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Analysis of large-scale droughts in the energy field by using mathematical programming: The case of the Paraná River basin

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C H R O N I C L E

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A B S T R A C T

Effects of climate change can already be observed in many regions of the world. The basin of the Paraná River, in South America, has been suffering an important drought since 2019 in the whole region. The extension of the crisis has increased the risks in the flora and fauna, losses in logistics of navigation, besides the problems of urban water cleansing. In this regard, the novel proposal presents a new mathematical model to study the impact of this crisis. Besides the traditional constraints of the literature for hydraulic systems, this paper enhances inventory constraints, connections with electric systems, and other considerations as the head effects in electricity generation. Because several equations related to electricity generation are nonlinear (which the subsequent computational effort impacts), this proposal applies linearization techniques to reduce CPU times. The core is related to hydropower production, and the consequences of the water crisis in the regional markets. The mathematical model analyzes the interrelationships between reservoirs and water flows of the basin. To study the effectiveness of the novel proposal, the reported situation of the basin of the Paraná River is studied by considering two scenarios (normal conditions of the river flow and the conditions related to the drought). Results show that the crisis implies daily net economic losses of about 7 million USD for the operators of the power plants. Other problems (different from the ones related to the energy field) are also mentioned and analyzed.

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Nomenclature

Indexes

i	Generator
t	Period
ld	Load
y, z	Generation and head level
c	Gate of the HP
Rn	Reservoir index

Constants

ρ_t^f	Forecast price ($/MWh)
σ_i , σ_cons_i	Generating cost due to production (or pumping) ($/MWh)

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I	Total number of generators
T	Total number of periods
ϑ_t	Load shedding cost ($/MWh)
$D_{ld,t}$	Estimate electricity demand (MWh)
$\delta_{in}, \delta_{out}$	Inflow (or outflow) river (m^3/s)
$\delta r_z^{min}, \delta r_z^{max}$	minimum (or maximum) difference of volumes for a considered head level (Hm^3)
$\overline{H}_z$, $\underline{H_z}$	maximum (and minimum) values of hydraulic head level (m)
$\overline{H}^{max}$	maximum head for all levels (m)
$P_{y,z,i}^{parameter}, Dg_{y,z,i}^{parameter}$	power output (or discharge) values for operating point y, z, i (MWh or m3/s)
$\underline{p_i}$, $\overline{p_i}$	Generation limits (MW)
Y, Z	Total number of generation and head levels
C	Total number of gates of the HP

Variables

$p_{i,t}$	Power output of generator *i* at *t* (MW)
$cu_{i,t}$	Startup cost of unit *i* at time period *t ($)*
$p\_cons_{i,t}$	Power consumption of generator *i* at *t* (MW)
$LS_{ld,t}$	Load shedding (MW)
$Dg_{i,t}, Dc_{c,t}$	Water discharge (m^3/s)
$qp_{i,t}$	Pumped flow (m^3/s)
$h_{s,t}$	Water elevation (m)
$x\_g_{i,t}, x\_p_{i,t}$	Binary variable for generating or pumping mode
v_t^{up}, v_t^{lo}	Volume of reservoir (Hm^3)
$wg_{y,z,s,t}$	Weight variable for power generation [0,1]
$\beta_{z,i,t}$	Binary variable for reservoir differences

Acronyms

HP	Hydropower plant
PSU	Pumped storage unit
MILP	Mixed-integer linear programming
NLP	Non-linear programming
GENCO	Generation company
ISO	Independent system operator

1. Introduction

Power generation has increased during the last decades (IEA, 2018). This increase is founded on the population density, world financial growth produced since the subprime credit crisis of 2008 (Helleiner, 2011), the industrial activities in emerging countries (Bonizzi, 2013), and great money amounts to invest in the energy sector. The expansion of the electric systems needs bearing in mind social individualities, financial situation, and above all, the eco-friendly influence of these movements. Electricity generation with non-renewable sources causes important environmental impacts because of the greenhouse gases emission (GHG). The molecules of these gases stock long-wave radiation energy as heat. It reduces the thermal balance between the Earth planet and the extraterrestrial cosmos (Sanaeepur et al., 2014). In this regard, the IPCC (Intergovernmental Panel on Climate Change from the United Nations) presented on 9th August 2021 a complete report that analyzes the global climate changes in the coming decades, based on more than 14,000 papers about the topic (BBC, 2021a; IPCC - Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 2021). The key conclusions of the report can be brief in five groups: 1) the climate change effects are expanding rapidly and intensifying. 2) An increase in the world temperature of at least 1.5ºC could be produced within the next decade. 3) The level of seas could be increased by over 2 m before the end of this century. 4) The level of CO_2 emissions could be higher than the supposed ones. 5) Methane emissions could originate over 20% of the current temperature increase. Due to the aforementioned environmental consequences, researchers have concentrated their effort during the two last decades in covering the increasing power demand with renewable technologies (Meyer, 2003).

Although the effects of climate change and renewable sources can be observed in different parts of the world (Alvarez, 2022; Singh and Venkata Rao, 2011). In recent years, serious effects at the level of basins of rivers have been observed in several South American countries. The Paraná River is the third-largest freshwater reservoir in the world. It has a surface area of approximately 2.5 million square kilometers and extends through Brazil, Argentina, Uruguay, and Paraguay. In Argentina, the government declared a state of water emergency in 2021 due to the low flow of the Paraná River. This problem not only affects the supply of drinking water to many populations but has also caused millions of dollars in losses in agro-exports. Paraná River is key for the country because it is used as a means of transportation for most of the country's exports, which are mainly foodstuffs (BBC, 2021b). The location of the Paraná River in the map of Argentina (south zone of Santa Fe-Argentina provinces) is illustrated in **Fig. 1.** Besides, the low flow of the Paraná River is compared with the situation two years before in the same figure (based on the satellite technology of (CONAE, 2021)). The situation in Brazil during 2021 is even more difficult. The country is suffering its worst drought in a century, with significant economic and environmental damage. This is because five reservoirs in the central and the southern area of the country recorded below-average water levels. The drought has produced an unprecedented energy crisis due to the large amount of installed hydroelectric power in the country. Deforestation in the Amazon is one of the factors contributing to the decrease in rainfall, causing droughts. In (Aragão et al., 2018), the authors conclude that CO_2 emissions are related to forest fires, deforestation processes, and changes in the reserve of Amazonia. The main causes and consequences of this crisis are described in (Hunt et al., 2022).

