POLITECNICO DI TORINO

Master of Science in Civil Engineering

Master thesis

Water Management of a Reservoir in the Córdoba Province (Argentina)

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ABSTRACT

Due to the abundance of water resources in Argentina, several dams were built such as the San Roque dam. This thesis analyzes and provides tools for the correct and efficient management of water resources applied to San Roque multipurpose reservoir, which plays an important role in water supply to more than one million and a half inhabitants, in the generation of hydroelectric power, together with irrigation and flood control.

Simulation and optimization models were applied using different software, which help to investigate and manipulate the management of the reservoir as well as they can serve in the future for different purposes. Firstly, the historical hydrologic and operation data of the basin in study is presented with the dam's characteristics. Afterwards, simulation in HEC-ResSim and optimization in Aquarius are developed using historical data to provide significant conclusions. In order to identify the most acceptable management configuration, a yield analysis, an assessment of performance indexes and an operational analysis are carried out, which are helpful tools used to improve and optimize the reservoir operations.

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1. INTRODUCTION

1.1. Scope of the study

Available water in quantity and quality is getting scarce due to rapidly increasing world population which is been aggravated by the current climate change scenario. In Cordoba, Argentina, this resource is fundamental for different social and economic activities. Presently, San Roque Dam satisfies the growing demand for water supply, irrigation and hydroelectric generation for more than a million and a half inhabitants, so an effective and optimal use is one of the most important challenges nowadays.

On one hand, this dam acts as a protection for downstream populations which can be affected by possible floods in different times of the year, saving lives and economic losses. For this scope, planners and operators must bear in mind that the operations taken can`t increase the negative effects in comparison to the natural flow. On the other hand, it is necessary to merge this purpose of management of flooding with the need to optimize the volume of water stored. This volume is necessary for water supply in dry seasons in the medium-long term and for maximizing the hydroelectric power production.

Optimal operations of these systems are challenging tasks due to uncertainty and complexity of the systems. Their management requires comprehensive and integrated decision-making strategies. Nowadays, planners and operators need new technologies that can be used to quickly develop alternative decisions by representative models. In fact, the time frame for decision making may be extremely short, the information available is generally scarce, and the predictability of the meteorological situation is very limited. The significance of gate operation decisions must be as precise as possible, since downstream property, human life or even the dam itself may be lost, with disastrous consequences. These decisions are most of the time taken under pressure, therefore providing resources for the operator to reduce uncertainties is important.

Nowadays literature abounds with many techniques which may help dam operators in reservoir management, setting up and using them gives the opportunity to explore different alternatives management scenarios for water resources planning and management. Mathematical techniques for reservoir modelling can be divided into two principal categories, simulation techniques and optimization technique. Simulations techniques are used to model the performance of a reservoir for a given hydrological input with prescribed operating policies. These operating policies are defined by the goals of the operator's decision, such as maximizing hydropower energy generation, and by different constraints that the reservoir may contain. In a simulation model the water allocation will follow these operating policies exclusively. On the other side, optimization techniques are used to model the best possible solution according to an objective function, so the water allocation will not be determined by operating policies as in simulation techniques. Apart from this difference, optimization techniques have complete foreknowledge of all future events, which in simulation models and in real time frame decisions is not possible, and determines the optimal allocation for the objective function. Hence, results will represent an impracticable but desirable goal (Basson et al. 1994).

Once these models are applied and represent the case study behavior, different analysis strategies using the models can be applied in order to reduce uncertainties in the outcomes of the water allocation. These analysis methodologies can be varied, but for the purpose of this study, a draft-yield analysis, definitions of performance indexes and an operational analysis are chosen according to the needs of the case study. The draft-yield analysis is important to represent the yield capability of the system to meet various demands with its probabilistic diagrams that provide risks and reliability of supply. The indexes will be defined following certain characteristics to make the profitable and will represent the intensity of events which can lead to possible conclusions. And finally, the operational analysis will evaluate operating guidelines to define operating strategies to be applied in the system over a prescribed time horizon (Basson et al. 1994).

Finally, the most acceptable management configuration is proposed based on the analysis performed through the thesis comparing with other possible solutions.

1.2. Organization of the thesis

Hereinafter, the organization of the thesis will be described.

To begin with, Chapter 1 is an introduction of the importance and scope of the thesis, in order to introduce and guide the reader on the topics that the thesis is going to develop. After this, Chapter 2 purpose is to familiarize the lector into the case study, San Roque Dam, from its geography, importance, functionality, structure, and every important aspect that will be needed for the models. Chapter 3 will describe the software used for the simulation and optimization, with the steps followed for modelling. Also, a description of the advantages and disadvantages of each technique will be addressed. In Chapter 4 a draft-yield analysis will be developed with a brief explanation of the key concepts, together with statistical diagrams that provide important outcomes. Chapter 5 will be divided into 3 sections. First an optimization section that will be useful to compare the operations in the simulation model with the optimal operations from the optimization model. Afterwards, an assessment of performance indexes is held which will lead to practical conclusions and lastly an operational analysis is performed for different time horizons. Chapter 6 will test different alternatives with different conditions in order to analyze the sensitivity of the model to these variations. And finally, the conclusion will summarize the research and will exhibit an analysis of the most acceptable management configuration based on the analysis of the thesis. Additionally, some recommendations for future works on the topic are addressed.

2. CASE STUDY: THE SAN ROQUE DAM (CÓRDOBA)

This chapter will present all the information to enlighten the reader with San Roque Dam. Firstly, a general description to localize the reader in the case study with a report of the geography and purposes in order to show the importance of this dam in the city, province, as well as for the country. Afterwards, all constructive aspects, as well as functionality will be detailed, with the environmental problems and physical limitation.

2.1. General Description

The San Roque reservoir is located in the Punilla Valley (31º22'36``S and 64 ° 27'54''O) at 608 m above sea level, between the Sierras Grandes and the Sierras Chicas in the province of Córdoba, Argentina (Fig. 1). It is an artificial water body whose first dam dates from 1888 and was replaced in 1944 by the current dam after some controversial politics. It constitutes a reservoir of approximate 201 Hm^3 with a surface area of 16 Km^2 and an average depth of 16m. According to 2010`s census, population around the reservoir is near 74000 habitants divided into 5 localities, Villa Carlos Paz, Bialet Massé, Villa Parque Siquiman, Villa Santa Cruz del Lago y San Roque.

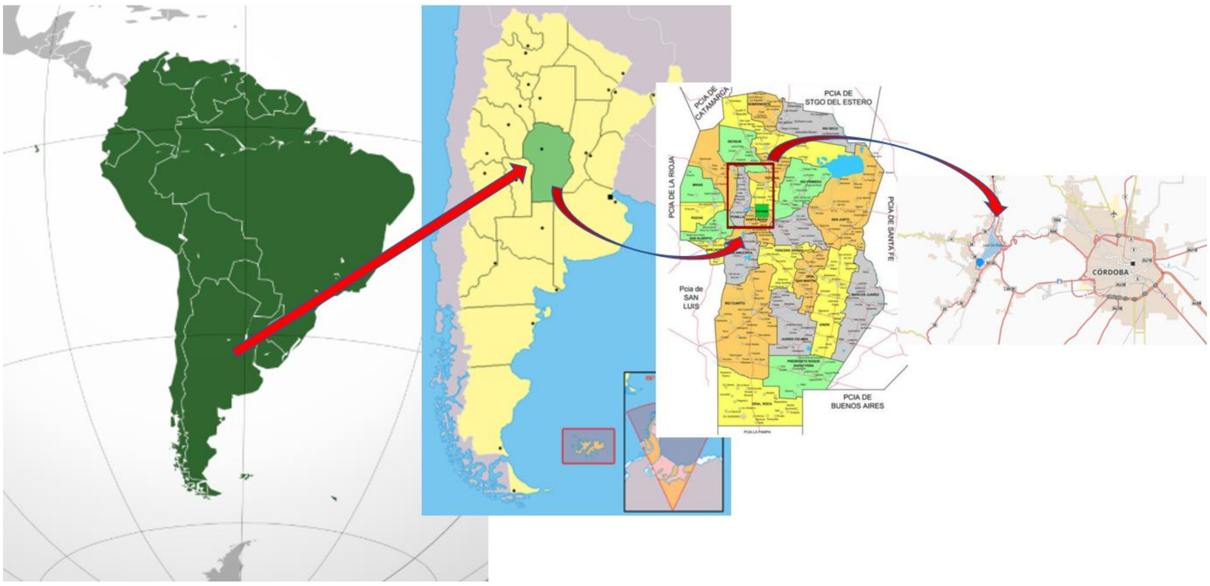

Figure 1 : San Roque Reservoir location

Downstream from the dam, on the banks of the river Rio Suquia, there are large urban settlements such as the city of Calera (13 km) and the city of Córdoba (42 km). The city of Córdoba is the second most populous city in Argentina after Buenos Aires, with about 1.5 million inhabitants according to the 2010 census and San Roque Dam provides water supply to 70% of the mentioned. Originally, the dam was designed for flood control, water supply to the city of Cordoba, water supply for irrigation and hydroelectric power generation. Upon completion, the dam was responsible of being the largest water reservoir in the world and the most important engineering work in South America. Engineer Alexandre Gustave Eiffel himself said: “Two engineering works concentrate the attention of the world, my Tower and the San Roque Dam, but my Tower is not productive.”

Nowadays, apart from the purposes mentioned, nautical activities are carried out and it has numerous beaches along its coast. Fishing competitions are organized, and it is the place of international yachting competitions. Moreover, in the city of Villa Carlos Paz, one of the cities surrounding the lake, in summer receives around 1 million tourists, so environmental requirements, as well as touristic and water supply demand are increased.

2.1.1. Characteristics of the basin

The Rio Suquia or Rio Primero initiate after the confluences of the San Antonio and Cosquín rivers to which they are joined by Los Chorrillos and the Arroyo de Las Mojarras. Currently, these rivers confluences on the San Roque lake and the Dam gives birth to the Rio Suquia.

