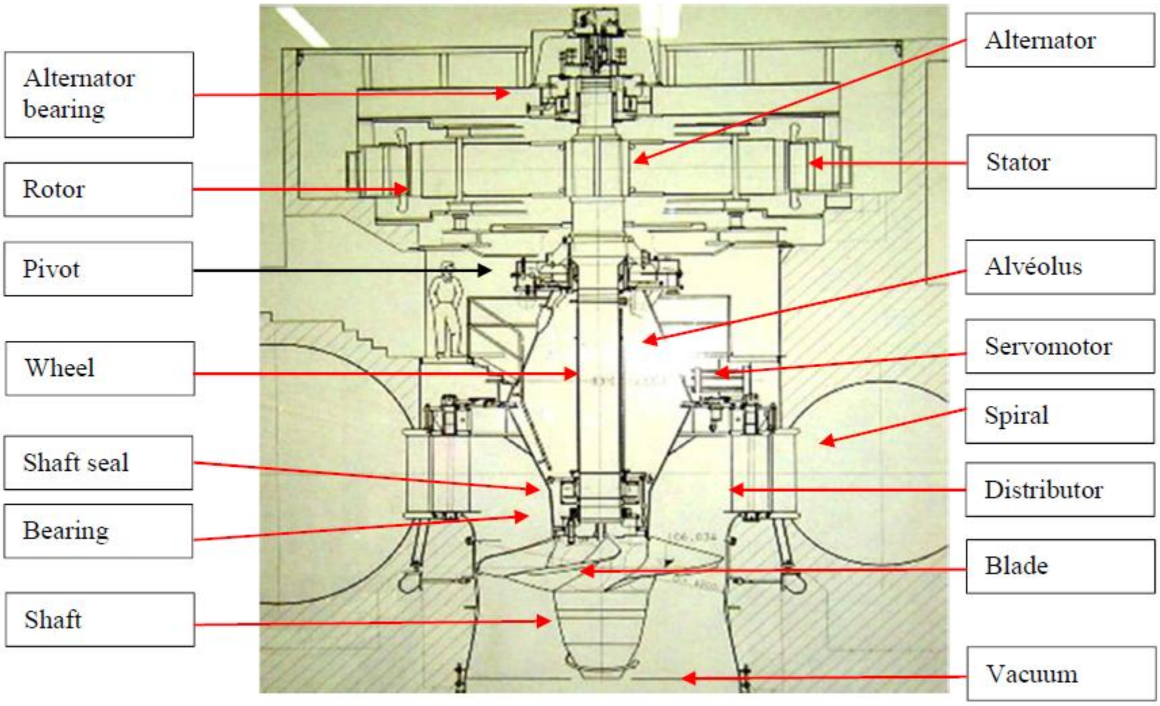


**Figure 1: Turbine-Alternator sectional view of the Nangbéto Hydroelectric Power plant [13]**

Nangbéto dam is made up of a main concrete dike with a total length of 430 m and two side dikes (the left bank side dike with a total length of 2.6 km and the right bank side dike with a total length of 2.8 km) [13]. The satellite image of Nangbéto hydroelectric site and the topography of the dam retention are shown in Figure 2.

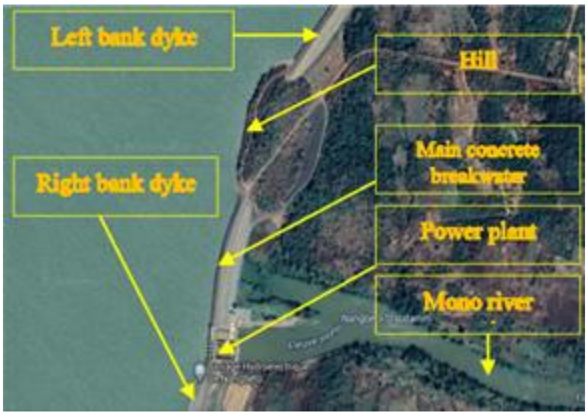


**Figure 2a: Satellite image of the Nangbéto Site [9]**

**Figure 2b: Nangbéto dam retention [9]**

The water level characterizing the normal retention is set at the level 144 m.o.s. The volume given by the capacity curve is 1,715 million cubic meters for a flooded area of 180 km². Regarding the intrinsic characteristics of this dam, it is possible to determine the volume (y) according to the level (x) by the following equation [13]:

$$y = -0,0001.x^6 + 0,101.x^5 - 33,933.x^4 + 6077,5.x^3 - 612079.x^2 + 3.10^7x - 7.10^8 \qquad (1)$$

The curves of the volume, of the surface area and of the electric producible energy as a function of the level of the retention are shown in Figures 3a, 3b and 3c, while the shape of the electric producible energy as a function of the volume of retention is shown in figure 3d below.