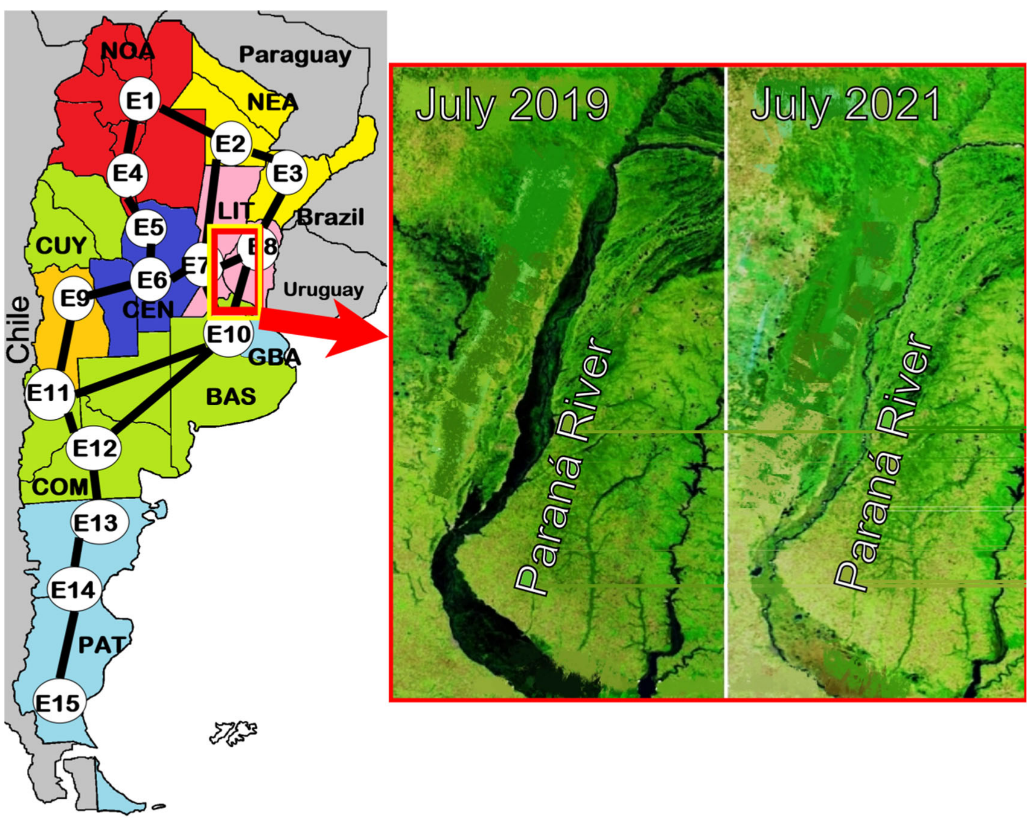

Fig. 1. Argentine 500 kV Electric System (left side); and comparison of the Parana River situation between years 2019 and 2021 (right side).

Paraná River, which has a historical average flow of about 17,000 m^3/s, fell to 7,000 m^3/s during the current crisis, close to the historical minimum of 5,800m^3/s (during 1944). This means that the river level is nearly three meters lower than the normal level. The crisis of the Paraná River, which for two years has registered its lowest levels in almost eight decades, is having somber consequences for the aforementioned countries. Researchers advise that the drought is also affecting the ecosystems. It is altering the natural balance that influences hundreds of plant and animal species. But the drought in the flow of the river also promotes other problems because it is one main highway in South America for thousands of ships. This situation brings three main problems for the whole region (Smink, 2021):

1. Paraná River along with the Paraguay River (a tributary suffering from a historic drought), form the so-called Paraná-Paraguay waterway (allowing continuous navigation among harbors in Argentina, Brazil, Bolivia, Paraguay, and Uruguay). The drought in the flow of the river has promoted limitations in the cargo capacity of ships, increasing transportation costs.

2. The drop in the height of the river increases the smuggling problem because the bootleggers have more available routes to cross the river between the different countries. All these actions increase the traffic of sex slaves, illegal merchandising, and other crimes.

3. The Paraná River not only is utilized as a highway for shipping and exports. It is also a key role in the circulation of fuels. Over 70% of the compressed natural gas from Argentina is transported through this river. An important share of oil is also transported through the river to several provinces of the country. However, the main impact of the drought of the river is in the field of electricity generation. There are many hydropower stations on the river (the most important is Itaipu (G. E. Alvarez, 2020)). If only the Itaipu plant is considered, it has been operating with 10-14 turbines of its 20 ones due to the drought. This has promoted over 15% drop in power generation in the production 2020, and 35% when it is compared with 2016 (maximum production level). A similar situation can be observed with the rest of the plants located in the Paraná River.

To correct the impact of variations of water reserve in hydropower generation, optimization techniques (based on mathematical models) constitute one of the best options to represent and study these units with an accurate level (Cohen and Wan, 1985). The problem that finds the best possible configuration to operate a hydropower plant (HP) is known as Hydro Unit Commitment Problem (or HUC) (Chao-An Li et al., 1997). In this regard, the authors of (Bozorg Haddad et al., 2014a) develop a nonlinear model (NLP) that solves the HUC problem for two plants from Iran. The approach considers reservoir volume constraints and the diameter of the water transmission facilities. Unfortunately, the main disadvantage of NLP (along with the Mixed Integer Nonlinear Programming models, MINLP) is the high computational effort to get solutions with an adequate level of precision. Consequently, the Mixed Integer Linear Programming (MILP) models have gained in interest representing large scale problems during recent years (Allaham and Dalalah, 2022). The models permit obtaining the benefits of linear models (as lower computational effort, ensuring global optimality, and the flexibility to annex constraints (Lima and Grossmann, 2011)). The pumped storage units (PSU) are a special case of hydropower generation. These units can generate electricity as a conventional hydropower unit, but they can also conduct water from the lower reservoir to the upper one (usually during low power demand periods). This increases the volume of the upper reservoir to compose an energy reserve. As a result, some approaches as (Borghetti et al., 2008), present a novel linearization technique for the curves of PSU operation. However, that paper does not contemplate the impact of hydraulic head changes for the pumping mode. The hydraulic head is the difference between the elevations of two water static columns. In (Narang et al., 2012), the hydraulic head is assumed as constant. A dynamic technique is utilized to solve combined power plants by including head effects in the work of (Catalao et al., 2009). But, the method is not convenient for the short-term operation because of dimensionality difficulties ((Cheng et al., 2015)). Authors of (Fruhmann et al., 2019) study the hydropower expansion relating to factors such as financial concerns of investors in some countries of Europe. The author of (G. Alvarez, 2020) develop a mathematical model that solves an integrated natural hydraulic system with two PSUs by using a linear model that accepts more breakpoints than the rest of the papers in the literature. It means solutions closer to reality. Besides, (Cheng et al., 2018) develops a MILP model for the scheduling of PSUs, by applying a nine-breakpoint technique, which decreases the differences between peak-valley for the residual load with hydraulic head effects. A similar nine-breakpoint process is involved in (Li et al., 2014) to linearize the operating curves (it only considers conventional hydropower units). Similarly, a management framework that optimizes a system composed of PSUs, irrigation amenities, and wind farms is settled in (Ghasemi, 2018). The main benefits and differences between the above-mentioned works and the present ones are brief in Table 1. Besides the development of mathematical models that attend the hydropower generation, the strategic importance of water resources for a country has been studied in several works, as in (Masud et al., 2020) for Bangladesh, or in (Fruhmann et al., 2019) for Austria and Slovenia.

Table 1

Key contributions and differences among related approaches

Approach	Key Contributions	Key Differences
(Bozorg Haddad et al., 2014a)	Non-linear programming (NLP) model for the scheduling of PSUs by using comparison of four criteria	NLP models could need a high CPU effort, even more in large scale systems
(Borghetti et al., 2008)	A Linear model that faces the PSUs maneuver with a lower computational requirement including transmission constraints	The model does not include the head effects when the PSU is working in pumping mode
(Narang et al., 2012)	A procedure for a combined predator-prey optimization along with a Powell's search technique	The hydraulic head is assumed as constant

Table 1
Key contributions and differences among related approaches (Continued)

(Catalao et al., 2009)	NLP model to solve systems considering hydraulic head effects	Problems in the short-term operation because the dimensionality factor
(G. Alvarez, 2020)	A MILP model for scheduling PSPs with more breakpoints that the rest of linearization techniques	The model does not consider the connections between different hydropower stations
(Cheng et al., 2018)	A MILP model to reduce the peak-valley variance with residual load series of each grid.	A nine-breakpoint method is used to linearize the operating curve
(Li et al., 2014)	A MILP model for scheduling hydropower plants that requires a lower amount of auxiliary variables	A nine-point technique is used to linearize the operating curve. Only conventional hydropower plants are considered. PSUs are not allowed
(Ghasemi, 2018)	Coordinated framework to improve the combined operation of PSUs, irrigation facilities, and unpredicted wind generation	Test cases are micro-grids, application to large scale systems is not analyzed