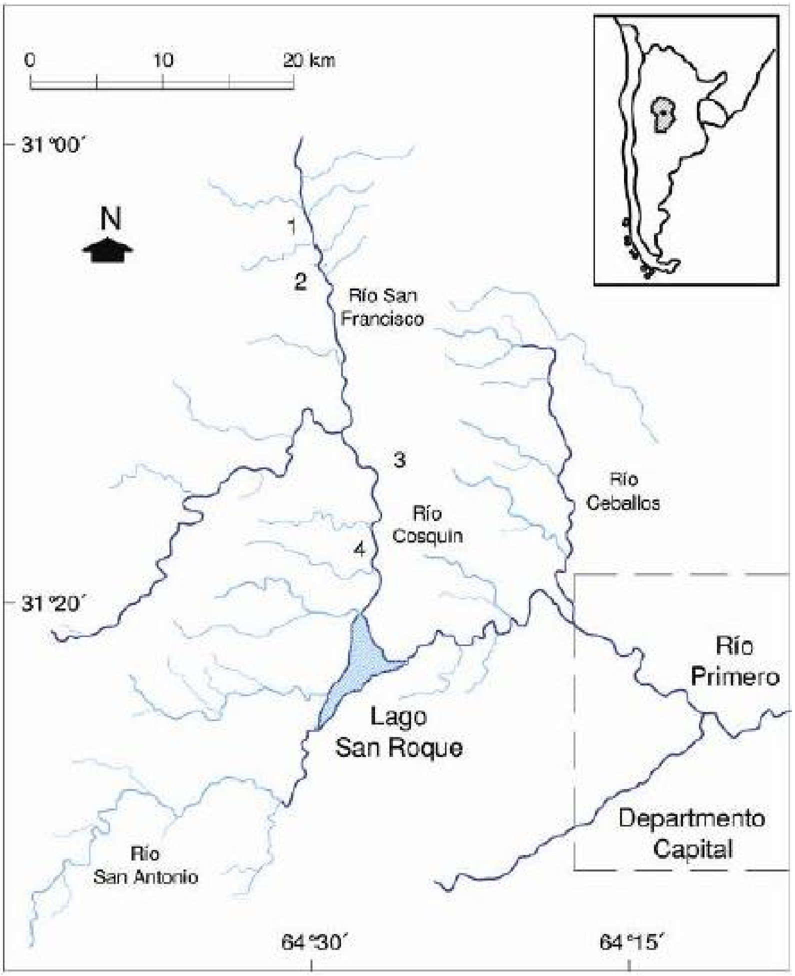

Figure 2 : San Roque tributaries (Vazquez et al., 1979)

The upper basin of Río Suquía or Primero, the only emissary of the reservoir, is made up by the sub-basins of the four tributaries that flow into the reservoir, with a total area of 1750 km2, they are: Río San Antonio (505 km2), Rio Cosquín (820 km2), Arroyo Las Mojarras (85 km2) and Arroyo Los Chorrillos (160 km2).

Before going through the city of Córdoba, it is regulated upstream with the San Roque reservoir, in addition it suffers several obstructions along its route with the El Diquecito weir and various bridges outside and inside the metropolis.

Its tributaries generate important problems upstream of San Roque Dam and the same river propagates them downstream through the city.

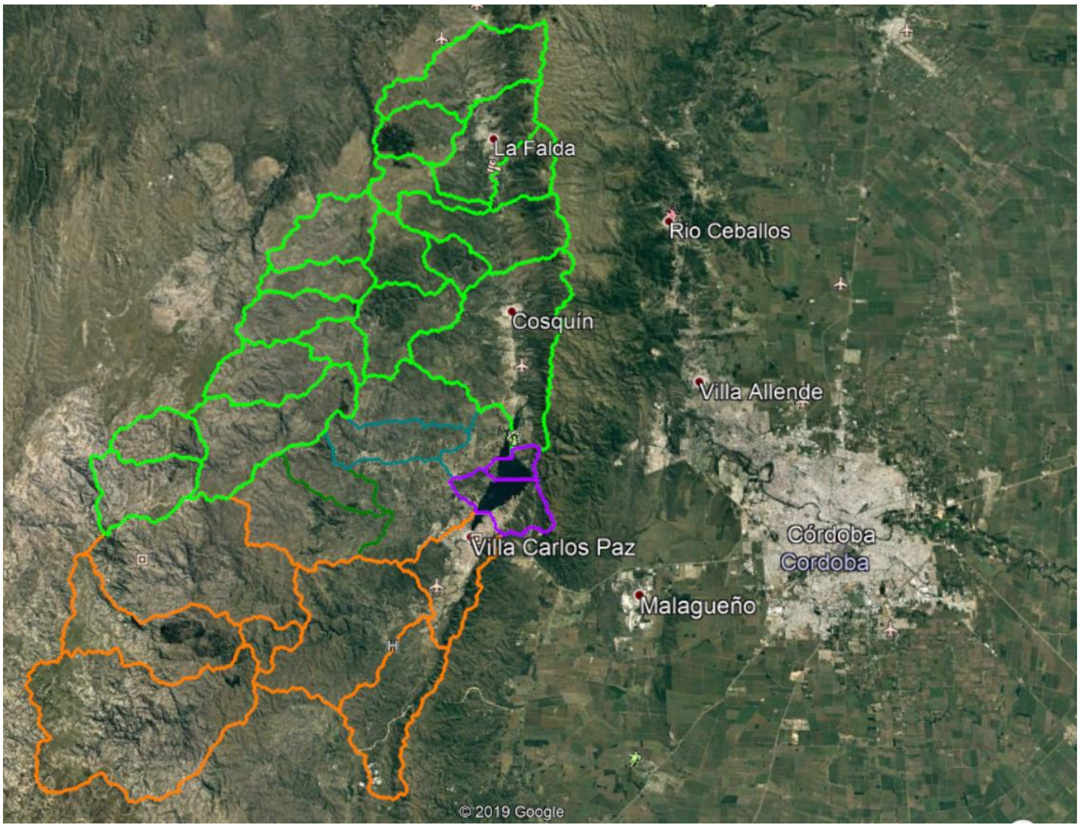

Figure 3 : Sub-basins

A summary of the basin characteristics is presented below:

- Surface: 1,750 km2.
- Length: 40 km
- Height: Variable between 600 m at the dam site, and 2,000 m at high peaks of the Los Gigantes mountain range.
- Rain regime: There are two seasons of marked difference in the distribution of rainfall, the rainy season begins in October and ends in May. On the other side, the dry season takes place between the months of June to September. The annual average varies from 700 mm to 850 mm in the region, with an annual maximum and minimum of 1100 mm and 457 mm, respectively. Besides, this region presents a meteorological phenomena identified as one of the most severe storms on the planet. Torrential rains with flash floods, destructive winds accompanied by tornadoes, large hail, and intense electrical activity, are some of the meteorological phenomena characteristic of the

area known as SESA (Southeast South America) This is phenomena is of such interest, that an international research campaign called RELAMPAGO will study the unique characteristics of Argentine storms.

- Runoff: The Rio Primero module has a value of 10 m3 / sec.
- Temperature: Under the domain of a mild climate, the average annual temperature is 14 ºC and the prevailing winds are from the south and north quadrant.

2.1.2. Hydrometeorological data

Regarding the rainfall data, in this basin they are obtained from measurements stations throughout all the territory. In appendix D, a list is presented with their coordinates.

For the historical inflow data, from 1945 till now, monthly step discharges were obtained by ADCP, ADV – Flow Tracker, mass balance equation, LSPIV and other techniques. Also, from 2017 hourly steps are available thanks to continuous measurements in the 4 tributaries.

The following figures where performed by MATLAB in order to represent the historical inflow data.