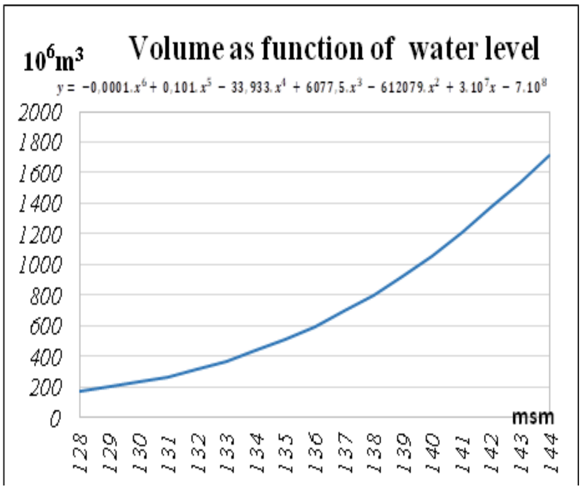


**Figure 3a: Evolution of the volume of Nangbéto Lake according to the water level**

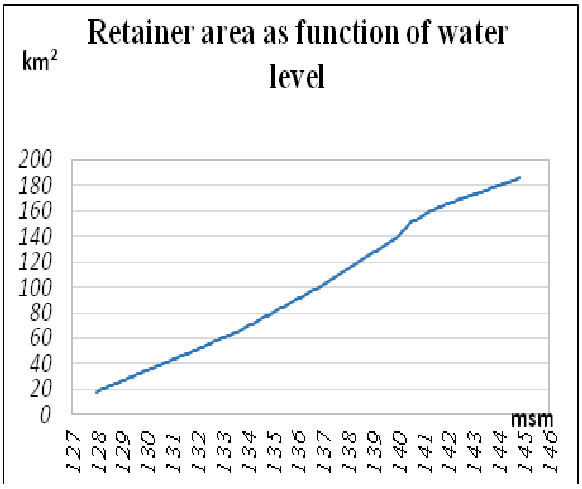


**Figure 3b: Evolution of the surface of Nangbéto lake according to the water level**

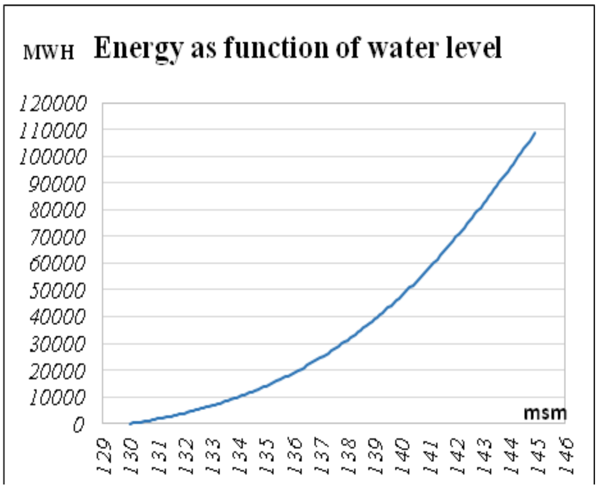


**Figure 3c: Energy producible as fonction of Nangbéto lake level**

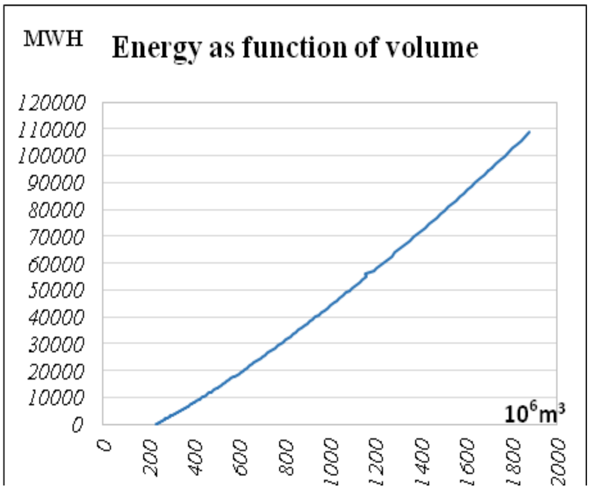


**Figure 3d: Energy producible as fonction of Nangbéto lake volume**

Flood flows can be calculated by the Passini formula. Indeed, Passini's formula is one of the many empirical formulas allowing the calculation of the concentration time of a rural watershed [14]. In a watershed, the time taken by water to travel the distance from the point furthest of the outlet to the outlet is called the concentration time. For rural watersheds, the concentration time is estimated using several methods, in particular that of Passini [15];

$$t_c = \alpha \, . \frac{(A.L)^{1/3}}{\sqrt{I}} \qquad (2)$$

*with:*

*A: Surface area of the watershed (ha).*

*α: Adjustment coefficient (between 0 and 4: for a rural watershed, = 0.14).*

*L: Longest water course (hundreds of meters).*

*I: Average slope of the longest route (in relation).*

*tc: Concentration time (minutes).*

The Caquot equation is used to determine the peak flow at the outlet of an urbanized watershed for different return periods. This flow is calculated from equation (3) below:

$$Q = 0{,}278.\,k\frac{H}{t_c}.\,A \; = \delta.\,k.\,I.\,A \; [10] \qquad (3)$$

*With:*

*Q: Flow in m3/s.*

*k: Coefficient of runoff.*

*H: Height of rain in mm that fell during a time equal to tc.*

*tc: Concentration time (minutes).*

*I: the average slope of the longest water course in the watershed.*

*A: area of the watershed (hectar)*

## HYDROLOGY AND OPERATION OF THE NANGBÉTO POWER PLANT

The climatic changes observed in recent years in Togo induce inevitable impacts in the hydrological cycle of the Mono [7]. In this part, we analyze the management mechanism of Nangbéto dam by the current operator and we observe the impacts of climate change by relying on hydrological data curves such as: (i) the input volume, (ii) the turbined volume, (iii) the discharged or released volume, (iv) the flow rate of Mono, (v) the evaporations, (vi) the level of the retention, etc. The results obtained will be discussed to redefine, if necessary, the appropriate operating mode in the face of the effects of climate change.
The data used come from the database of Nangbéto Power Plant [16].

### Evolution of water volumes

The analysis of the hydrology and the exploitation of the water inflows in the Nangbéto retention is carried out based on the data in figures 4 and 5. The evolution curves of the inflow volumes, of the turbined volumes and of the downstream released volumes of the dam (Turbined volume + discharged volume) are shown in Figure 4 below.

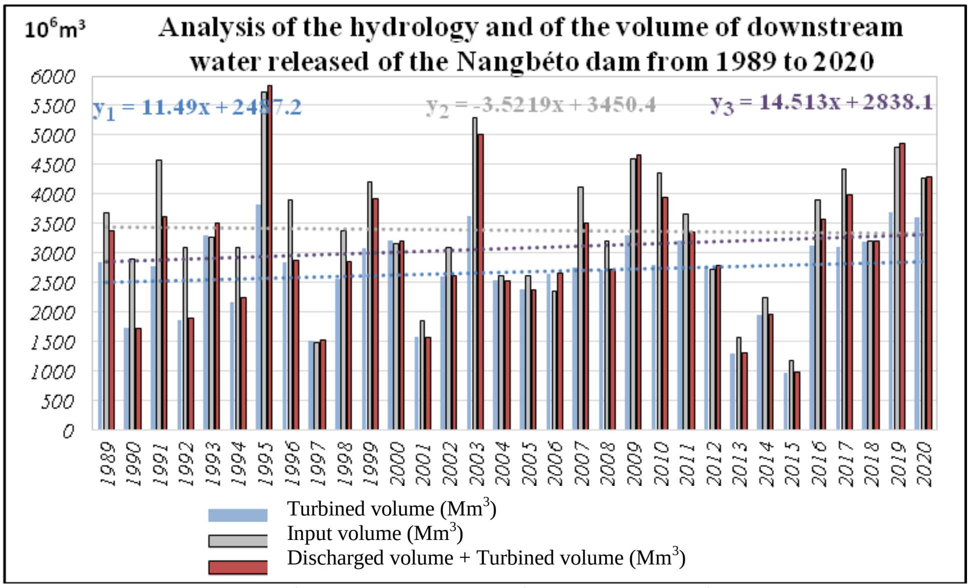


**Figure 4: Evolution of the hydrology and the of the water released from 1989 to 2020**

The curves of the annual volumes discharged, and useful reserves (on January 1 of each year) are shown in Figure 5 as follows:

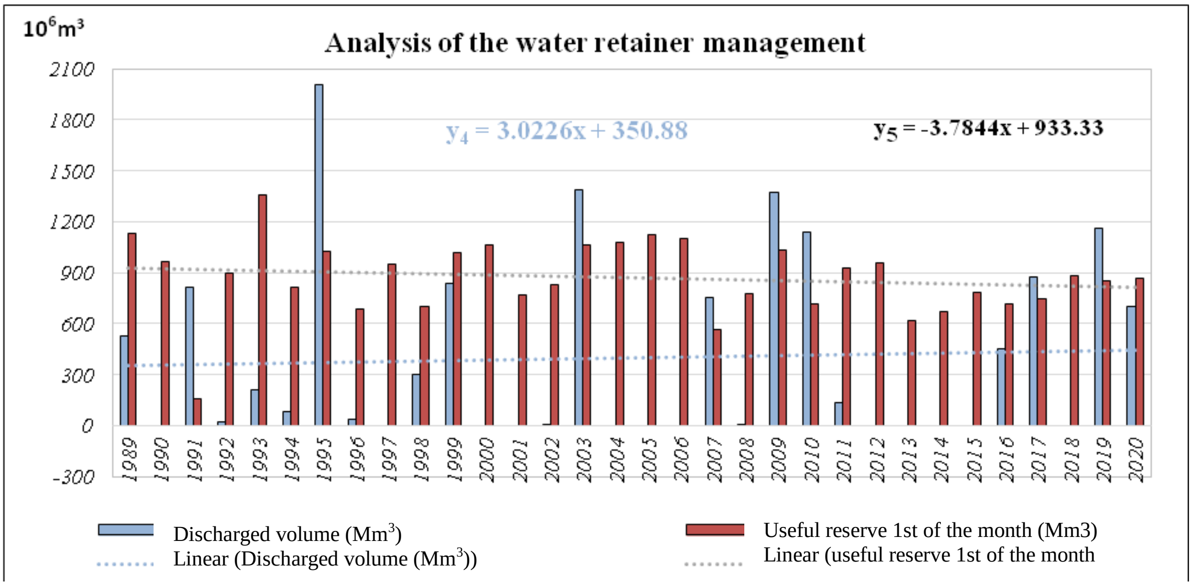


**Figure 5: Hydrology evolution from 1989 to 2020**

The analysis of the curves obtained in Figures 4 and 5 above emerges from the following observations:

- The total annual volume of water inflows is greater than the sum of the annual turbined volume and the annual discharged (released) volume except in 1989, 1994, 1999, 2003 and 2019;
- The annual turbined volume is greater than the annual discharged volume for all years;
- The annual discharged volume and the annual turbined volume are all the greater, the input volumes are higher;
- The volume of the useful reserve is almost decreasing over the entire period of the study;
- The linear trend curve for the volume of inflows is increasing.
- The curves of useful reserves and annual evaporated volumes are shown in Figure 6 below where we can notice that the two curves have very similar shapes.

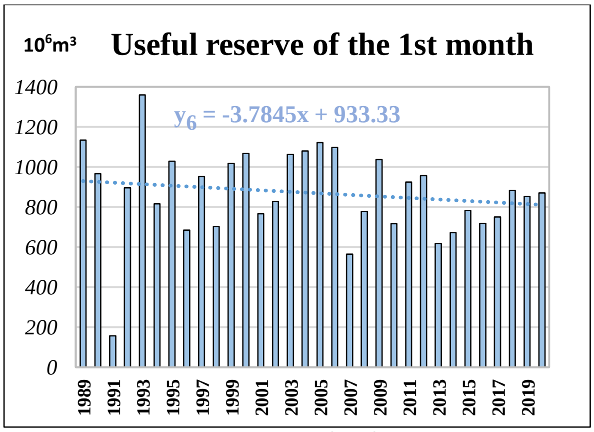


**Figure 6a: Evolution of useful volume**

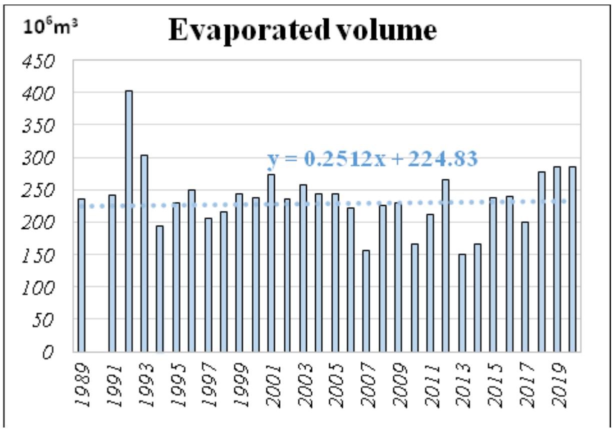


**Figure 6b: Evolution evaporated volume**

The curves in Figures 6a and 6b call for the following observations:

- The useful reserve curve on January 1st keeps a similar shape to that of evaporation;
- The linear trend curve of the useful reserve on January 1st is decreasing while that of evaporation is increasing;