Given the above, this paper is characterized by the following contributions:

- A MILP model that allows flexibility in the representation of the case studies, based on linearizing techniques that allow representing, with a sufficient degree of approximation, real situations of these systems that are non-linear (and would therefore require a significant computational requirement to be solved). MILP models present several advantages that make them very useful for the test systems considered in this work (Lima and Grossmann, 2011).
- Reductions in the computational effort of the real systems represented, would allow applying the present work to other areas besides the one presented in this paper. An example of this could be the daily programming of the power plants when real data provided by their GENCOS (owners of the plants) and the ISO (independent system operator) is considered.
- An environmental technology study about the impact of droughts and floods in the areas crossed by the Paraná River (considered the main plants located in the Paraná basin, excluding tributaries and outflows). The core of the study is related to hydropower generation, and the influence of these events in the electricity market.
- A detailed mathematical representation of the connection of large water flows. For this, it is necessary to analyze the interrelationships between the different reservoirs, the transported flows, the tributaries of the rivers, and the outflows of the basin. Events occurring in one reservoir have effects on all reservoirs connected by cascading effects. In turn, actions in the reservoirs influence the heads and hydraulic heads of the plants. Changes in the hydraulic head have an impact on power plant production.

The rest of this paper is systematized in the following manner. Section 2 presents the formulation of the mathematical model, along with the linearization techniques. Section 3 details the novel proposal for modeling reservoirs of hydropower stations in a common river basin. The numerical test based on the real case of the Paraná Basin and its plants is introduced and described in Section 4. The main results are presented in Section 4. Section 6 comments on the analysis of the results of the test case. Lastly, the main conclusions of the paper are discussed in Section 7.

2. Mathematical model for representing hydropower generation

This section describes the original mixed-integer nonlinear programming model for operating the hydropower stations in the first part. After, the proposed linearization technique for obtaining MILP models is detailed.

2.1 Original model for the operation of hydropower plants (HPs)

The scheme of an HP is illustrated in **Fig. 2**. The whole system is located between an upper and a lower water reservoir. The water elevation difference between these two reservoirs is called *hydraulic head* (or simply, *head*). Furthermore, HPs are crossed by internal penstock pipelines with turbines connected to generators. If the turbines are reversible, the plant is designed as a Pumped Storage Unit (Margeta and Đurin, 2014). The plant produces electricity to a closer power substation, which suits and transmits the electricity to the grid (by using high voltage transmission lines). The values of the water reservoirs depend on the turbine water flows beside the river inflows and outflows.

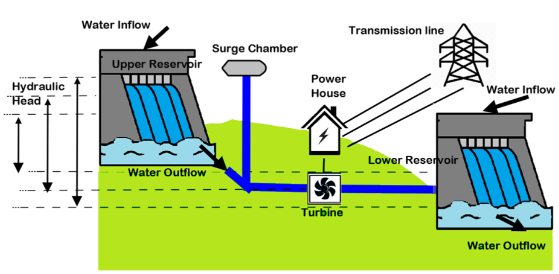

Fig. 2. Scheme of a basic hydropower plant

Based on (Lehtonen, 2015), the model aims to maximize the profit (PR) produced by the hydropower plant. While the lower the associated production cost, the higher the profit. The mentioned objective function is shown in (1).

$$\max\ PR = \sum_{i=1}^{I}\sum_{t=1}^{T}\left[\rho_t^f\left(p_{i,t} - p\_cons_{i,t}\right) - p_{i,t}\sigma_i \ - p\_cons_{i,t}\sigma\_cons_i\ \right] - \sum_{t=1}^{T}\vartheta_t\left[\sum_{ld=1}^{LD}\left(LS_{ld,t}\right)\right] \quad (1)$$

The model considers I turbines for a HP and the programming horizon is designed with T. Besides, i is the index for a single turbine of the HP, t is the index for the periods (usually 1 hour), $p_{i,t}$ is the power output, $p\_cons_{i,t}$ is the consumed power (when the plant has the pumped storage capacity, if not, the value of this variable is zero), ρ_t^f is the hourly price paid to the operators of HP for each period t, σ_i and σ_cons_i are the production costs ($\sigma\_cons_i = 0$ is the HP has not the pumped capacity). In several cases, these two costs could be assumed as negligible. The last term is the cost (ϑ_t) of having load shedding ($LS_{ld,t}$) when the demand cannot be completely covered.

There are other systems constraints that must be solved. The first one is to meet the electricity demand (2). Where $D_{ld,t}$ is the estimated electricity demand by the load ld at time t, which is reported by the operator of the electric system (Pirbazari, 2010).

$$\sum_{i=1}^{I} p_{i,t} \geq \sum_{ld=1}^{LD} D_{ld,t} + \sum_{ld=1}^{LD} LS_{ld,t} \quad , \quad t = 1, \dots, T \quad (2)$$

The power output produced by a unit of the HP is planned in (3), based on (Bozorg Haddad et al., 2014b). $Dg_{i,t}$ is the variable that designs the water discharge variable, it means the quantity of cubic meters of water that crosses the turbine i at time t. Besides, $h_{i,t}$ is the hydraulic head variable, μ_g_i is the coefficient of the generator efficiency (its value is usually between 0.92 and 0.97), μ_t_i is the coefficient of turbine efficiency (its value is usually between 0.75 and 0.94), and μ_cp_i is the coefficient of mechanical efficiency of the turbine-alternator link (is usually between 0.95 and 0.99).

$$p_{i,t} = 9800\ Dg_{i,t}h_{s,t}\mu\_g_i\ \mu\_t_i\ \mu\_cp_i\ /(1 * 10^6)\ , \quad i = 1, \dots, I; t = 1, \dots, T \quad (3)$$

If the plant has the pumping capacity, the power consumed by the unit can be read in (Paine et al., 2014). The equation is influenced by the variables that represent the pumped water flow and the hydraulic head. Consequently, the equation has a product between the two aforementioned variables (the same case occurs of the power generation). As a consequence, both constraints are nonlinear and could require an elevated computational requirement to be solved.

To avoid mechanical complications for the HPs, the system requires an operating mode exclusivity constraint. Consequently, if one or more units of the HP are operating in generating (or pumping mode), the rest of the turbines will be working in the same mode or they can remain offline. To follow this purpose, two auxiliary variables are utilized for representing the generating ($x\_g_{i,t}$) and the pumping mode ($x\_p_{i,t}$). The mode exclusivity restrictions are detailed in (4-9). For instance, constraint (4) requires that only one of the two auxiliary variables can be equal to 1 if the HP is operating in generating mode (or in pumping mode), or is equal to 0 otherwise.

$$x\_g_{i,t} + x\_p_{i,t} \leq 1 \quad i = 1, \dots, I; t = 1, \dots, T \quad (4)$$

The variable $x\_p_{i,t}$ is programmed to avoid that the rest of the units operate in pumping mode if one unit is working in generating mode. Consequently, when $x\_g_{i,t}$= 1, at least one unit must be operating in generating mode. Besides, if $x\_p_{i,t}$=1 for the unit i, the sum of $x\_g_{i,t}$ must be equal to zero. Else, if $x\_p_{i,t}$=0 for the unit i, the sum of $x\_g_{i,t}$ must be equal to zero or 1. This exclusivity constraint is modeled in (5).

$$\sum_{i=1}^{I} x\_g_{i,t} \leq I\ x\_g_{i,t}, \quad t = 1, \dots, T \quad (5)$$

With a similar reasoning, constraint (6) avoids the overlapping of modes by using the binary variable $x\_p_{i,t}$. It is noticeable that the core of the proposed paper is considering HPs that only have the generating mode. However, it is important to give a complete formulation to give flexibility to the representation and allows the modeling of real cases with different configurations.