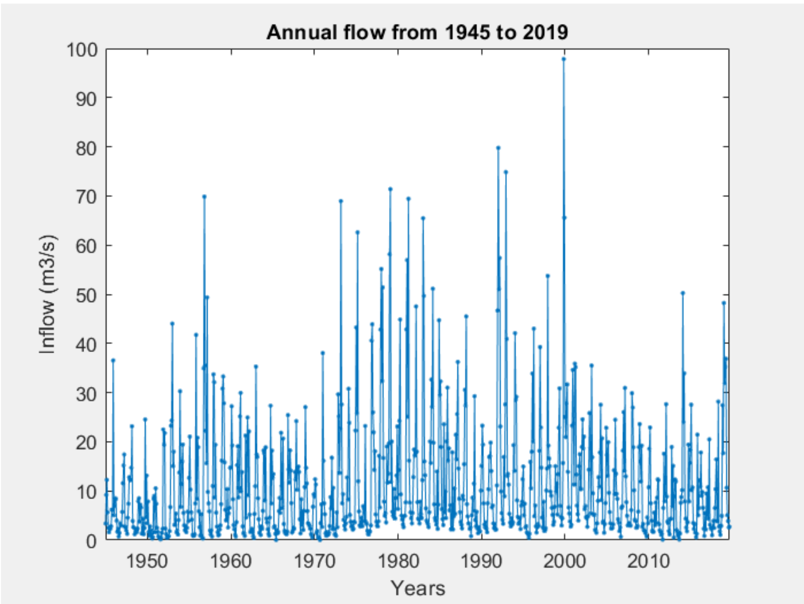

Figure 4 : Annual Flow

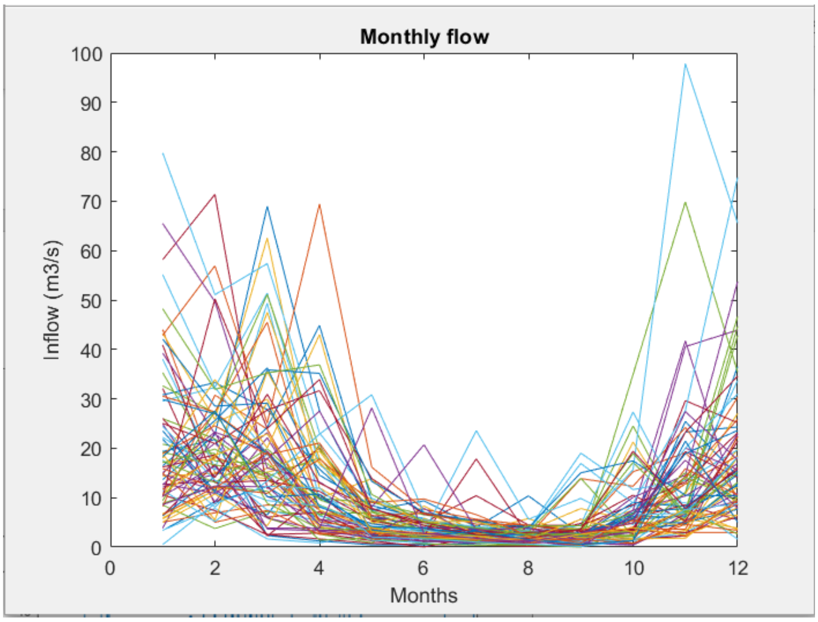

Figure 5 : Monthly Flow

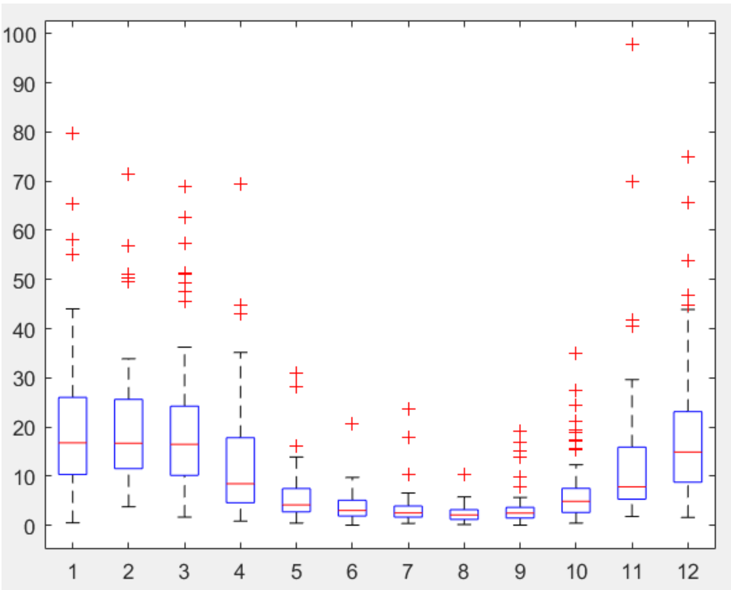

Figure 6 : Boxplot of Monthly Inflow

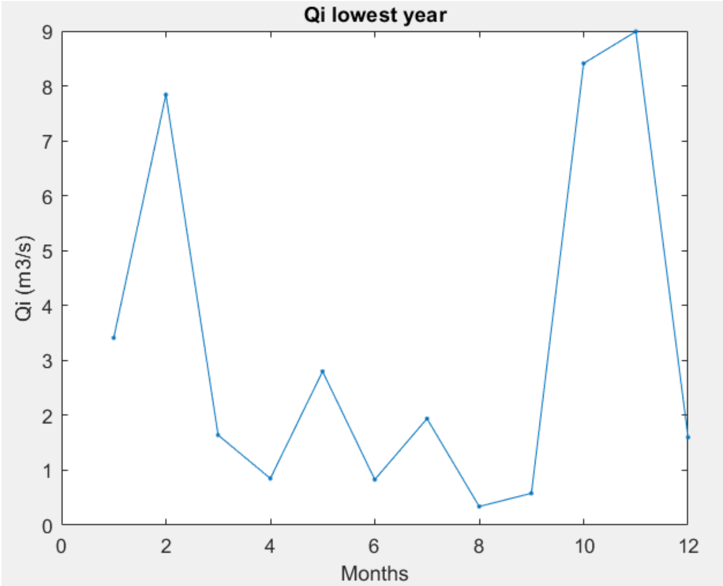

Figure 7 : Lowest Year Recorded

Mean annual historical flow: 10.94 m3/sec

2.2. Constructive aspects

The San Roque dam is a gravity dam type with a curved floor. The height of its closure is 51.30 m, with a crowning length of 145 m. The width of the dam at the crowning is 5 m while at the level of foundations its width reaches 43 m. In relation to its plant form, it was designed with a radius of curvature of 200 m.

The San Roque dam was built in order to take advantage and dominate the waters of the Rio Cosquín and Rio San Antonio in their confluence that give rise to the current Rio Suquía. The main reasons that propelled the construction of this dam and justified it were:

• Attenuation of the floods suffered in the City of Córdoba and its surroundings (flood control).

• Provision of drinking water to the city of Córdoba (second city in the country).

• Irrigation in times of drought.

• Hydroelectric use to allow the development of the City of Córdoba and its surroundings.

This dam is located downstream of the old San Roque dam.

Some of its main constructive features are summarized below(Lábaque, Reyna, and Reyna 2011):

- Foundation level: 601 masl. (meters above sea level)
- Riverbed level: 608 meters above sea level.
- Spillway level: 643.30 masl. - 35.30 m. s. local zero (D. P. H.).
- Elevation at crest: 651 meters above sea level - 43 m. s. local zero (D. P. H.).
- Crown level: 652.30 meters above sea level.
- Surface lake at spillway level: 1,501 Ha (hectares).
- Lake surface for maximum reservoir: 2,478 ha.
- Volume reservoir at spillway level: 173.58 Hm^3. (cubic hectometres)
- Maximum volume of reservoir: 350 Hm^3.
- Surface of the feeding basin is 1,750 Km^2.

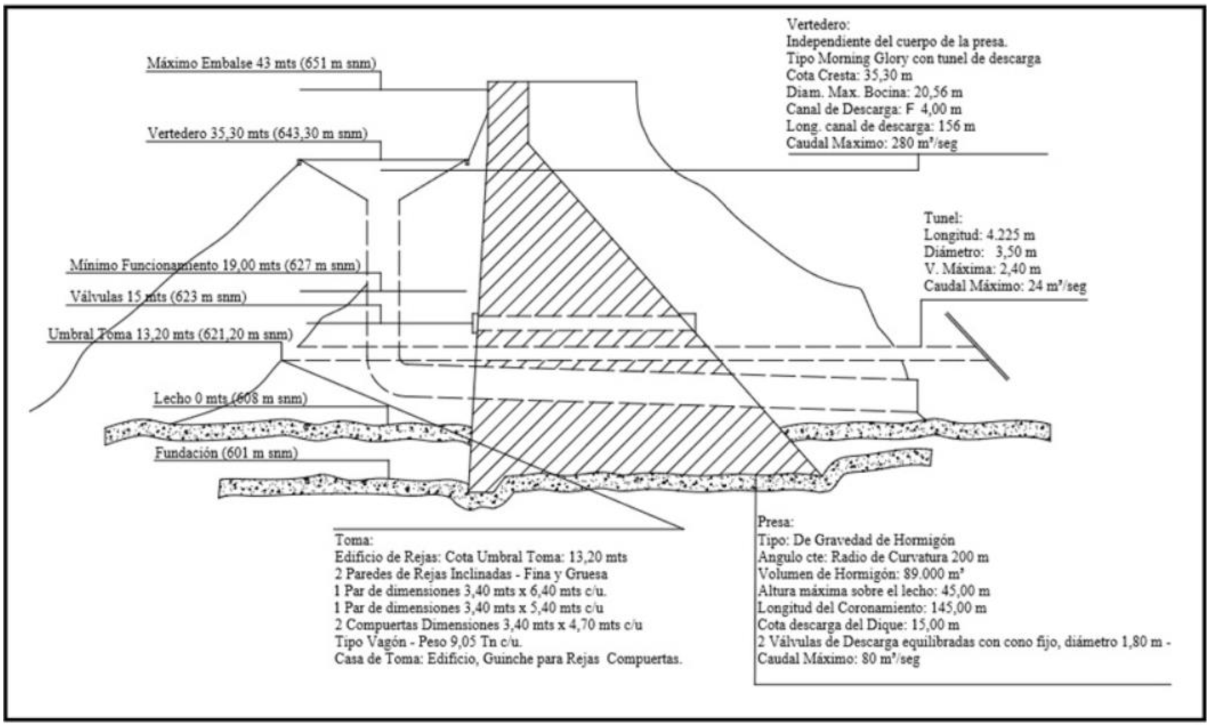

Figure 8 : Dam`s scheme (Castelló et al., 2000).