## Flow rate evolution

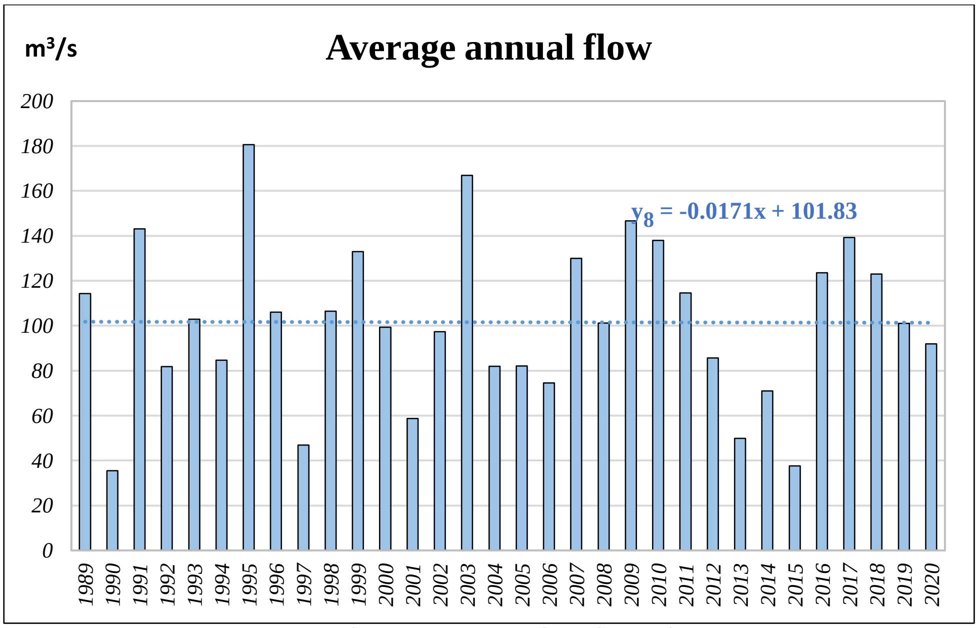
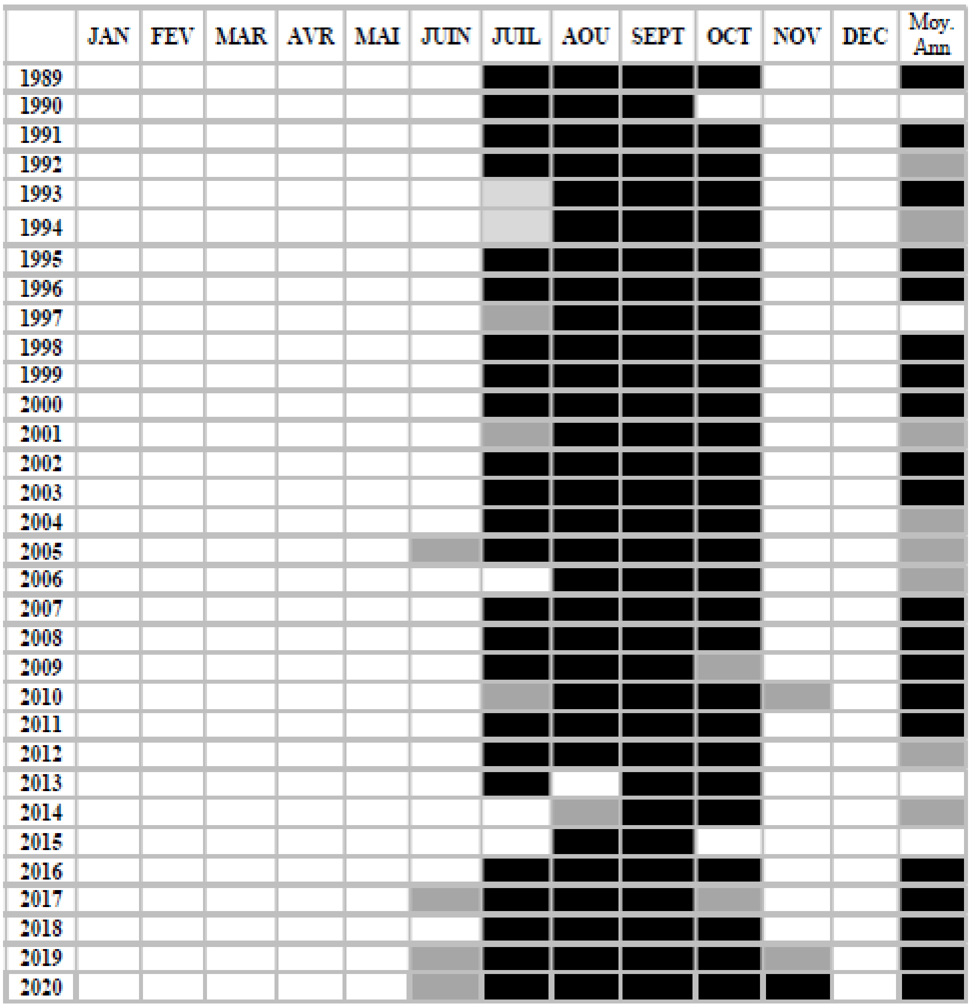


**Figure 7: Evolution of the average annual flow of Mono from 1989 to 2020**



| | JAN | FEV | MAR | AVR | MAI | JUIN | JUIL | AOU | SEPT | OCT | NOV | DEC | Moy. Ann |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1989 | | | | | | | ■ | ■ | ■ | ■ | | | ■ |
| 1990 | | | | | | | ■ | ■ | ■ | | | | |
| 1991 | | | | | | | ■ | ■ | ■ | ■ | | | ■ |
| 1992 | | | | | | | ■ | ■ | ■ | ■ | | | ▒ |
| 1993 | | | | | | | ░ | ■ | ■ | ■ | | | ■ |
| 1994 | | | | | | | ░ | ■ | ■ | ■ | | | ▒ |
| 1995 | | | | | | | ■ | ■ | ■ | ■ | | | ■ |
| 1996 | | | | | | | ■ | ■ | ■ | ■ | | | ■ |
| 1997 | | | | | | | ▒ | ■ | ■ | ■ | | | |
| 1998 | | | | | | | ■ | ■ | ■ | ■ | | | ■ |
| 1999 | | | | | | | ■ | ■ | ■ | ■ | | | ■ |
| 2000 | | | | | | | ■ | ■ | ■ | ■ | | | ■ |
| 2001 | | | | | | | ▒ | ■ | ■ | ■ | | | ▒ |
| 2002 | | | | | | | ■ | ■ | ■ | ■ | | | ■ |
| 2003 | | | | | | | ■ | ■ | ■ | ■ | | | ■ |
| 2004 | | | | | | | ■ | ■ | ■ | ■ | | | ▒ |
| 2005 | | | | | | ▒ | ■ | ■ | ■ | ■ | | | ▒ |
| 2006 | | | | | | | | ■ | ■ | ■ | | | ▒ |
| 2007 | | | | | | | ■ | ■ | ■ | ■ | | | ■ |
| 2008 | | | | | | | ■ | ■ | ■ | ■ | | | ■ |
| 2009 | | | | | | | ■ | ■ | ■ | ▒ | | | ■ |
| 2010 | | | | | | | ▒ | ■ | ■ | ■ | ▒ | | ■ |
| 2011 | | | | | | | ■ | ■ | ■ | ■ | | | ■ |
| 2012 | | | | | | | ■ | ■ | ■ | ■ | | | ▒ |
| 2013 | | | | | | | ■ | | ■ | ■ | | | |
| 2014 | | | | | | | | ▒ | ■ | ■ | | | ▒ |
| 2015 | | | | | | | | ■ | ■ | | | | |
| 2016 | | | | | | | ■ | ■ | ■ | ■ | | | ■ |
| 2017 | | | | | | ▒ | ■ | ■ | ■ | ▒ | | | ■ |
| 2018 | | | | | | | ■ | ■ | ■ | ■ | | | ■ |
| 2019 | | | | | | ▒ | ■ | ■ | ■ | ■ | ▒ | | ■ |
| 2020 | | | | | | ▒ | ■ | ■ | ■ | ■ | ■ | | ■ |

**Figure 8: Evolution of the average monthly and annual flow of Mono from 1989 to 2020** [17]

The record of average annual and monthly flows from 1989 to 2020 can be a determining element for the analysis of climate impacts on the water system of Mono River. The curves in Figures 7 and 8 represent the evolution of annual flows and monthly flows from 1889 to 2020.