$$\sum_{i=1}^{I} x\_p_{i,t} \leq I\ x\_p_{i,t}, \quad t = 1, \dots, T \quad (6)$$

Constraints (7) and (8) calculate the volumes of the upper and lower water reservoirs by following the traditional literature (Chen et al., 2017). The mentioned constraints consider variables that represent the turbined water flows (and the pumped water flow $qp_{s,t}$, if it corresponds), along with the parameter that characterizes the river inflow and the river outflow. The presented paper considers that all units are connected to the same reservoirs. If all units share reservoirs (and these units are installed by considering the same height), the values of the hydraulic head variable can be considered as equals for all units and each period t (it reduces the computational effort). Also, the river inflows and river outflows can be assumed as constants when the daily scheduling is considered (Chen et al., 2017). However, if the units are connected with different reservoirs (for instance, a common upper reservoir and different lower ones), the hydraulic head variables will have different values.

$$v_t^{up} = v_{t-1}^{up} + \delta_{in}^{up} + \delta_{out}^{up} - \sum_{i=1}^{I} Dg_{i,t} + \sum_{i=1}^{I} qp_{i,t}\,, \qquad t = 1, \dots, T \tag{7}$$

$$v_t^{lo} = v_{t-1}^{lo} + \delta_{in}^{lo} + \delta_{out}^{lo} + \sum_{i=1}^{I} Dg_{i,t} - \sum_{i=1}^{I} qp_{i,t}\,, \qquad t = 1, \dots, T \tag{8}$$

Regarding the water reserve, constraint (9) guarantees that the quantity of volume in the upper reservoir at the last period of the programming horizon should be greater than or equal to the volume at the first period. This establishes an energy reserve condition.

$$v_{t=T}^{up} > v_{t=1}^{up} \tag{9}$$

2.2 Linearization techniques for obtaining a linear model

This subsection details the linearization technique required for solving the HP operations by using MILP models. Many papers linearize the nonlinear operating curves of HPs by considering the hydraulic head variation effects. But, these papers only admit up to 9 breakpoints (with three head levels). The reason for this limitation is the fact that these papers are based on the utilization of an eight triangle method that divides the breakpoint into three head levels with three segments. By contrast, the model implemented in this proposal is based on (G. Alvarez, 2020) and supports a greater amount of breakpoints, with the subsequent greater numbers of head levels and segments. This represents an enhancement of the quality of the solutions, in terms of values closer to reality. To better understand the proposal, a graphical illustration of the dependences between the power output and the water discharge of an HP is represented in **Fig. 3**. The figure considers real information belonging to unit number 1 of HP Los Reyunos in Argentina (Ministry of Energy and Mining (MINEM), 2016). The graph included in the figure characterizes the operating curves for five hydraulic head levels (they are 98.7, 92, 87, 82, and 77.5 m, respectively). Regarding the power output, eight generating segments are computed (64 MW, 68 MW, 71 MW, 77 MW, 83 MW, 90 MW, 95 MW, and 118 MW respectively).

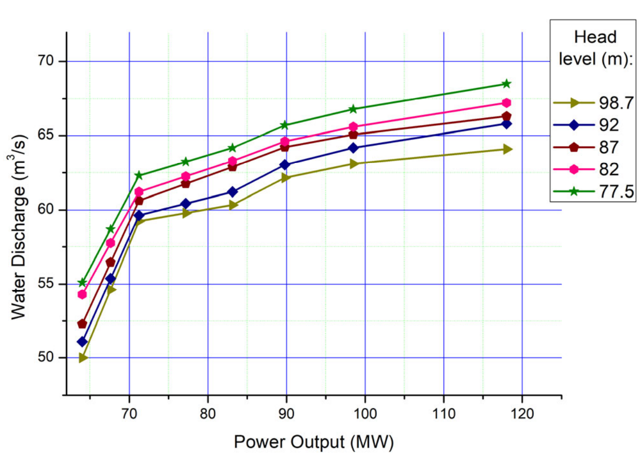

Fig. 3. Generation-discharge curves for a real case (Los Reyunos Hydropower Plant).

To linearize these operating curves, the following constraints will be presented. Constraint (10) indicates that the auxiliary variable $x\_g_{i,t}$ is equal to the sum of all the weight variables $wg_{y,z,s,t}$ [0,1] (for the generating mode). In this constraint, y is the index that represents the generation segment, z is the index that represents the considered head level. Besides, Y is the total of generation segments, and Z is the total of hydraulic head levels. The sum of these weight variables must be equal to the variable $x\_g_{i,t}$.

$$\sum_{y=1}^{Y}\sum_{z=1}^{Z} wg_{y,z,s,t} = x\_g_{i,t}, \qquad i = 1, \ldots, I; t = 1, \ldots, T \tag{10}$$

Also, constraint (11) establishes the interdependency between the differences of reservoir volume with a binary variable ($\beta_{z,s,t}$). The value of the variable will be equal to 1 if the difference between the volumes of reservoir matches with the corresponding hydraulic head level, or 0, otherwise. δr_z^{min} and δr_z^{max} are constants that relate with the minimum and maximum difference of volumes for a considered head level (z).

$$\sum_{z=1}^{Z} \beta_{z,i,t}\, \delta r_z^{min} \le v_t^{up} - v_t^{lo} \le \sum_{z=1}^{Z} \beta_{z,i,t}\, \delta r_z^{max}, \qquad i = 1, \ldots, I; t = 1, \ldots, T \tag{11}$$

Constraints (12-13) determine the value of the variable that represents the hydraulic head $h_{i,t}$ for each unit i by including the variables of weight of generation $wg_{y,z,i,t}$. Where $\overline{H}_z$ and $\underline{H_z}$ are parameters that represent the maximum (and minimum) values of hydraulic head level. Besides, $\overline{H}^{max}$ is the value for the maximum head corresponding to all levels.

$$h_{i,t} \le \sum_{y=1}^{Y}\sum_{z=1}^{Z} wg_{y,z,i,t}\, \overline{H}_z + \overline{H}^{max}(1 - x\_g_{i,t}), \quad i = 1, \ldots, I; t = 1, \ldots, T \tag{12}$$

$$h_{i,t} \ge \sum_{y=1}^{Y}\sum_{z=1}^{Z} wg_{y,z,i,t}\, \underline{H_z}, \qquad i = 1, \ldots, I; t = 1, \ldots, T \tag{13}$$

The values of the produced power ($p_{i,t}$) and water discharge variable ($Dg_{i,t}$) are controlled by constraints (14-15). Where $P_{y,z,i}^{parameter}$ and $Dg_{y,z,i}^{parameter}$ are parameter related to the power output and discharge values for the unit i, along with segments y and z.

$$p_{i,t} = \sum_{y=1}^{Y}\sum_{z=1}^{Z} wg_{y,z,i,t}\, P_{y,z,i}^{parameter}, \qquad i = 1, \ldots, I; t = 1, \ldots, T \tag{14}$$

$$Dg_{i,t} = \sum_{y=1}^{Y}\sum_{z=1}^{Z} wg_{y,z,i,t}\, Dg_{y,z,i}^{parameter}, \qquad i = 1, \ldots, I; t = 1, \ldots, T \tag{15}$$

Each unit of the HP has upper and lower operating bounds due to technical reasons, these limits are modeled in (16). Where $\overline{p_i}$ and $\underline{p_i}$ are the bounds for each unit i.

$$\underline{p_i}\, x\_g_{i,t} \le p_{i,t} \le x\_g_{i,t} \overline{p_i}, \qquad i = 1, \ldots, I; t = 1, \ldots, T \tag{16}$$