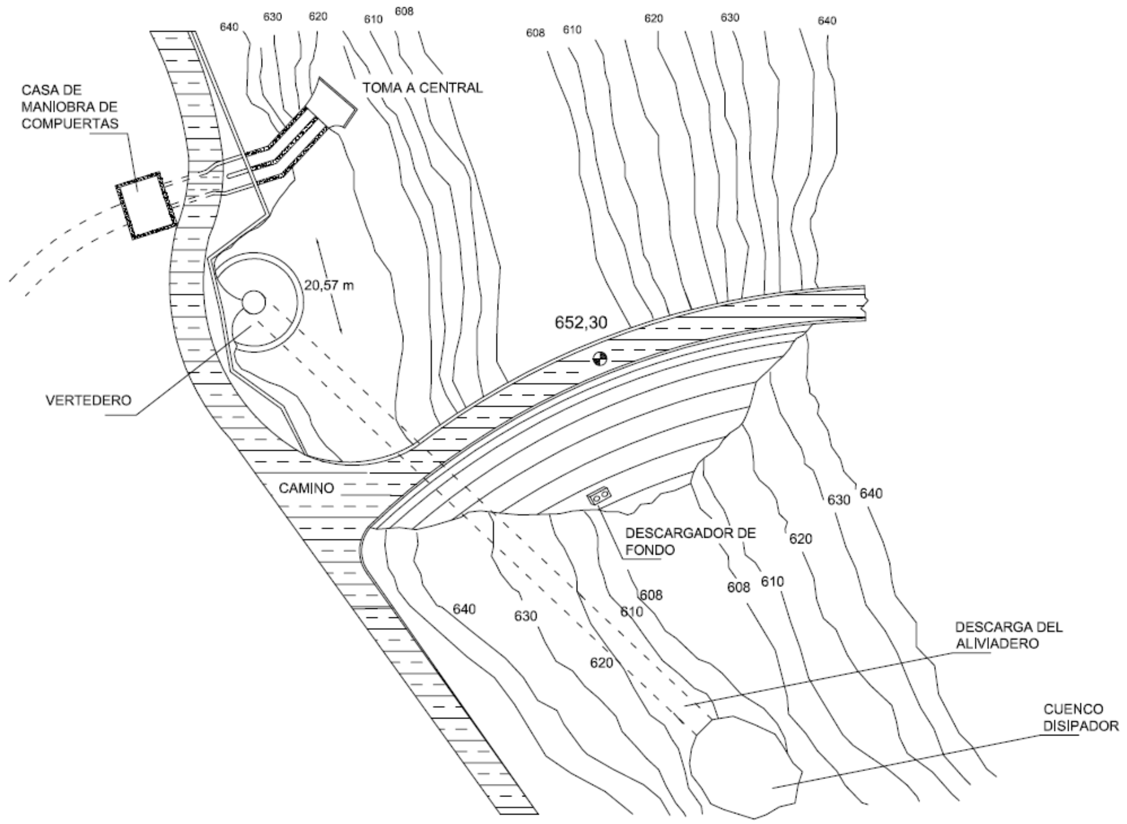

Figure 9 : Bathimetry

As we can see in the figures, this Dam has different outlets. On one hand, controlled outlet is constituted by 2 two balanced discharge valves of fixed cone with a diameter of 1.8m. Both valves reach a discharge of approximately 82 m^3/s. The discharge of each valve and its variation with the level of the reservoir is presented below:

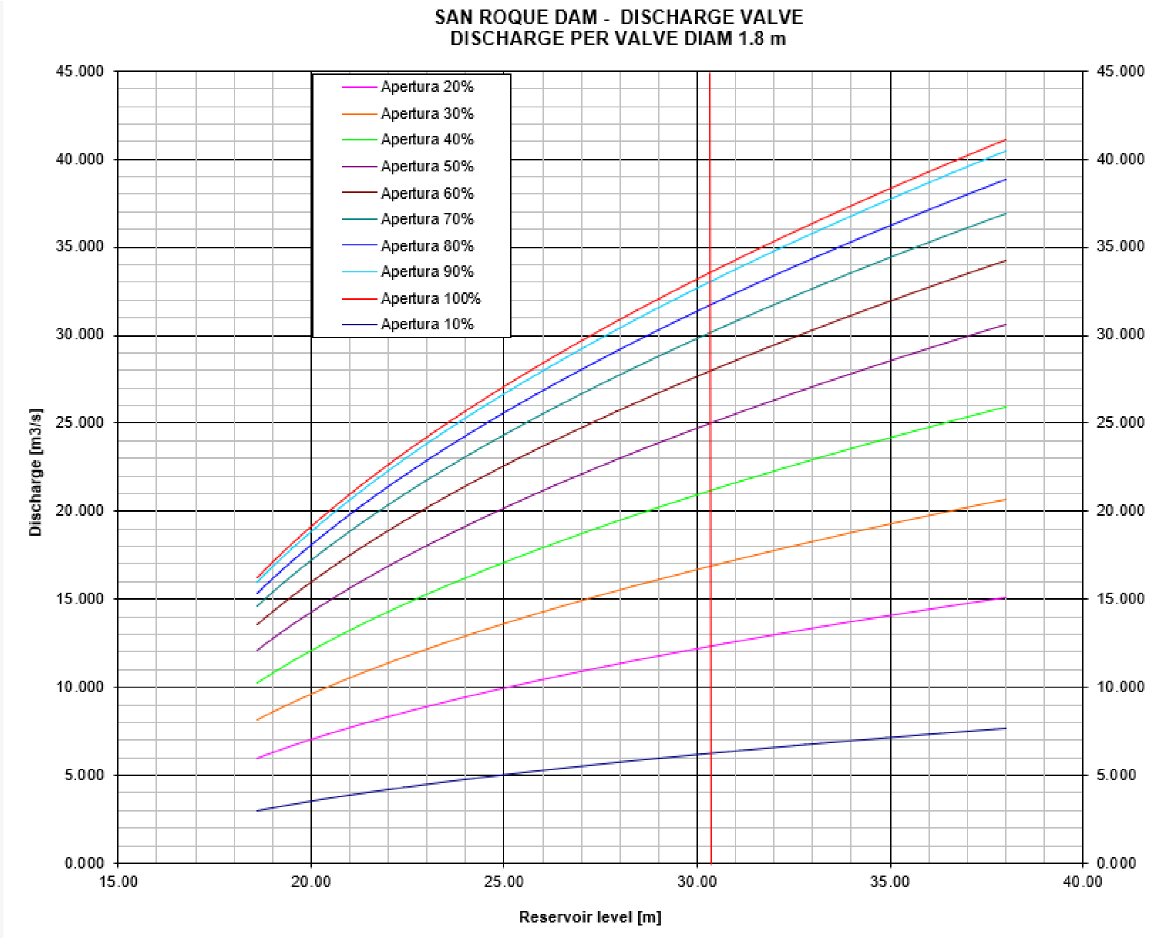

Figure 10 : Discharge valve vs Reservoir level

In respect of the uncontrolled outlets, there is a Morning Glory Spillway designed at 643.3 masl (or 35.3m from local zero). It is independent of the structure of the dam itself and releases up to 280 $\frac{m^3}{s}$. A general scheme of the spillway is presented as well as the H-Q relations:

- For H<169.2m

  Q=179.606*$H^{0.07164}$

- For H>169.2m

  Q=0.07519*$H^{1.5874}$

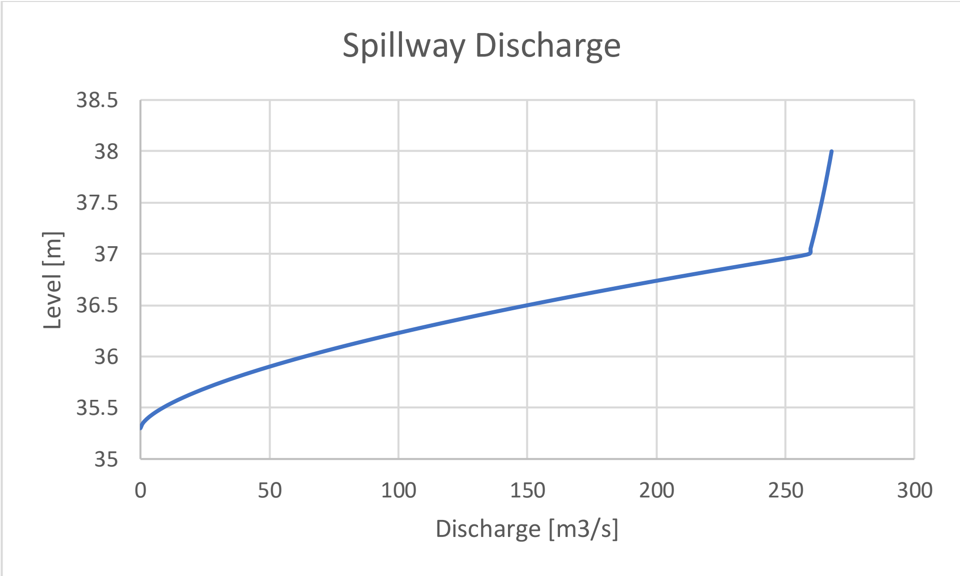

Figure 11 : Spillway Discharge

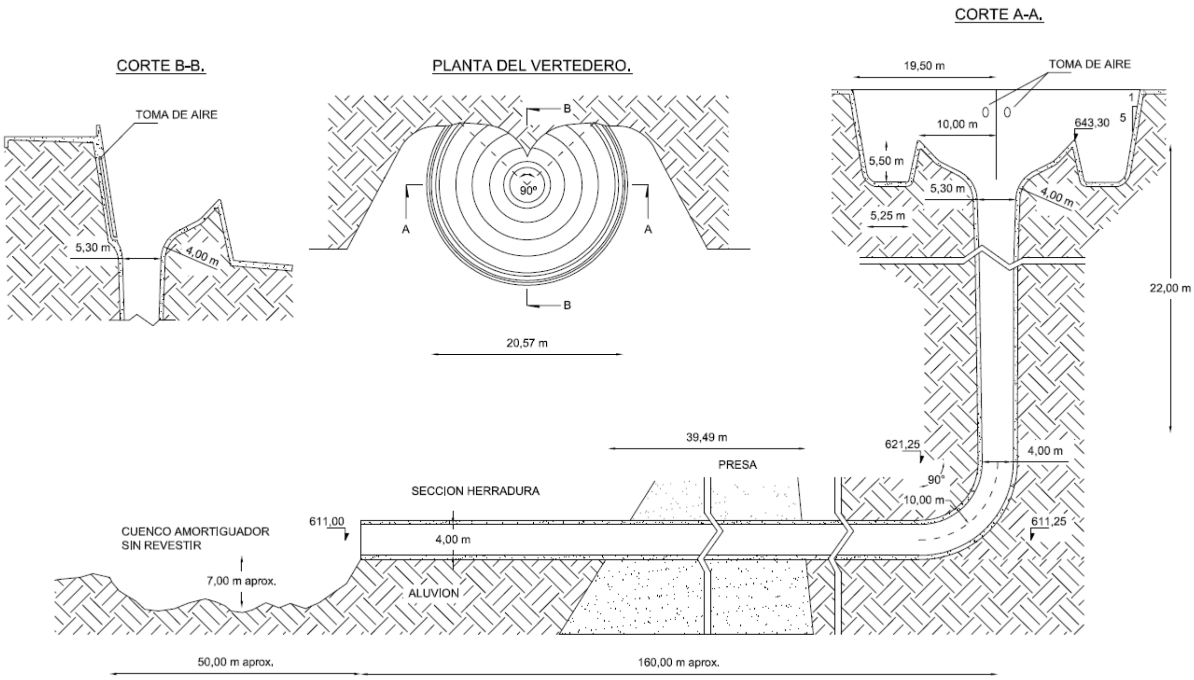

Figure 12 : Spillways

Finally, the power plant has 4 turbines with a maximum discharge of 6 m^3/s and an installed capacity of 6MW each. It works permanently and the water used to produce in the plant, is release again in the Rio Suquia, together with the controlled and uncontrolled outlets, which will be used afterwards for irrigation and for the water treatment plant. Details of the plant are well descripted in the following figure:

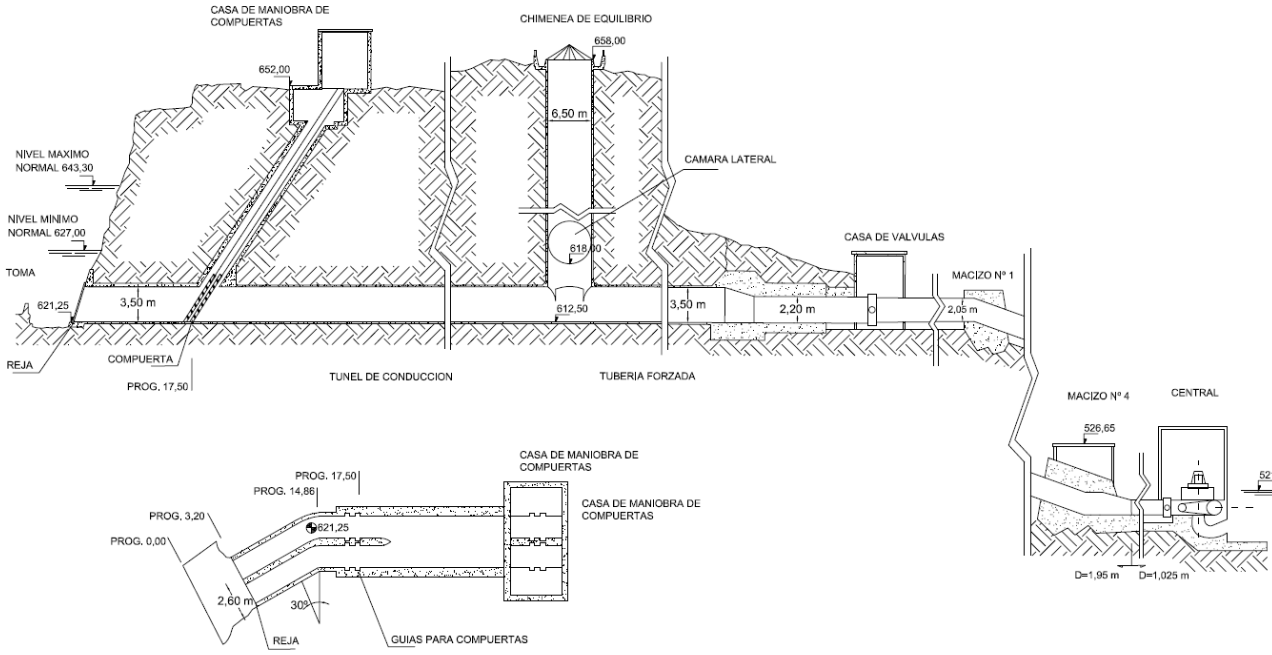

Figure 13 : Power Plant

2.3. Reservoir Characteristics

The most important characteristics of a reservoir are:

- Dead Storage: Represents that portion of volume of the reservoir below the elevation of the lowest outlet or bottom gate. The water located there can only be removed by pumping.
- Inactive Storage: Represents that portion of volume of the reservoir that, due to operating policies or operating constraints of the dam itself, cannot be used. It`s maximum level is limited by the minimum operating level.
- Active Storage: It is the portion of volume included between the minimum operating level and the maximum operating level. It is the profitable volume, so it is the actual volume that should satisfy the demand.
- Flood Storage Capacity: It is the portion of storage intended for flood control. It is included between the maximum operating level and the maximum extraordinary operating level.

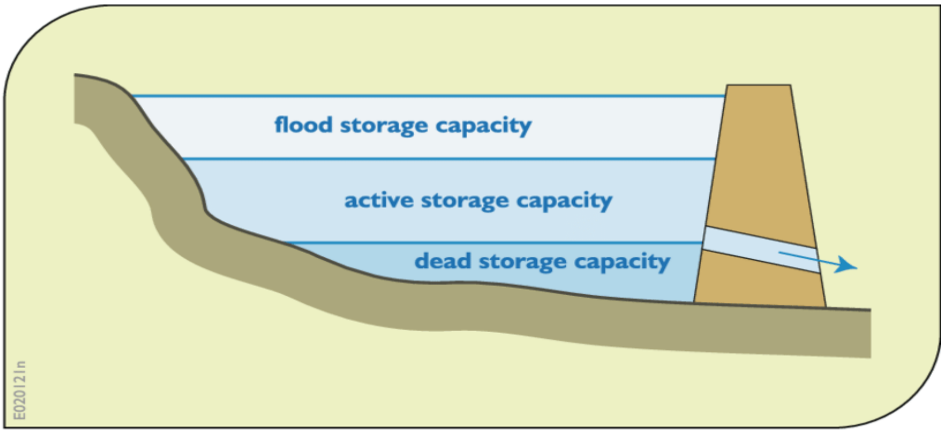

Figure 14 : Reservoir's storage division

Apart from these definitions, the relations between Storage-Elevation and Surface-Elevation are also relevant characteristics. A summary of these characteristics is presented below:

	Levels comprehended [m]		Storages comprehended [Hm3	
	Bottom Level	Top Level	Bottom Storag	Top Storage
Dead Storage	0.00	13.20	0.00	0.01
Inactive Storage	13.20	21.00	0.01	20.27
Active Storage	21.00	35.30	20.27	173.58
Flood Storage	35.30	36.50	173.58	192.48

Table 1 : Summary of Storage division

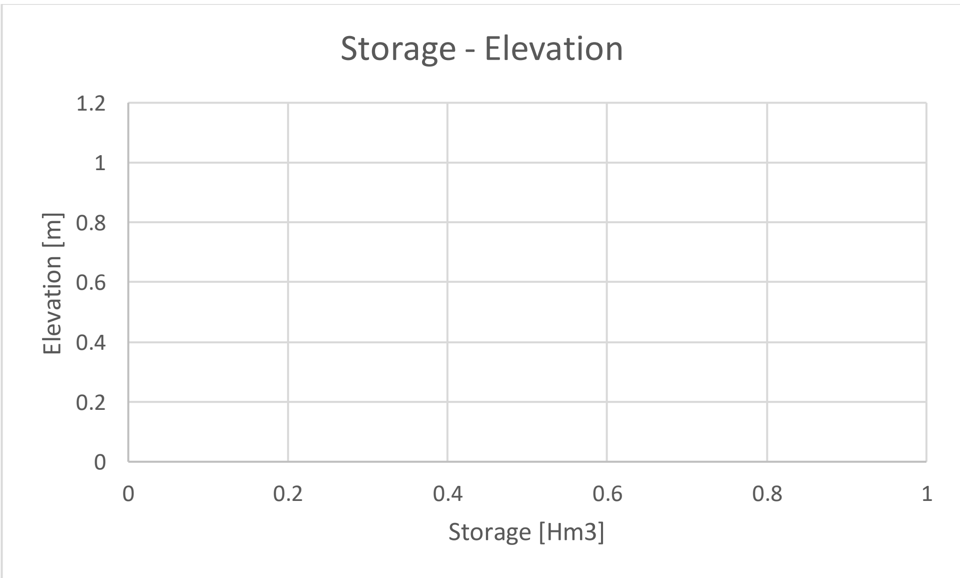

Figure 15 : Storage - Elevation curves

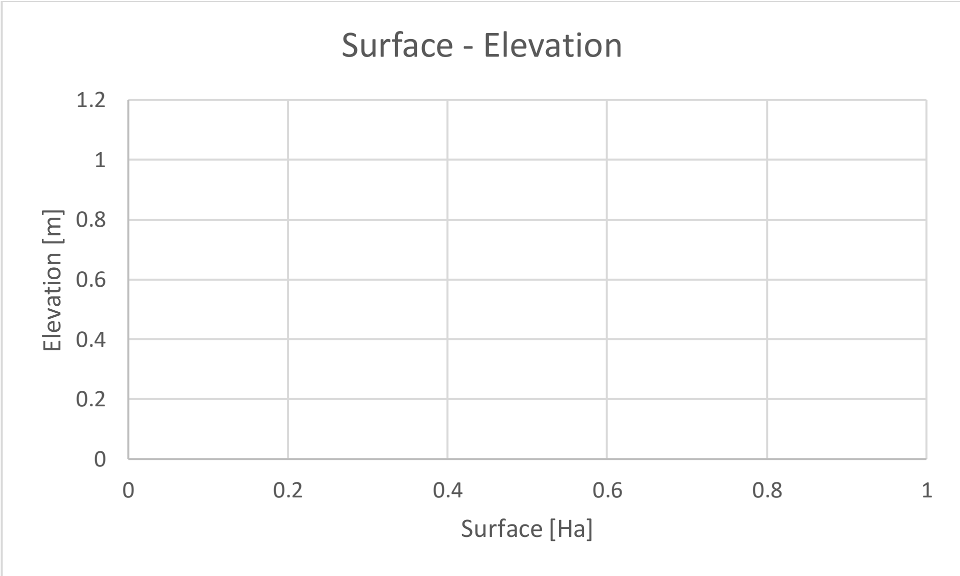

Figure 16 : Surface – Elevation

2.4. Limitations and Constraints

Throughout the years, due to different reasons, several constraints were developed and nowadays, operations strategies are limited to them. Limitations are listed below:

- Maximum discharge from the dam must be less than 190 m^3/s: Even though the maximum discharge capacity of the spillway is 280m^3/s, downstream, in the banks of the Rio Suquia, there are some settlements that can be affected if the discharges are higher than 190m^3/s. Also, can affect the city of Cordoba causing floods in some neighbors.
- Maximum elevation of the reservoir must be less than 36.5m (local reference): The city of Carlos Paz begins to suffer from floods if reaches this level. This prejudice the total development of the reservoir because the spillway can function just between 35.3m and 36.5, far below from the levels that it was projected.
- Minimum level of the reservoir must be higher than 21m: For environmental reasons.