### Interprétation of figure 8

To determine the months when Mono River records high flow, we used the "Bertin file" which allows us to determinate the rainfall as a percentage of excess or deficit compared to the normal rainfall calculated over a time series [17]. According to figure 8 above, we note that:

- Periods of low flow are represented by the boxes in white color;
- Periods of medium flow are represented by the boxes in gray color;
- The high flow periods are represented by the boxes in black color.

### Assumption and method for determining average flow rates

The approach used for determining the average flow rates is illustrated in Figure 9 below.

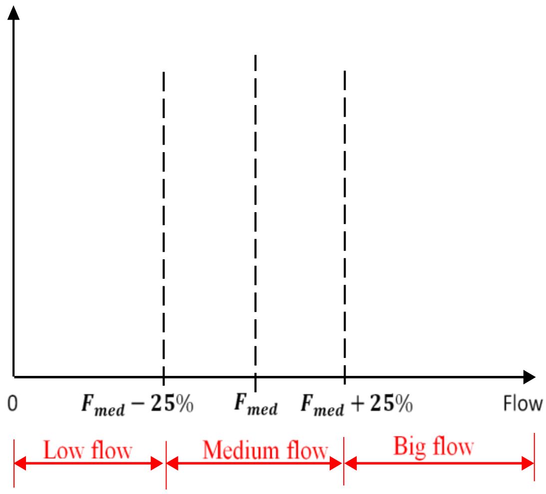


**Figure 9: Flows determination**

***Interprétation*:** We have announced above that the expected annual producible energy of Nangbéto dam is 150 GWH. Based on this forecast, we determine the useful power for a continuous operation of the alternators and by ricochet, the flow necessary to produce this power. Around this calculated flow, we have created a dead band of ± 25% which represents the values of the average flow ($\boldsymbol{F_{med}}$) for the month.

Considering that an alternator operates continuously for a whole year, we have defined the flow rate necessary to produce the expected producible energy (150 GWH) from the following equation 4:

$$\boldsymbol{E = P\,.\,T} \qquad \textbf{(4)}$$

*With:*

*E designates the producible energy (150 GWH);*

*P designates the instantaneous power of the group;*

*T designates the duration in hours (for one year of operation T= 8640 hours).*

*What gives instantaneous producible power equal to 17,5 MW.*

Based on the calculated instantaneous power, we determine the waterfall from the builder's abacus [18]. The flow rate can be obtained from equations 5 and 6 below:

$$\boldsymbol{P = \rho.g.D.h.r} \qquad \textbf{(5)}$$

$$\boldsymbol{D = \frac{P}{\rho.g.h.r}} \qquad \textbf{(6)}$$

*With:*

*P: Alternator active power (17,5MW);*

*ρ: Density of water (1 kg/m$^3$);*

*g: Gravity value in Nangbéto (9,78 N/kg);*

*H: Waterfall height (variable from 20 to 30m depending on the abacus);*

*r: Group performance.*

The flow rate is determined by varying the waterfall height over the range defined above and the following table is obtained.