To improve the understanding of the proposed approach in this section, it is important to notice that constraint (10) computes the sum of the weights of the breakpoints belonging to the curves. By following this method, when a unit is generating, the weighting sum for the constraint is equal to 1, or 0 otherwise. Also, constraints (12-13) determine the interpolation to obtain the value for the head variable. When the unit is working, the interpolated value must be equal to the sum of the weighted head in each breakpoint. At last, (16-17) calculate the weighting sum for the power output variable and the amount of water discharge. The employment of the weighting variable $wg_{y,z,i,t}$ allows determining the operating point with a high level of precision and preserves the concordance among the variables $p_{i,t}$, $h_{i,t}$ and $Dg_{i,t}$. The behaviors and dependencies between the three aforementioned variables and the weighting variable have been deeply studied in (Li et al., 2014). **Fig. 4** shows the differences between the traditional linearization methods and the new approach. **Fig. 4 A**) illustrates the traditional approach to linearize the operating curve. This technique depends on the utilization of nine breakpoints that correspond to three hydraulic head levels and three segments. Each breakpoint implies the intersections between the one head level and one segment. The selected operating point is established by choosing one of the multiple triangles (as is shown in the figure) by using auxiliary variables. The main drawback of this process is that it only supports nine breakpoints. Otherwise, **Fig. 4 B**) represents the proposed technique that can deal with a greater amount of hydraulic head levels, segments, and, as a result, a higher number of breakpoints. The proposed technique can define the right share of the operating curve. The greater amount of real breakpoints, the more accurate level of the obtained solutions (in terms of closeness to reality).

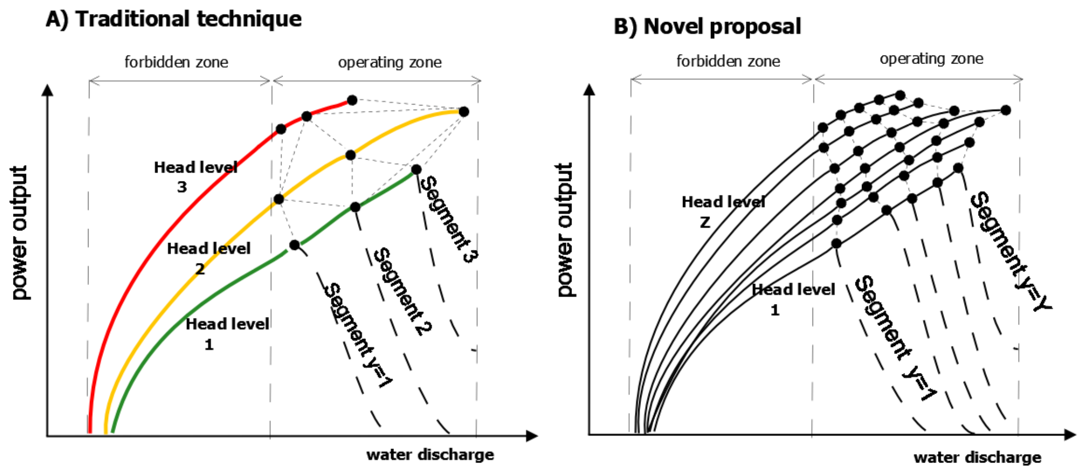

Fig. 4. Determination of operating point. **A)** With the traditional technique. **B)** With the novel proposal.

The previously described method is related to the generating mode because all considered HPs of the test case only operate under this model. To address the pumping mode in the case of pumped storage units, it is recommended to read the method detailed in (G. Alvarez, 2020).

3. Novel proposal for modeling reservoirs of HP in river basins

One of the main contributions of the present work is that it allows representing in sufficient detail the basin of a river, where several HPs are located. In the example of **Fig. 5**, it can be seen a basin with 3 HPs installed, each HP has its own reservoirs. These reservoirs are influenced by several factors. The first factor is the water flow turbined by each of the units ($Dg_{i,t}$). In this regard, if the station also has the pumping capacity, the pumped flow rate ($qp_{i,t}$) also affects the volume of reservoirs. Another important factor, which is not often taken into account in the literature, is the water flow discharged through each of the HP gates ($Dc_{c,t}$). Finally, as mentioned above, the water inflow (δ_{in}) and outflow (δ_{out}) also have an influence. Following these indications, constraints (17-19) model the reservoir volumes (v_t) for the three HPs shown in the example in the figure.

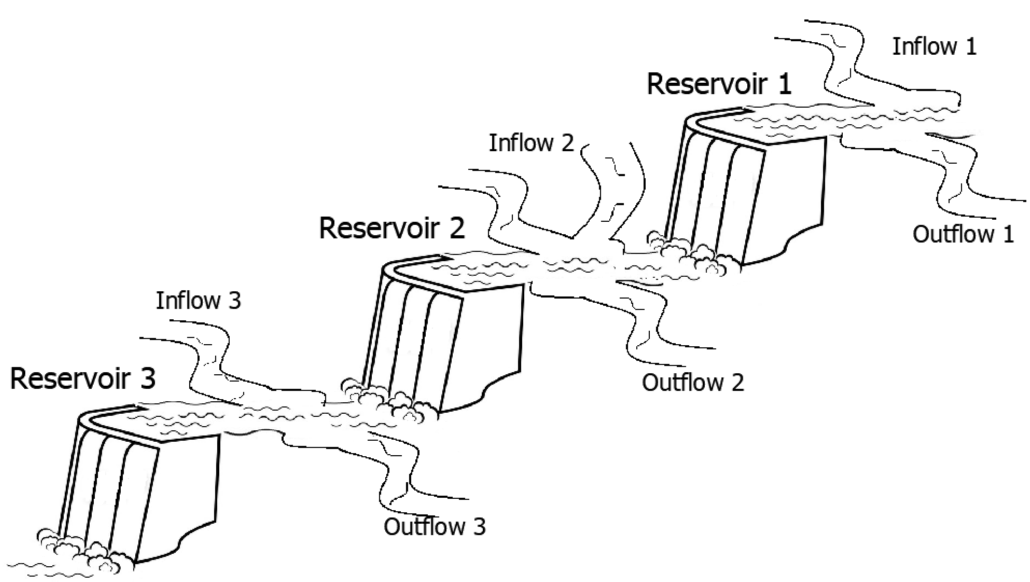

Fig. 5. Scheme of a river basin with 3 hydropower stations.

$$v_t^{R1} = v_{t-1}^{R1} + \delta_{in}^{R1} + \delta_{out}^{R1} - \sum_{i=1}^{I} Dg_{i\epsilon R1,t} - \sum_{c=1}^{C} Dc_{c\epsilon R1,t} - \sum_{i=1}^{I} qp_{i\epsilon R1,t} + \sum_{i=1}^{I} qp_{i\epsilon R2,t}$$
$$t = 1, \dots, T \tag{17}$$

$$v_t^{R2} = v_{t-1}^{R2} + \delta_{in}^{R2} + \delta_{out}^{R2} - \sum_{i=1}^{I} Dg_{i\epsilon R2,t} + \sum_{i=1}^{I} Dg_{i\epsilon R1,t} - \sum_{c=1}^{C} Dc_{c\epsilon R2,t} + \sum_{c=1}^{C} Dc_{c\epsilon R1,t}$$
$$- \sum_{i=1}^{I} qp_{i\epsilon R2,t} + \sum_{i=1}^{I} qp_{i\epsilon R3,t} \quad , \quad t = 1, \dots, T \tag{18}$$

$$v_t^{R3} = v_{t-1}^{R3} + \delta_{in}^{R3} + \delta_{out}^{R3} - \sum_{i=1}^{I} Dg_{i\epsilon R3,t} + \sum_{c=1}^{C} Dc_{c\epsilon R2,t} - \sum_{c=1}^{C} Dc_{c\epsilon R3,t} + \sum_{c=1}^{C} Dc_{c\epsilon R2,t}$$
$$- \sum_{i=1}^{I} qp_{i\epsilon R3,t} \quad , \quad t = 1, \dots, T \tag{19}$$