2.5. Main Goals of the Study

The aim is to develop a reservoir simulation integrated decision support tool and an optimization support tool, both for long-term and short-term purposes, in order to evaluate and optimize operations strategies under various case scenarios with different approaches.

For this purpose, HEC-ResSim and Aquarius software were used, each one with their advantages and disadvantages, which must be considered. With this two software, several supporting tools are performed with the objective of guiding and assist dam operators in analysing the consequences in the performance of the reservoir for different decisions. This provides an overview that relaxes uncertainty and that can be used in the real-time scale of water resource management, which are not the same than for scientific purposes.

3. RESERVOIR MANAGEMENT TOOLS

The focus of this chapter is on the description of the software used with the steps followed to model the reservoir. Each software has different calculation approaches that make them useful depending on the needs. This aspect must be considered in order to arrive to significant results that allow us to reach interesting and representative conclusions. Apart from this, the model implementation strategy will be exposed to show how to use them in the case study, and how and why are being used for this reservoir.

3.1. HEC-ResSim

HEC-ResSim is the successor to "HEC-5, Simulation of Flood Control and Conservation Systems" program (HEC 1998). HEC-ResSim is used to model reservoir operations at one or more reservoirs for a variety of operational goals and constraints. The software simulates reservoirs operations for a flood risk management, water supplies studies and also serves as a real-time decision support. Additionally, ResSim is comprised of a graphical user interface (GUI), a computational program to simulate reservoir operation, data storage and management capabilities, and graphics and reporting facilities. The Data Storage System, HEC-DSS (HEC 1995 and HEC 2006) is used for storage and retrieval of output of time-series data. (Klipsch and Hurst 2013)

Moreover, ResSim offers three separate sets of functions called "Modules" that provide access to specific types of data within a watershed. These modules are Watershed Setup, Reservoir Network and Simulation. Each module has a unique purpose and associated set of functions accessible through menus, toolbars, and schematic elements (Klipsch and Hurst 2013). Figure 17 illustrates the basic modeling features that are available in each module.

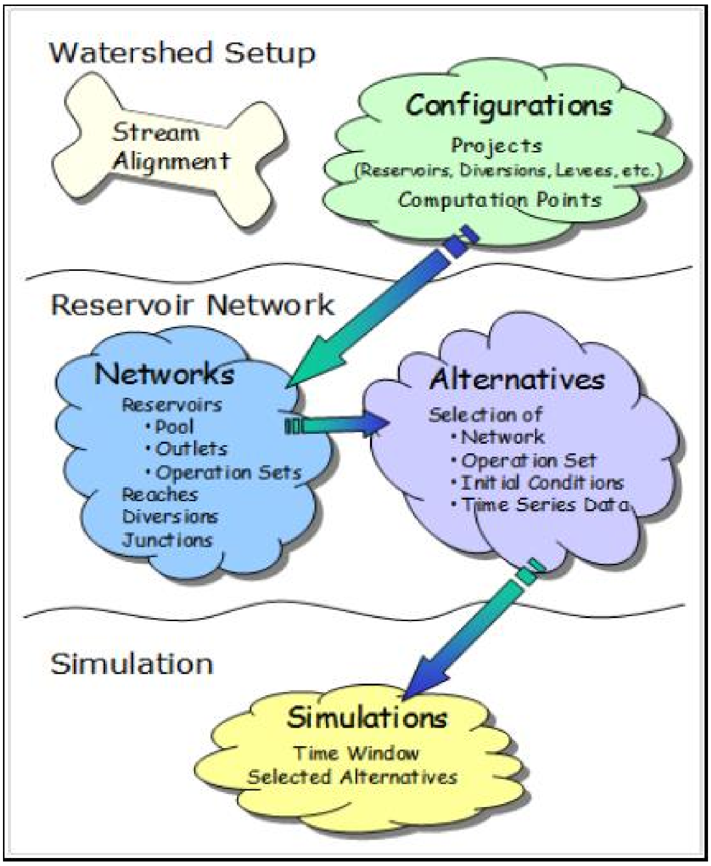

Figure 17 : HEC-ResSim Module Concepts

3.1.1. Watershed Setup Module

The objective of the Watershed Setup Module is to provide a common framework for the creation of watersheds and the definition between the different modelling applications.

Water Setup Module is the background data for the entire project, it is used to create and setup your watershed. In this module it will be configured the physical disposition of watersheds such as background maps, alignment current, streams, reservoirs, projects and georeferenced data. Projects and computation points associated with a specific configuration of the basin are defined (projects may include reservoirs, dikes, diversions and other future projects).

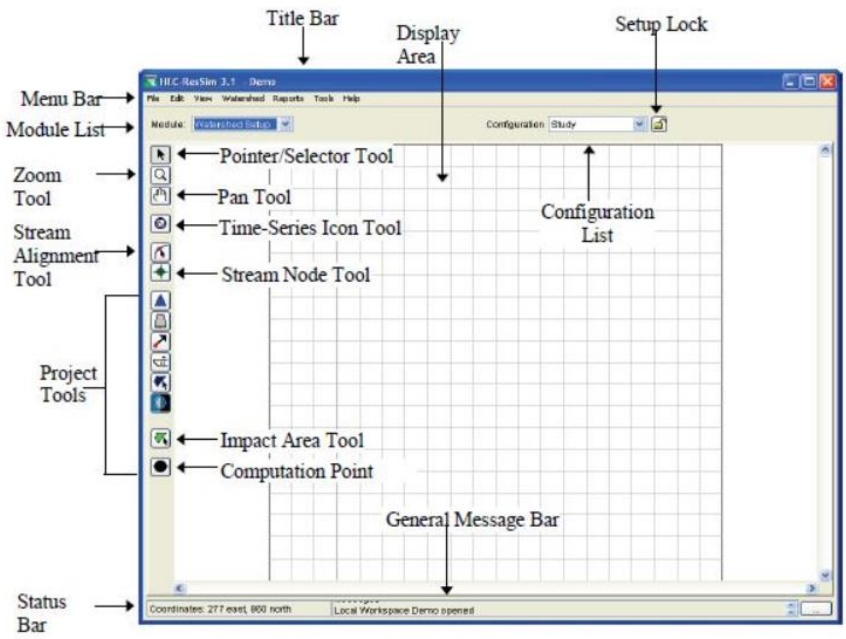

Figure 18 : Watershed Setup Module display

3.1.2. Reservoir Network Module

A reservoir network represents a collection of watershed elements connected by routing reaches. The elements created in the Watershed Setup Module belong to specific configurations, and when a reservoir network is created, reference is made to one of them.

The calculation points defined in the Watershed Setup Module are automatically converted at the junctions in the reservoir network module. Its main objective in the development of a reservoir network is to connect the routing reaches.

This module provides user to create reservoir network elements. The physical and operational data that describe an operation plan or scheme upon which it can base its decision are provided into the model using these elements.

An operation set (Figure 19) holds all the information that describes the reservoirs operating goals and constraints. The key elements are: Zones, Rules and the identification of the Guide Curve. A reservoir can have more than one operation set defined.