**Table 2: Determination of the medium flow ($F_{med}$)**

| | | Values of the waterfall (H) | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **20** | **20,5** | **21** | **21,5** | **22** | **22,5** | **23** | **23,5** | **24** | **24,5** | **25** | **25,5** | **26** | **26,5** | **27** | **27,5** | **28** | **28,5** | **29** | **29,5** | **30** |
| **Values of the group performance (r)** | **0,98** | 91,3 | 89,1 | 86,9 | 84,9 | 83,0 | 81,2 | 79,4 | 77,7 | 76,1 | 74,5 | 73,0 | 71,6 | 70,2 | 68,9 | 67,6 | 66,4 | 65,2 | 64,1 | 63,0 | 61,9 | 60,9 |
| | **0,97** | 92,2 | 90,0 | 87,8 | 85,8 | 83,9 | 82,0 | 80,2 | 78,5 | 76,9 | 75,3 | 73,8 | 72,3 | 71,0 | 69,6 | 68,3 | 67,1 | 65,9 | 64,7 | 63,6 | 62,5 | 61,5 |
| | **0,96** | 93,2 | 90,9 | 88,8 | 86,7 | 84,7 | 82,8 | 81,0 | 79,3 | 77,7 | 76,1 | 74,6 | 73,1 | 71,7 | 70,3 | 69,0 | 67,8 | 66,6 | 65,4 | 64,3 | 63,2 | 62,1 |
| | **0,95** | 94,2 | 91,9 | 89,7 | 87,6 | 85,6 | 83,7 | 81,9 | 80,2 | 78,5 | 76,9 | 75,3 | **73,9** | 72,4 | 71,1 | 69,8 | 68,5 | 67,3 | 66,1 | 64,9 | 63,8 | 62,8 |
| | **0,94** | 95,2 | 92,9 | 90,6 | 88,5 | 86,5 | 84,6 | 82,8 | 81,0 | 79,3 | 77,7 | 76,1 | 74,7 | 73,2 | 71,8 | 70,5 | 69,2 | 68,0 | 66,8 | 65,6 | 64,5 | 63,5 |
| | **0,93** | 96,2 | 93,9 | 91,6 | 89,5 | 87,5 | 85,5 | 83,7 | 81,9 | 80,2 | 78,5 | 77,0 | 75,5 | 74,0 | 72,6 | 71,3 | 70,0 | 68,7 | 67,5 | 66,3 | 65,2 | 64,1 |
| | **0,92** | 97,2 | 94,9 | 92,6 | 90,5 | 88,4 | 86,4 | 84,6 | 82,8 | 81,0 | 79,4 | 77,8 | 76,3 | 74,8 | 73,4 | 72,0 | 70,7 | 69,5 | 68,2 | 67,1 | 65,9 | 64,8 |
| | **0,91** | 98,3 | 95,9 | 93,6 | 91,5 | 89,4 | 87,4 | 85,5 | 83,7 | 81,9 | 80,3 | 78,7 | 77,1 | 75,6 | 74,2 | 72,8 | 71,5 | 70,2 | 69,0 | 67,8 | 66,7 | 65,5 |
| | **0,9** | 99,4 | 97,0 | 94,7 | 92,5 | 90,4 | 88,4 | 86,4 | 84,6 | 82,8 | 81,2 | 79,5 | 78,0 | 76,5 | 75,0 | 73,6 | 72,3 | 71,0 | 69,8 | 68,6 | 67,4 | 66,3 |
| | **0,89** | 100,5 | 98,1 | 95,7 | 93,5 | 91,4 | 89,4 | 87,4 | 85,6 | 83,8 | 82,1 | 80,4 | 78,8 | 77,3 | 75,9 | 74,5 | 73,1 | 71,8 | 70,5 | 69,3 | 68,2 | 67,0 |
| | **0,88** | 101,7 | 99,2 | 96,8 | 94,6 | 92,4 | 90,4 | 88,4 | 86,5 | 84,7 | 83,0 | 81,3 | 79,7 | 78,2 | 76,7 | 75,3 | 73,9 | 72,6 | 71,3 | 70,1 | 68,9 | 67,8 |
| | **0,87** | 102,8 | 100,3 | 97,9 | 95,7 | 93,5 | 91,4 | 89,4 | 87,5 | 85,7 | 83,9 | 82,3 | 80,7 | 79,1 | 77,6 | 76,2 | 74,8 | 73,5 | 72,2 | 70,9 | 69,7 | 68,6 |
| | **0,86** | 104,0 | 101,5 | 99,1 | 96,8 | 94,6 | 92,5 | 90,5 | 88,5 | 86,7 | 84,9 | 83,2 | 81,6 | 80,0 | 78,5 | 77,1 | 75,7 | 74,3 | 73,0 | 71,7 | 70,5 | 69,4 |
| | **0,85** | 105,3 | 102,7 | 100,2 | 97,9 | 95,7 | 93,6 | 91,5 | 89,6 | 87,7 | 85,9 | 84,2 | 82,6 | 81,0 | 79,4 | 78,0 | 76,6 | 75,2 | 73,9 | 72,6 | 71,4 | 70,2 |
| | **0,84** | 106,5 | 103,9 | 101,4 | 99,1 | 96,8 | 94,7 | 92,6 | 90,6 | 88,8 | 86,9 | 85,2 | 83,5 | 81,9 | 80,4 | 78,9 | 77,5 | 76,1 | 74,7 | 73,5 | 72,2 | 71,0 |
| | **0,83** | 107,8 | 105,2 | 102,7 | 100,3 | 98,0 | 95,8 | 93,7 | 91,7 | 89,8 | 88,0 | 86,2 | 84,5 | 82,9 | 81,4 | 79,8 | 78,4 | 77,0 | 75,6 | 74,3 | 73,1 | 71,9 |
| | **0,82** | 109,1 | 106,4 | 103,9 | 101,5 | 99,2 | 97,0 | 94,9 | 92,9 | 90,9 | 89,1 | 87,3 | 85,6 | 83,9 | 82,3 | 80,8 | 79,4 | 77,9 | 76,6 | 75,2 | 74,0 | 72,7 |
| | **0,81** | 110,5 | 107,8 | 105,2 | 102,7 | 100,4 | 98,2 | 96,0 | 94,0 | 92,0 | 90,2 | 88,4 | 86,6 | 85,0 | 83,4 | 81,8 | 80,3 | 78,9 | 77,5 | 76,2 | 74,9 | 73,6 |
| | **0,8** | 111,8 | 109,1 | 106,5 | 104,0 | 101,7 | 99,4 | 97,2 | 95,2 | 93,2 | 91,3 | 89,5 | 87,7 | 86,0 | 84,4 | 82,8 | 81,3 | 79,9 | 78,5 | 77,1 | 75,8 | 74,6 |
| | **0,79** | 113,3 | 110,5 | 107,9 | 105,3 | 103,0 | 100,7 | 98,5 | 96,4 | 94,4 | 92,4 | 90,6 | 88,8 | 87,1 | 85,5 | 83,9 | 82,4 | 80,9 | 79,5 | 78,1 | 76,8 | 75,5 |
| | **0,78** | 114,7 | 111,9 | 109,2 | 106,7 | 104,3 | 102,0 | 99,7 | 97,6 | 95,6 | 93,6 | 91,8 | 90,0 | 88,2 | 86,6 | 85,0 | 83,4 | 81,9 | 80,5 | 79,1 | 77,8 | 76,5 |

The choice of the average flow is made under two conditions:

- **First condition:** the dam must not be filled to the maximum height throughout the year at the risk of destroying it.
- **Second condition:** the dam must not be emptied to its minimum height under penalty of destroying the core which will result in its destruction during the following filling season.
- The minimum elevation of the Nangbéto dam is 130 m.o.s. while the maximum elevation is 144.5 m.s.m. Under these conditions, the average operating level is 137.5 m.o.s.

  With a downstream level of 112 m.o.s. (downstream level during the operation of the machines), we end up with a gross watrfall H = 137.5-112 or H = 25.5 m.

  According to the manufacturer's document [19], the ideal efficiency for this waterfall is 95%.

  This corresponds in table 2 above to a flow rate $F_{med}$ = 73.9 **m$^3$/s** thus giving:

  $F_{med} + 25\%$ = **93,33 m$^3$/s**

  $F_{med} - 25\%$ = **55,38 m$^3$/s**

We then conclude that:

- The month in which the average flow is less than 55,38 m3/s will be considered as a month of low flow;
- The month whose flow is in the range of 55,38 m3/s to 93,33 m3/s will be considered as a month of medium flow.

- The month in which the average flow will be greater than 93,33 $m^3/s$ will be considered as a month of high flow.

## Evolution of temperature in Nangbéto

The variation of maximum and minimum temperatures at Nangbéto compared to the variation of evaporation recorded during the study period, will allow us to confirm or deny the increase in global warming indicated by the WMO (World Meteorological Organization) over the period 2016 to 2020 [20].

In Nangbéto, evaporation is evaluated by two methods: (i) The evaporation pan method and (ii) the method of calculating the volumes of evaporated water.

The first method is to use a class A evaporation pan with weather station and protective cage. The evaporation pan measures the rate of evaporation of a given volume of water. This evaporation rate is transcribed as an accumulation of millimeter per day, per month and per year [21]. An evaporation pan is an evaporometer consisting of a basin or pan of water with a large surface and deep enough where the variation in water level due to evaporation can be measured [22]. The water level is kept a short distance below the edge of the tank. The variations in the water level in the tank, measured at fixed intervals, reflect the intensity of evaporation [23]. Evaporation is evaluated in millimeter. The image in Figure 9 below shows a weather station equipped with a class A evaporation pan.