As can be seen, the volume of a reservoir increases due to inflows, the water turbined from an upper reservoir, discharged by the gates of an upper reservoir, or the water pumped from a lower reservoir. On the other hand, the volume of the reservoir decreases due to river outflow, the water discharged by its turbines, the water discharged by its gates, or pumped to an upper reservoir. Considering this, a single constraint can be formulated in a generic way that allows modeling the volume for the reservoir n with all possible configurations (20).

$$v_t^{Rn} = v_{t-1}^{Rn} + \delta_{in}^{Rn} + \delta_{out}^{Rn} - \sum_{i=1}^{I} Dg_{i\epsilon Rn,t} + \sum_{i=1}^{I} Dg_{i\epsilon Rn-1,t} - \sum_{c=1}^{C} Dc_{c\epsilon Rn,t} + \sum_{c=1}^{C} Dc_{c\epsilon Rn-1,t}$$
$$- \sum_{i=1}^{I} qp_{i\epsilon Rn,t} + \sum_{i=1}^{I} qp_{i\epsilon Rn+1,t} \quad , \quad t = 1, \dots, T \tag{20}$$

Fig. 6 explains the flowchart of the novel procedure by explaining all the steps. The mathematical model that schedules the operation of a PH takes into account simultaneously all constraints. The procedure is organized by following steps to improve the understanding of this proposal. Inputs of the model are related to the hourly energy bills, costs associated with the operations, the estimated demand, and the water reservoir forecasts. The model planes when is more suitable to produce energy (or consume if the pumping mode is available), to make the most amount of the benefits. To determine the best combination of decisions for operating the HPs, the model studies the dynamics of the power generation-water discharge curves, the reservoir connections, and the relationships with the system operators. The major inconvenience is the elevated computational effort that traditional approaches require to model the operating curves due to their nonlinearity. Consequently, this proposal determines the operating point by applying the linearization techniques explained above. The proposed approach considers an improved representation of the operating curves according to the inclusion of more breakpoints, in comparison with the rest of traditional methods (which only consider up to nine breakpoints). As a result, the present method can obtain solutions closer to reality due to the utilization of a higher amount of breakpoints. After analyzing the former inputs, the method determines the most convenient operation of the turbines to increase the profit by considering the amount of covered demand and load shedding. It means that the model solves the objective function (1) along with constraints (2-6) and (9-16). When the curves are linearized and computed, the hydraulic system must be solved. To achieve this objective constraint (20) is applied to each reservoir and solved. If the obtained solution is feasible, the process is completed and the HP can be operated by following the obtained solution.

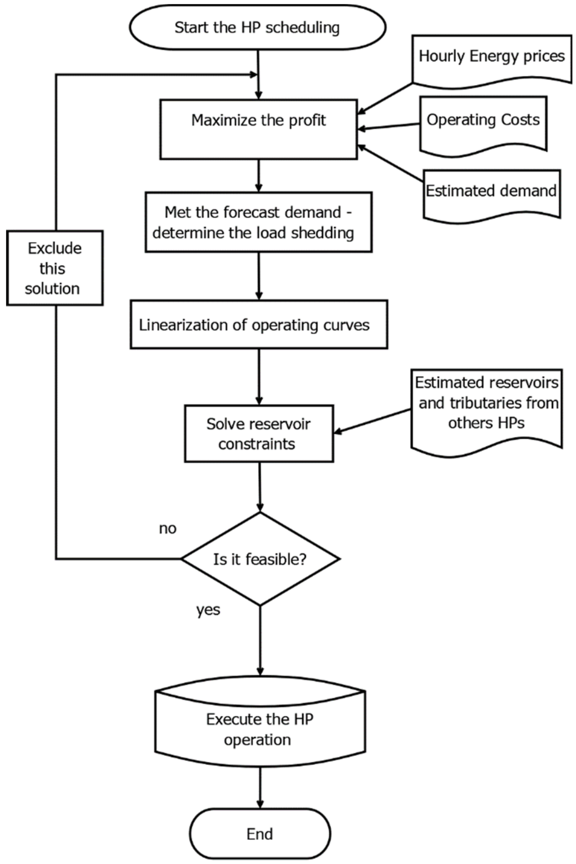

Fig. 6. Flowchart of the novel method.

4. Test case

As mentioned above, the test case is a sector of the Paraná river basin. This section starts at the Ilha Solteira power plant in Mato Grosso do Sul (State of Sao Paulo) up to the Itaipu power plant on the border between Paraguay and Brazil, near the city of Foz do Iguaçu. The section is approximately 800 km long. **Fig 7** illustrates the section, referencing the 5 HPs that compose it. On the left of the figure is shown the map of the South American region, where the area that is enlarged on the right is marked. In the enlarged area, the basin can be observed from a satellite image, according to data provided by (Operador Nacional do Sistema Eléctrico, 2021). The first plant as mentioned above is Ilha Solteira, marked with the number 1. The power plant marked with number 2 is called Eng. Souza Dias. Number 3 is Eng. Sergio Motta. Finally, HP 4 is the Itaipu plant. The hydraulic scheme showing the connections between the plants and their tributaries is illustrated in **Fig. 8**. Information on the plants and their tributaries is given in **Table 2.** The hourly price adopted is the one indicated in (G. E. Alvarez, 2020), the associated generation costs adopted are 25 USD per MW, the turbine start-up cost is 2,100 USD, as well as the shutdown cost.

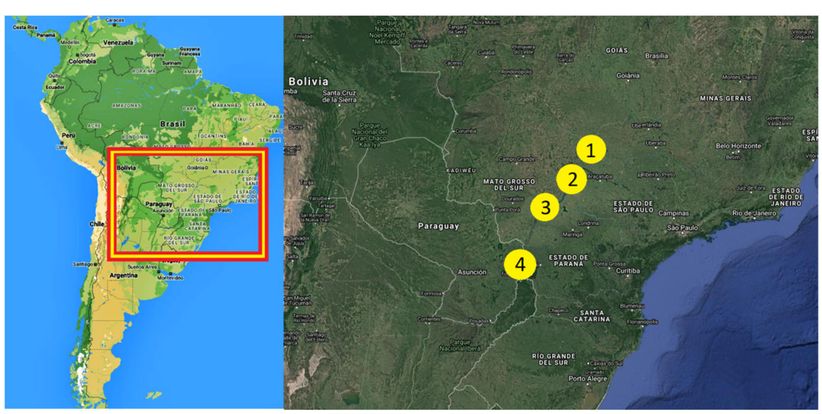

Fig. 7. Test case. Left: Marked zone on the map of South-America. Right: Enlarge zone with the four hydropower stations (1-4) on the Paraná River basin. Based on (Operador Nacional do Sistema Eléctrico, 2021).

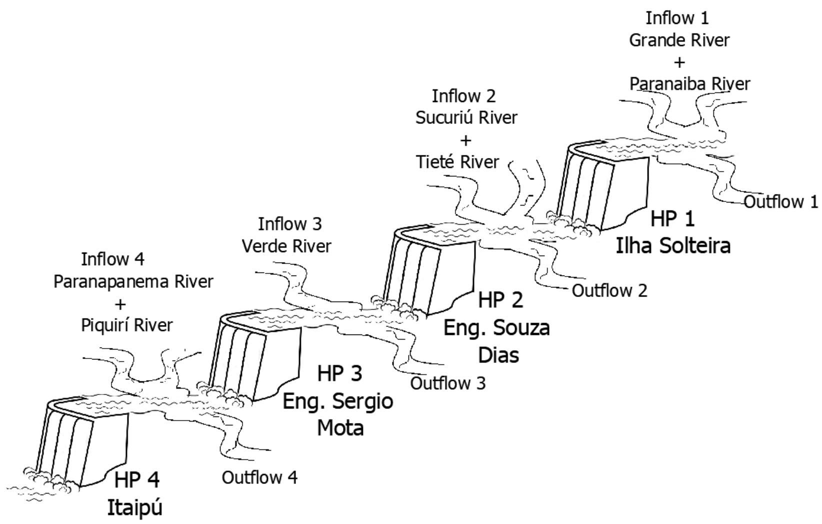

Fig. 8. Scheme of the test case.