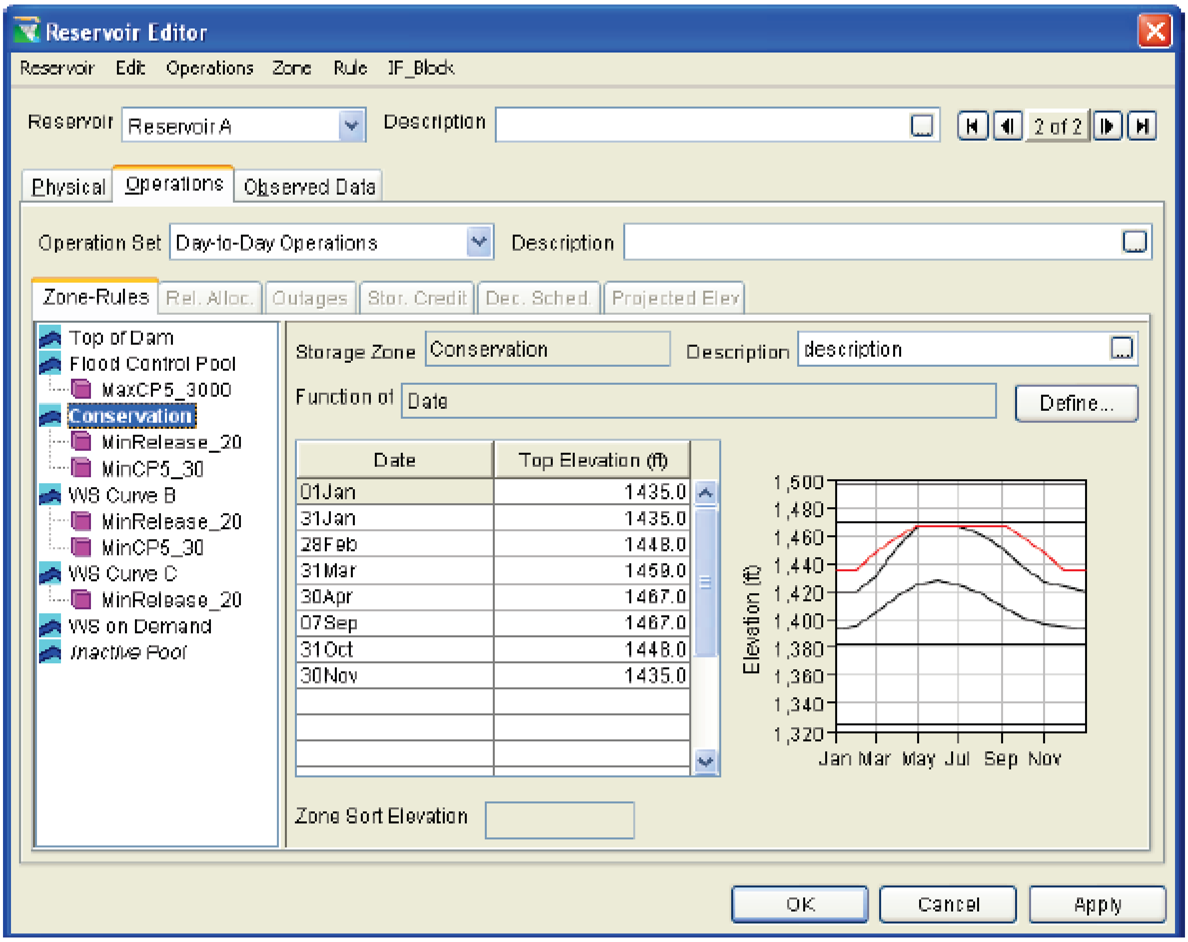

Figure 19 : Operation Set

- Zones are operational subdivisions of the Reservoir Pool. Each zone is defined by a curve describing the top of the zone, which may vary seasonally.

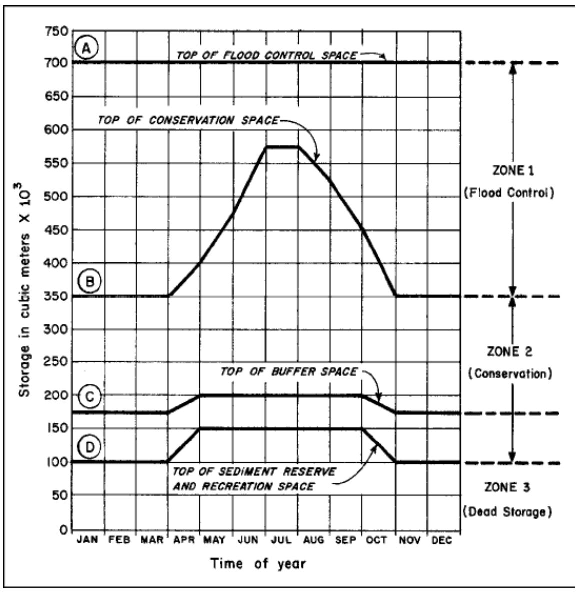

Figure 20 : Zones

- Rules represent the goal and constraints upon the releases. This are specified in terms of Flow (maximum, minimum or specified), Elevation/Stage, Energy Generation, Flow Rate-of-Change, Pool Elevation Rate-of-Change.

- Guide Curve is the target elevation. The process of determining the releases from a reservoir in order to get to and maintain the reservoir pool at a certain level are held searching for this curve. ResSim tries to reach this target as fast as possible. However, this process is limited by physical outlet capacity, elevation, release, reservoir operating rules and zone boundary logic.

3.1.3. Alternatives

An alternative is a specific selection of:

- A reservoir network
- Flow computation method and time step
- Operation Set
- Lookback data (initial conditions)
- Inflow and time series input (in format .dss)

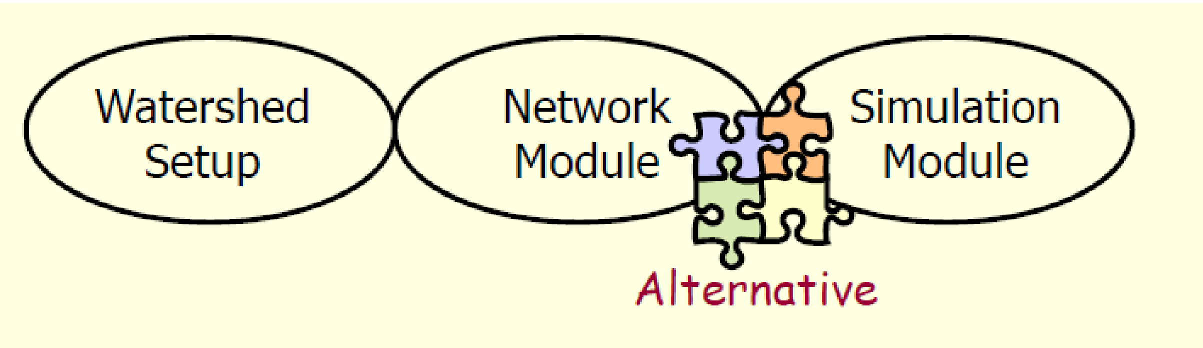

Figure 21 : Alternative

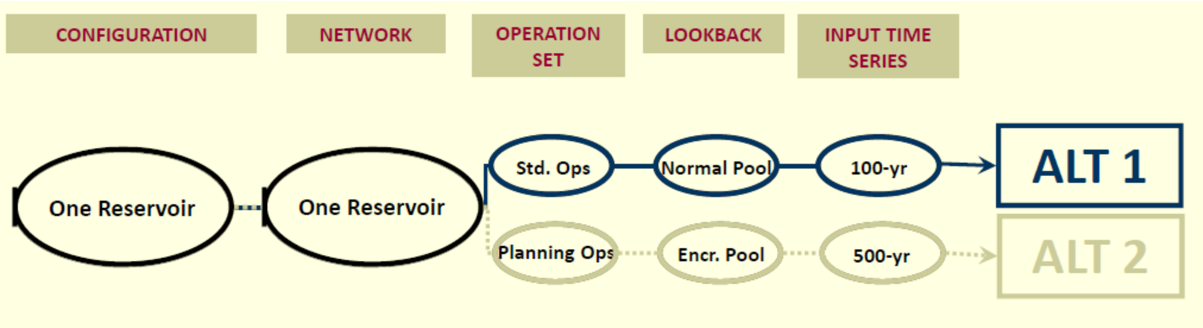

Figure 22 : Scheme of Alternatives

Each alternative can be chosen in advance and compared with each other in simulation module.

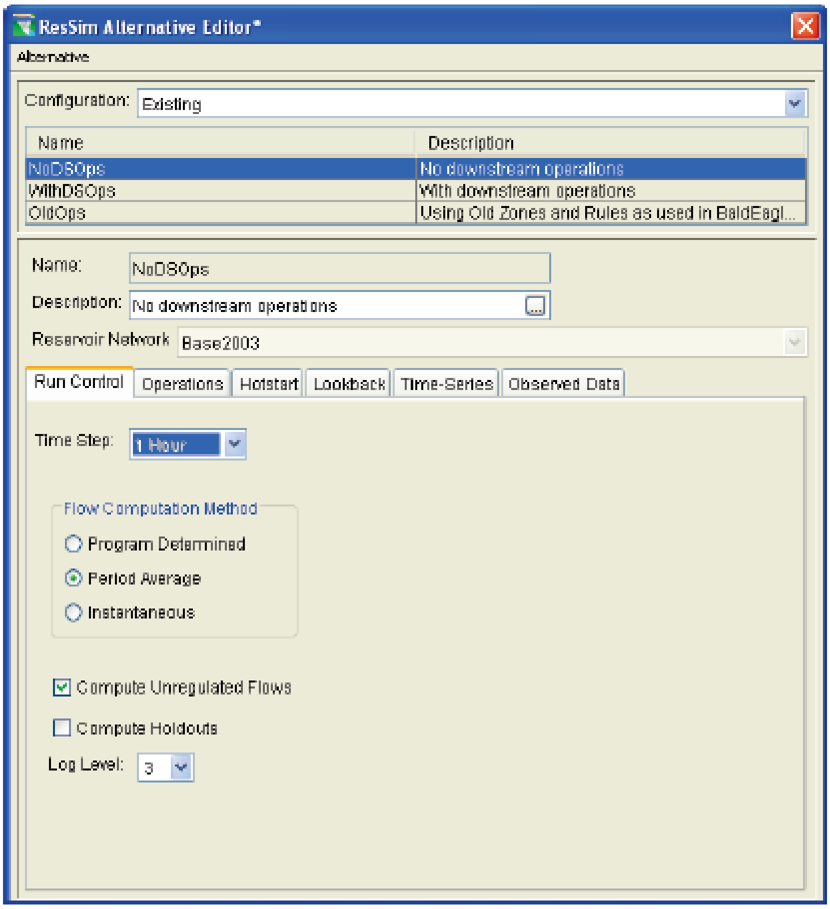

Figure 23 : Alternatives Editor

3.1.4. Simulation Module

The simulation module has been designed to facilitate the analysis phase of the reservoir modeling, in which simulations are created and run. Once reservoir model is complete and alternatives defined, Simulation Module is used to configure the simulation:

- Simulation time window,
- Computation interval,
- Alternatives to be analyzed.