**Figure 9: Class A evaporation pan with weather station and protective cage [24].**

The simplified expression of the water balance of a tank is written as follows [25] :

$$\boldsymbol{E_{BAC}} = \Delta \boldsymbol{H} + \boldsymbol{P} \qquad (7)$$

*With:*

*$E_{BAC}$: Evaporation of the pan (mm);*

*P: rain falling on the tank (mm);*

*ΔH: difference in elevation of the body of water in the tank between two measurements (mm).*

The change from evaporation of the tank to evaporation of the water body is done by multiplying the measurement results on the tank by the coefficient of the tank [25]**:**

$$\boldsymbol{E} = \boldsymbol{K} \, . \boldsymbol{E_{BAC}} \qquad (8)$$

*With:*

*E: Evaporation of the water body (mm);*

*K: pan coefficient, (K= 0,7- 0.8, for class A pan and Colorado);*

*$E_{BAC}$: evaporation measured on the pan (mm).*

The second method is to determine the evaporation rate from the volume of evaporated water and the volume of water in the dam retention. This is a method specific to the Nangbéto power plant manager. Nangbéto power manager uses this method to confirm the values obtained with the evaporation pan method.

This is because the change in the evaporation rate is considered to reflect the image of evaporation.

The evaporation rate $k_i$ for year i is calculated using the following equation:

$$\boldsymbol{k_i} = \frac{\sum_{m=1}^{m=12} \boldsymbol{V_{e_m}}}{\boldsymbol{V_{ri}} + \sum_{m=1}^{m=12} \boldsymbol{V_{a_m}}} \qquad (9)$$

*with:*

*$k_i$ : evaporation rate for year i;*

*$V_{e_m}$: Total volume of water evaporated during the month m;*

*$V_{a_m}$: Total input volume during the month m;*

*$V_{ri}$: Volume of the initial water reserve for the year i.*

The volume of evaporated water is determined by the equation [13]**:**

$$V_{e_m} = V_{a_m} - V_{vr_m} - V_{t_m} - V_{d_m} \quad (10)$$

*With*

$V_{e_m}$*: Total volume of water evaporated during the month m;*

$V_{a_m}$*: Total input volume during the month m;*

$V_{vr_m}$*: Total change in reserve during the month m;*

$V_{t_m}$*: Total volume of water turbined in the month m;*

$V_{d_m}$ *: Total volume of water discharged in the month m.*

The minimum and maximum temperature curve and that of evaporation are shown in Figure 10 below.

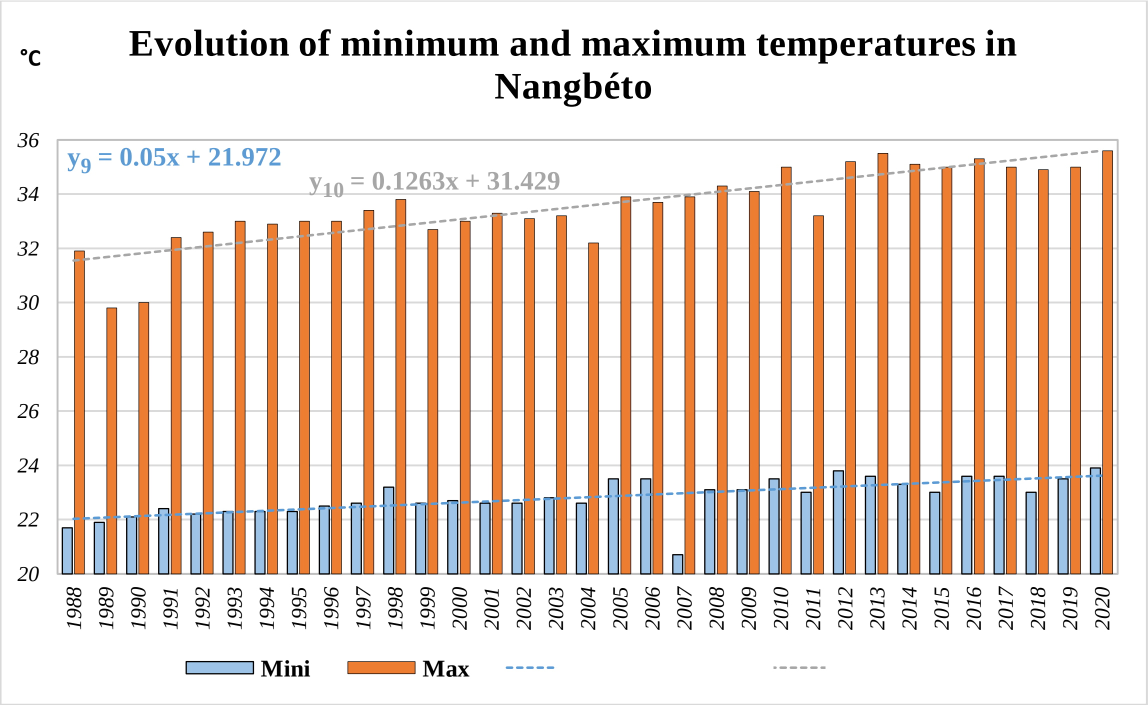


**Figure 10a: Evolution of minimum and maximum temperatures**

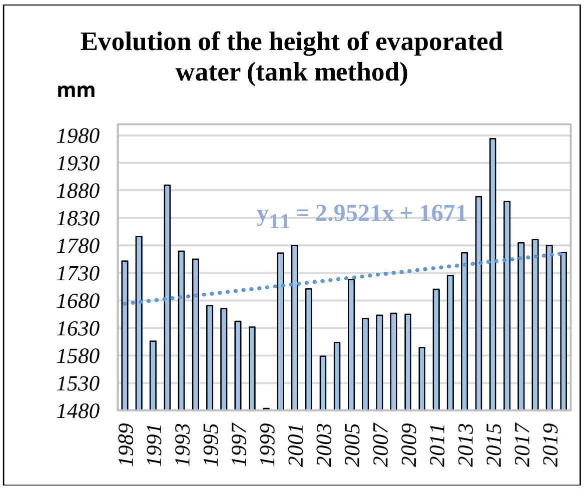


***Figure 10b: Evolution of evaporation (tank method)***

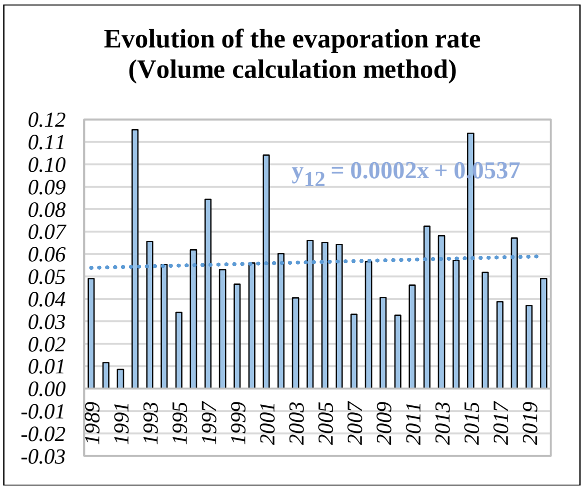


***Figure 10c: Evolution of the evaporation rate (volume calculation method)***

Curves 10a, 10b and 10c call for the following observations:

- The minimum temperature values recorded in Nangbéto over the study period are between 21.7 and 23.9 ° C.
- The maximum temperature values recorded in Nangbétos over the study period are between 29.8 and 35.6 ° C.
- The evaporation rate curve looks like the evaporation curve.