Table 2
Information about hydropower plants.

Item	Name and refer-ences	Installed Capacity (MW)	Number of turbines	Type of Turbines	Spillway Capacity (m^3/s)	Discharge per generator (m^3/s)	Capacity reservoir (km^3)	Minimum level (m)	Medium Level (m)	Maxmun Level (m)
1	Ilha Solteira (Gupta and Harihar, 2022)	3,444	11 x 170 (MW) 5 X 174 (MW) 4 x 176 (MW)	Francis	40,000	502	21.2	-	41.5	-
2	Eng. Souza Dias	1,551	14 x 110.8 MW	Kaplan	44,696	600	3.35	-	280	-
3	Eng. Sergio Motta (GLR, 2022)	1,540	14 x 110 MW	Kaplan	44,150	510	19.9	257	259	259
4	Itaipú (G. E. Alvarez, 2020)	14,000	20 x 715 MW	Francis	62,200	500	2,900	98	111	122

5. Numerical Results

In order to evaluate the effects of the water crisis, two scenarios will be studied. The first is a scenario with normal flow conditions of the Paraná River (with an average flow of 17,300 m^3/s). The second scenario includes the water crisis situation. The model is set in GAMS with CPLEX solver (IBM Corp., 2009).

5.1. Scenario with normal water conditions

The first scenario considers an average flow of 17,300 m^3/s. This is the flow that fits into the conditions considered normal because they are the ones that have been repeated most of the time in the records (Itaipu, 2022). Therefore, considering the objective function (1) that maximizes the profits of the plants, and is subject to the constraints (2-20), the mathematical model is formed by 25,185 equations, 30,869 simple variables, and 5,280 binary variables. The total revenue is USD

19,751,921 and the resolution time is 1 second for a relative gap of 0. The total revenue is obtained through the total production of the 4 plants. It is important to mention the unit production of each of the plants in this scenario. Due to the initial conditions and the normal flow, which are considered for the design of the plant, their production is constant and all available turbines are used. This implies therefore that the hourly productions are 13,804.2 MWh for Itaipu, 1,540 MWh for Motta, 1,551.2 for Souza, and 3,212 MWh for Ilha. The share of daily production per plant can be detailed in **Fig. 9**.

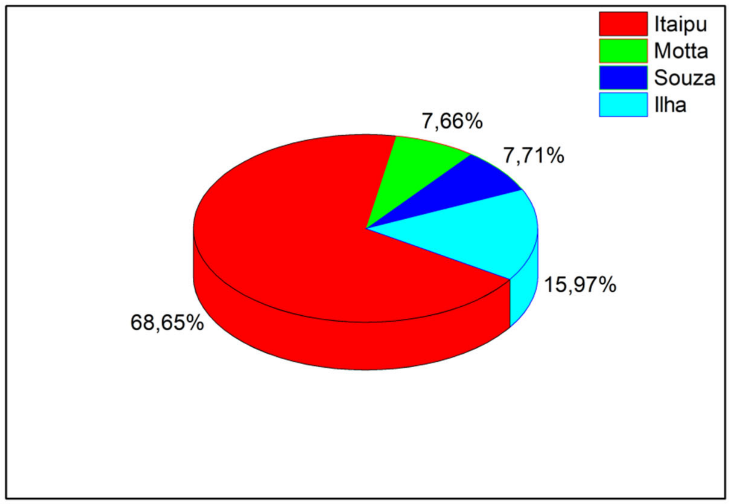

Fig. 9. Chart with shares of power generation.

When reservoir levels of each of the HP are analyzed, a significant dynamic can be observed (unlike the generation profile for scenario 1). There is a large decrease in the first three hours (from 19,601 Hm^3 to 19,381 Hm^3). Subsequently, there is a linear increase until the hour 24 hour to reach the same volume level as in hour 1. The Motta HP volume ranges from 190 Hm^3 to 198 Hm^3. The constraint imposes a minimum volume of 190 Hm^3 at the end of the programming horizon. A fluctuant situation is observed for Ilha with oscillations between 167 Hm^3 and 210 Hm^3. The minimum level at the end of the programming horizon is 203 Hm^3. As for the Souza plant, the volume remains almost constant, oscillating only between 30 and 31 Hm^3. The profile of the reservoirs is shown in **Fig. 10**.

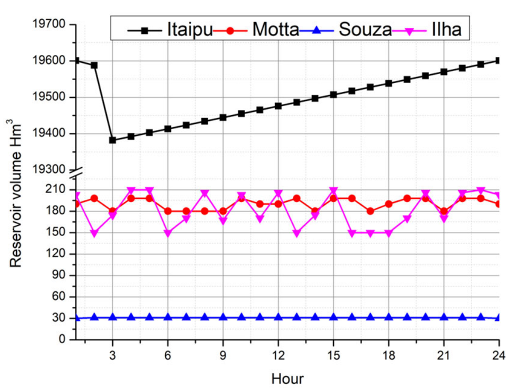

Fig. 10. Reservoir volumes for the first scenario.

5.2. Scenario with water crisis conditions

This scenario considers a flow corresponding to a water crisis developing in the basin since 2019 (6,400 m^3/s). Therefore, with this low flow level, the objective function (1) is the same that the previous case, which maximizes the profits of the plants and is subject to constraints (2-20). The mathematical model has the same size as the previous subsection. The total revenue is USD 12,445,377 and the resolution time is 2.75 seconds for a relative gap of 0. The total revenue is lower than the previous case due to the lower generation of the plants. The initial conditions and the low flow promote a fluctuant production of the power plants (unlike the previous scenario) and its dynamics can be observed in **Fig. 11**. The Itaipu plant, which has the highest production capacity of the four HPs, starts generating 13,804 MWh during the first hour of the programming horizon and then reduces it from hour 2 to hour 13. It shuts down turbines at hour 24. The total production of this HP is 154,837 MWh. As for the Motta plant, it is operating during the whole programming horizon (at least some of its machines are operating). It produces a maximum of 1,540 MWh at hours 1, 21, and 22. The total production of the plant is 32880 MWh. The Souza plant produces 1551 MWh in hour 1, and the rest of the programming horizon produces 1,329.6 MWh during each hour. At the end of the programming horizon, the plant produces 32,132 MWh. Finally, the Ilha plant has a fluctuating generation between 1,330 and 3,212 MWh. At the end of the programming horizon, the plant produces about 64,168 MWh.

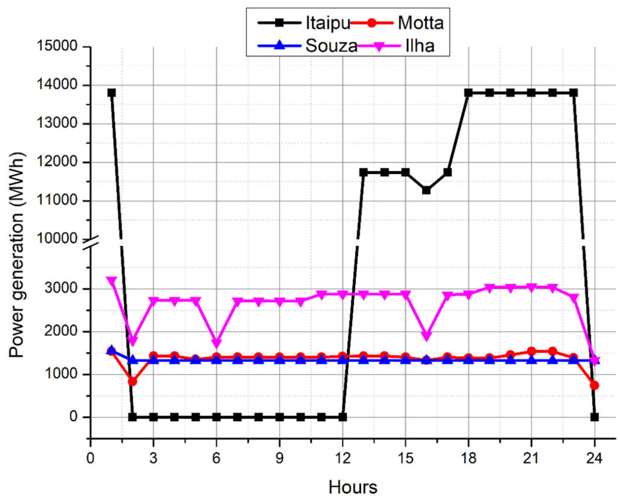

Fig. 11. Generation profile. Scenario with hydraulic crisis.