## RESULTS AND DISCUSSIONS

### Analysis of the impacts of global warming

Global warming has negative impacts on the hydrological cycle of the Mono River and indirectly on the Nangbéto hydroelectric power plant. From the analysis of the different curves drawn above, five (05) situations emerge which confirm the effects of climate change:

1. ***The decrease in the volume of Nangbéto lake inflows***: Figure 4 illustrates, among other things, the evolution curve of the annual inflow of water into Nangbéto Lake over the period of our study. The trend curve of equation y2 = -3.5219x + 3450.4 confirms that the inflows are in decline from 1989 to 2020.

2. ***The decrease in the flows of the Mono river***: The trend curve of the average annual flow of the Mono river with equation y8 = -0.0171x + 101.83 represented in figure 7 shows that this flow is also decreasing over the period of the study.

3. ***The increase in the temperature in Nangbéto***: The annual average minimum and maximum temperatures recorded over the study period and shown in Figure 10a are increasing. The two trend curves of respective equations y9 = 0.05x + 21.972 and y10 = 0.1263x + 31.429 show this progression of the annual mean temperature. This increase in the temperature is observed since 1960 [8].

4. ***The increase in evaporations at Nangbéto***: The evaporation curve shown in Figure 10b using the evaporator pan method is constantly increasing. This trend is confirmed by the curve obtained by the method of evaporated volumes; this curve is shown in FIG. 10c. The equations of the respective trend curves y11 = 2.9521x + 1671 and y12 = 0.0002x + 0.0537, confirm this increase in evaporation over the study period.

5. ***Irregularity of rains***: Precipitation in the Mono river basin is aperiodic, and forecasts are almost impossible because their variation does not respect any law [8].

For illustration, the largest inflows were recorded during the years 1991, 1995, 1999, 2003, 2007, 2009, 2010, 2016 and 2017. The low flows were recorded during the years 1990, 1997, 2001, 2013 and 2015.

### Analysis of the management and operation of the Nangbéto dam

The management of a dam like that of Nangbéto has three (03) objectives [26]:

***Economic***: Production of electric energy at a competitive cost by aiming for the efficient use of available water resources;

***Stream regulation:*** Make the river's water resources available throughout the year to facilitate the irrigation of crops and the development of fishing upstream and downstream of the dam;

***Flood control***: Reduction and control of flooding downstream of the dam. If necessary, an alert can be given to warn residents of the imminent flooding.

Indeed, the trend curves confirm the following situations:

**Table 3: Trends summary**

| **Parameter** | **Upward trend over the period** | **Downward trend over the period** | **Figure** |
|---|---|---|---|
| Input volume | | | 4 |
| Turbined volume | | | 4 |
| Discharged volume | | | 5 |
| Released volume (turbined + discharged) | | | 4 |
| Volume of the useful reserve on January 1 | | | 5 |
| Average flow | | | 7 |
| Evaporation | | | 10b |
| Temperature | | | 10a |

The analysis of the trend curves of the operating parameters of the Nangbéto plant reveals that the experiences capitalized by Nangbéto power plant operator have made it possible to improve the operation and management of the dam to: (i) limit at the strict minimum the volumes discharged,

(ii) reduce the initial reserves, (iii) increase the turbined volumes, etc.

These provisions have enabled very interesting operating results in terms of production / input flow.

However, it is observed that, while the input volume decreases, the volume discharged increases; this situation deserves to be reassessed by the operator with a view to possible improvement in the management of the water retention. Better results, in particular economic results, can be achieved provided that the volume of water discharged changes in the same proportion as the inputs.

The efficiency of the management of the Nangbéto dam by the operator can be demonstrated from the following three (03) parameters:

***Increase in the total annual volume of turbined water:*** The trend curve (Figure 4) of this volume with equation $y_1 = 11.49x + 2487.2$ confirms this increase. The increase in the annual turbined volume reflects an increase in machine operating time and consequently an increase in the production of electrical energy by the Nangbéto Power plant.

***Decrease in the useful reserve of the 1st month of the year (figure 5):*** The trend curve of the useful reserve with equation $y_5 = -3.7844x + 933.33$ confirms that the volume of this reserve is declining over the study period. This reduction reflects the operator's desire to optimize the operation of the machines to prevent a large reserve from contributing to water spills (releases) during the year. This provision must be continued and improved to reverse the trend curve of the volumes discharged (Figure 5) which continue to increase according to its linear representation of equation $y_4 = 3.0226x + 350.88$.

***Efficient management of input volumes (figure 4):*** A comparison of the curve of annual input volumes and that of turbined volumes increased by released volumes, shows that the latter is always lower than the first over the entire period of the study. This confirms the operator's efforts to considerably reduce flooding by letting downstream a volume of water less than the volume of inflows.

## CONCLUSION

This study allowed us to highlight the history of the hydrology of the Mono River and the Nangbéto dam from 1989 to 2020. The minimum and maximum temperatures were recorded and analyzed over the period of the study. Evaporation data was recorded using two methods: the evaporation pan method and the evaporated volume method. These two methods, first gave interesting results and secondly, confirmed the increase in the volumes of evaporated water over the period. With the trend curves obtained, it was shown that climate change has real negative impacts on the hydrology of the Mono River and on the operation of the Nangbéto power plant, in particular: (i) The irregularity of the rains, (ii) the decrease in the input volume of Mono river, (iii) the decrease in the flows of the Mono River, (iv) the increase in temperatures which, consequently, causes (v) an increase in evaporations in Nangbéto. Likewise, we carried out an analysis on the management of the Nangbéto power plant by the current operator. As a result, the inhibiting effect of global warming on the dam's water resources requires optimal integrated management likely to promote better energy and economic profitability of Nangbéto dam. To this end, the operator is recommended to improve the current management of Nangbéto dam to reverse the curve of flood water discharges.

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