The dynamics of the reservoir volumes can be seen in **Fig. 12**, which shows different behavior in the previous scenario. In the case of Itaipu, which produces the major portion of the total generation, it can be seen that the reservoir volume is increased in order to have greater availability during the hours when energy prices are higher. The volume in hour 1 is 19,601 Hm^3, which increases until hour 12 to reach 19,854 Hm^3. Subsequently, the volume decreases (due to electricity generation) until it reaches the same value as hour 1, due to the constraint (9). The Motta plant has a volume fluctuating between 181 Hm^3 and 198 Hm^3. The Souza plant has an almost constant volume throughout the programming horizon, close to 30 Hm^3. The Ilha plant has a minimum level of 200.86 Hm^3 and a maximum of 210 Hm^3.

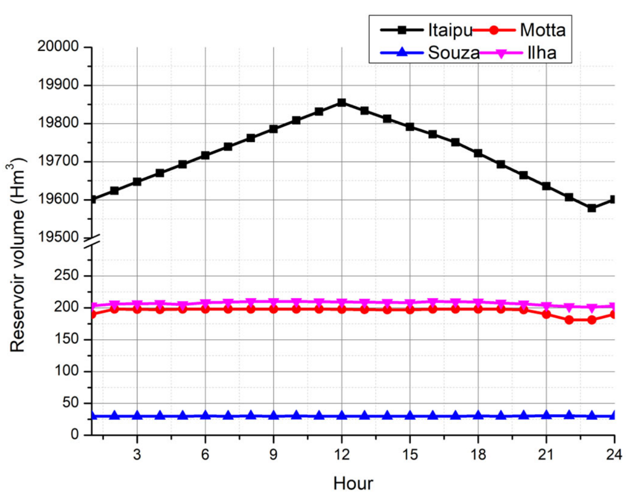

Fig. 12. Volume profile. Scenario with hydraulic crisis.

6. Analysis of results

The importance of the analysis of the results makes it possible to determine whether to continue or discontinue operations of the plants (partially or totally). It identifies and evaluates the economic impact of the water crisis on the income of these plants. It recommends whether to start electricity production or continue storing water in reservoirs. This analysis establishes a framework for analyzing the level of viability of the plant operation.

This paper presents a study of the economic impact in an integrated manner, for instance, comparing revenues between different scenarios. The gross economic losses, in this case, are defined as the incomes that the plants lose due to lower water availability. In this case, the revenues of scenario 1 are compared with the revenues of scenario 2. Clearly, the incomes of scenario 1 are higher. Consequently, **Fig. 13** shows the gross losses of scenario 2, due to the water crisis. The higher the capacity of the power plant, the higher the losses. For the Itaipu plant, the losses amount is 10,717,313 USD. The model suggests that losses from producing less electricity occur in periods where the price paid for generation is lower. Because of this, the losses are higher between hours 2-12 and are close to 0 during the hours of high consumption (hours 18-23). For the Motta plant, the total losses amount to 258,000 USD. In this context, the highest losses are produced in hour 2 (38,000 USD) and hour 24 (50,000 USD). The Souza plant has total losses of 337,442 USD, with hourly losses fluctuating slightly between 12,016 USD and 17,478 USD. Finally, the Ilha plant represents losses of 812,781 USD, with the highest hourly losses at hour 2 (76,946 USD) and hour 24 (119,990 USD).

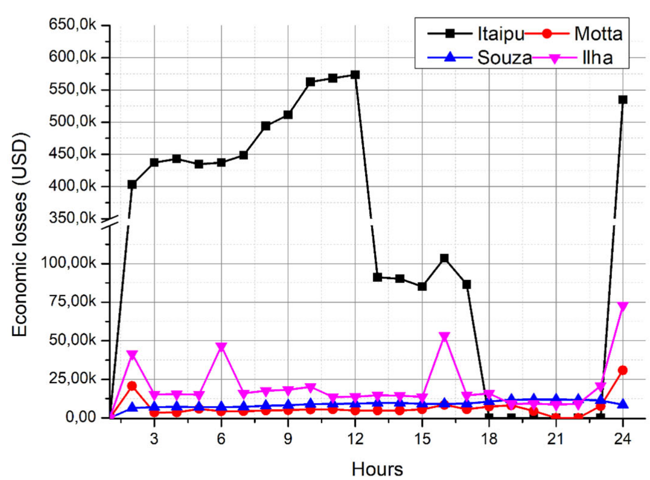

Fig. 13. Gross loss profile. Comparison between scenarios.

To obtain the net economic losses, it is necessary to deduct the gross losses from the generation inherent costs. Once this discount is made, the losses per plant are ordered as follows: Itaipu 6,341,949 USD, Motta 192,229 USD, Souza 246,247 USD, and Ilha 526117 USD. In addition to the significant decrease in the contribution to the numerous river courses of the basin, there has been a gradual decrease in the reserves of the reservoirs. Consequently, in the basing belonging to Argentina, it was defined that the greatest impact is the decrease in river levels in the face of urban water intakes. There are other economic losses in addition to the losses in the energy area. There also are economic losses due to costs related to the need to adjust the volume of cargo on ships. There are increases in costs since some ships must complete their cargo in other ports. Other losses are due to higher transportation costs because of a lower loading capacity of the ships that circulate through the Paraná River. All these cost overruns have caused, for instance in the Argentine basin sector, losses of 620 million USD since 2020 (Diamante, 2022).

7. Conclusions

The drought of the Paraná River produced since 2019 has produced an important crisis in the whole region. This decrease in flow has a direct impact on water supply for human consumption, electricity production, navigation, among other main issues. The extension of the period of drought increases the risks in reproduction and feeding of fauna, troubles the logistics related to the maintenance of the waterway, losses in logistics of navigation, in addition to the processes of urban water cleansing.

Regarding this situation, this paper develops a new MILP model which is programmed to study the impact of this crisis in the region. In addition to the traditional constraints of the hydraulic systems extended in the literature, the paper includes inventory constraints, connections with power grids, and considerations of the hydraulic head effects in electricity production. As several constraints belonging to electricity generation are originally nonlinear; which means a lot of computational effort to be solved, the novel proposal applies linearization techniques to enhance the performance of the model (in terms of the CPU times). The considered linearization techniques have advantages as including a higher number of breakpoints, in comparison with classical approaches available in the literature (as the classic 9-breakpoint performance curve models). These advantages imply reaching more realistic models.

To demonstrate the effectiveness of the novel proposal, the real case of the basin of the Paraná River is studied by considering two scenarios. The first one considers the normal conditions of the flow; results show that the plants were designed to operate under these conditions. It can be deduced that normal conditions imply that hydropower plants utilize all turbines and they have constant production. On the other hand, the second scenario implies the conditions related to the hydraulic crisis. Results indicate that the drought implies daily net economic losses of approximately 7 million USD for the operators of the hydropower plants. This water crisis has also caused other problems in addition to losses in the energy field. These problems are briefly discussed throughout this paper. However, the core of the proposal is to demonstrate how the impact on the energy sector can be analyzed in detail through mathematical formulation in order to generate actions that could mitigate the effects of this crisis. Over the years, the impacts due to climate change are increased at the global level. Consequently, optimization tools for studying efficiently these impacts will become crucial support. The models introduced in this proposal follow this premise. Due to the low CPU times required to solve the test cases, the model can be easily modified to deal with similar cases.

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