3.2. Aquarius

Aquarius is driven by an economic efficiency operational criterion that calls for the reallocation of stream flows until the marginal returns in all water uses are equal, i.e., until a Pareto optimal arrangement is reached. (Diaz et al. 2000)

"Aquarius is an analysis framework rather than a single dedicated model for water allocation. The model was implemented using an object-oriented programming (OOP) language (C++). Water systems are ideal candidates for modeling under an OOP framework, where each water system component is an object in the programming environment. V05 supports the modeling of two types of water sources (surface water and groundwater); several water control structures (storage reservoir, spill controller, reservoir outlet works, diversion structures, junction points); two types of conveyance structures (river reaches and man-made canals and pipelines); and seven water uses (agriculture irrigation, hydropower generation, instream flow protection, instream recreation, municipal and Industrial water supply, reservoir recreation, flood control areas)." (Diaz et al. 2000)

"An economic efficiency criterion was adopted for determining water allocation because economic demands play a key role in water allocation decisions, and because of the greater accessibility of economic value estimates for nontraditional water uses such as recreation. This decision criterion calls for reallocating stream flows until the marginal returns in all water uses are equal. Each traditional use and nontraditional use is, if possible, represented by a demand curve (i.e., a marginal benefit function) that is characterized by an exponential or constant function."(Diaz et al. 2000)

"For a water use with a predetermined level of allocation but without a defined economic demand function, the analyst can either constrain the model to meet the specified allocation or experiment with surrogate demand curves until the required level of water allocation is reached. The latter approach indicates the level of economic subsidy required to provide the

incremental increases of flow to sustain the use in open competition with other uses. The interactive nature of Aquarius facilitates such experimentation."(Diaz et al. 2000)

"The water allocation problem solved by Aquarius, involving a set of exponential/linear/constant demand functions, requires a complex nonlinear objective function. The solution technique uses the special case of the general nonlinear programming problem that occurs when the objective function is reduced to a quadratic form and all the constraints are linear. The method approximates the original nonlinear objective function by a quadratic form using Taylor Series expansion and solves the problem using quadratic programming. A succession of these approximations is performed using sequential quadratic programming until the solution of the quadratic problem reaches the optimal solution."(Diaz et al. 2000)

"The software runs on a personal computer under the Microsoft Windows operating system. The latest distribution of the program Aquarius, together with it technical documentation, can be downloaded from the World Wide Web visiting the Aquarius web-page at:

http://www.fs.fed.us/rm/value/aquariusdwnld.html. Usage is free for government agencies and for teaching and research purposes."(Diaz et al. 2000)

3.2.1. CREATING A FLOW NETWORK

"The user interacts with the model through the so-called network-worksheet screen (Figure 2), which allows the analyst to readily represent the water system of interest using the inherent capability of the object-oriented paradigm for graphical representation. The model provides four elements for user interaction: (i) the network worksheet (NWS), (ii) the menus, (iii) the water system components (WSC) palette, and (iv) the object tools palette.

In the NWS each system component corresponds to a graphical node or link (object) of the flow network. These components are represented by icons, based on a pictorial representation of the object. By dragging and dropping these icons from the menu, the model creates instances of the objects on the screen. In this manner, one by one, all the necessary system components are created. WSCs can be repositioned anywhere in the NWS or be removed from *it. Once nodes (e.g., reservoirs, demand areas) are placed, they can be linked by means of natural river reaches and conveyance structures, which are also objects available from the WSC palette. This operation is carried out by simply left-clicking on the outgoing terminal of a node, and next into the incoming terminal of the other node. This procedure facilitates the assembly or alteration of water systems by simply "wiring up" their system components in the NWS. The creation and alteration of flow networks is further facilitated by copying and inserting an object or whole portions of an existing network onto the same or a new NWS. The Copy/Paste procedure not only creates new instances of the object(s), but also duplicates their data structure (creating clones of the original objects).”*(Diaz and Brown 1997)

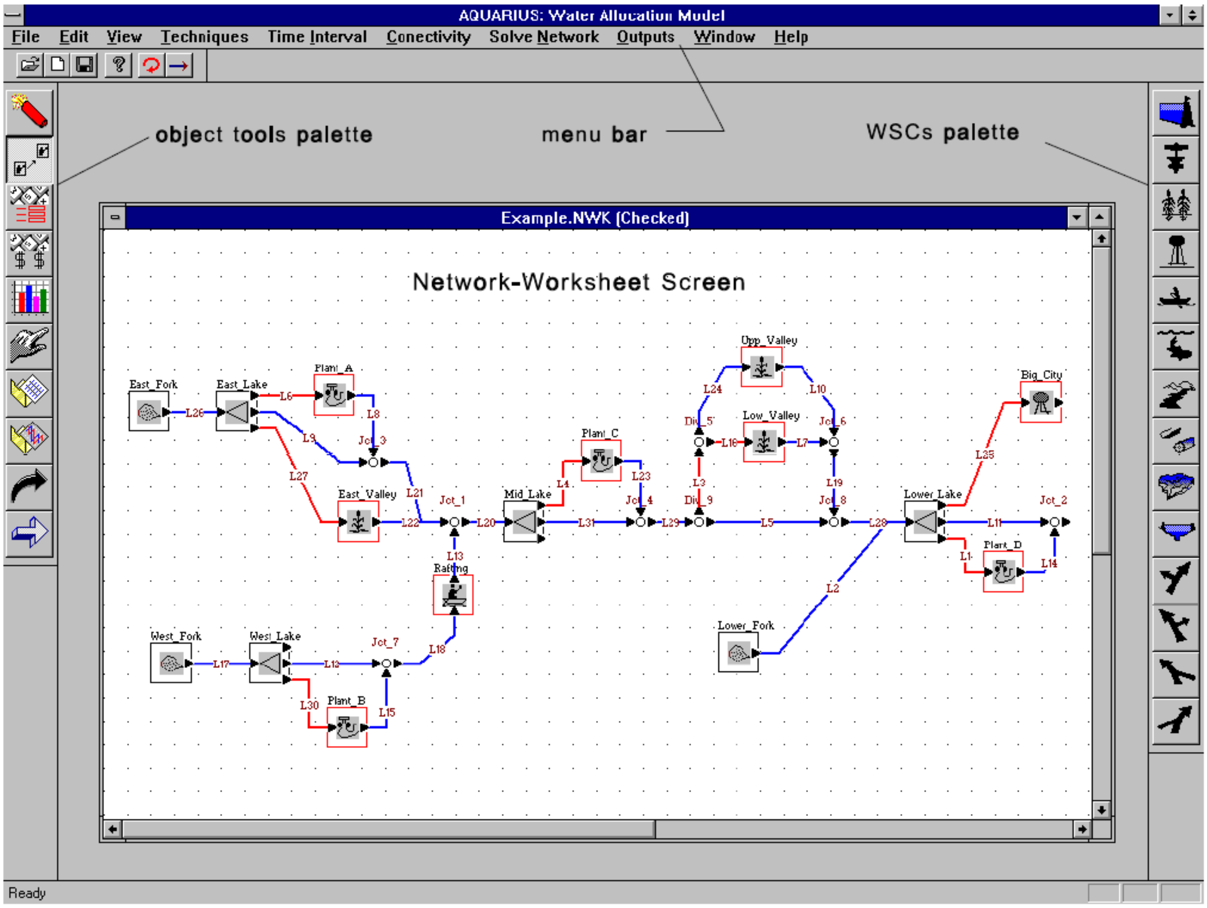

Figure 24 : Aquarius Worksheet

3.2.2. ENTERING INPUT DATA

“The input data to the model have been divided into two basic groups: physical and economic data. The physical data include the information customarily associated with the dimensions and operational characteristics of the system components, such as maximum capacity of a

reservoir, percent of return flow from an offstream demand area, and efficiency of a powerplant. The economic data consist mainly of the demand functions of the various water uses competing for water. The input data entered for any system component remain part of the object, even after the network is saved on a storage disk. When the network is reloaded, all data saved from the previous session are retrieved in exactly the same form."(Diaz and Brown 1997)

3.2.3. SOLUTION OF THE WATER ALLOCATION PROBLEM

"In the model, water allocation throughout a river system and for an entire planning horizon is based on a global objective which is to maximize the sum of all economic benefits stemming from the instream and offstream use of water —as expressed by their willingness to pay— subject to the operational constraints of the system such as: reservoir storage limits, firm water supply levels, max/min instream flows, max/min diversions, seasonality of water demands, etc. Given demand functions for the various water uses j, the global benefit function (B) to be maximized over the various time periods i is:

$$B = \sum_{i=1}^{np} \sum_{j=1} \int_0^{a_{ij}} f_{ij}(x_{ij})\, dx_{ij}$$

np : total number of time periods
nu : total number of water uses

where x is the level of output in the demand function f(x) and a denotes the level of allocation. It should be remembered that B is maximized when a_{ij} are set such that the marginal prices are equal for all i,j. In other words, total benefits are maximized when levels of consumption are such that the marginal benefits for each use across all uses and time periods are equal (provided that an unconstrained solution to the allocation problem is found). B can, of course, only be maximized over the j uses for which marginal benefit functions are specified. If relevant uses are omitted because their benefit functions cannot be specified, the model can still represent them by adding the necessary physical constraints to the formulation. The solution technique implemented in Aquarius takes advantage of the special case of the general nonlinear programming problem that occurs when the objective function is reduced to a quadratic form and all the constraints are linear."(Diaz and Brown 1997)

3.3. Model Implementation Strategy

In the analysis of a water resource system, many different aspects must be modelled. The operators must develop different tools in order to investigate a water resource system. These tools are developed through different modelling techniques. A water resource operator without modern-day modelling techniques is helpless, different speculations about the problem can be predicted, but the real evaluation of the different components cannot be performed.(Basson et al. 1994)

On one hand, simulation techniques can be used in water resource analysis to model the behaviour of a water resource system. These systems consist of different components like reservoir lake, dam, junctions, streams, outlet works, reaches, diversions etc. A simulation technique allows the analysis of a water resource system response over different time scales, for a wide variety of system configuration and hydrological conditions. This technique must be extremely adaptable to different problem definitions and system configurations in order to represent a complex water resource system. (Basson et al. 1994)

The technical modelling requirement of a simulation model can be very extensive, and it should be also capable of representing an operating policy within the context of a dynamic operating strategy. Typically, operating policies are maximizing firm water yield, maximize firm hydropower energy generation, minimize operating costs, etc. (Basson et al. 1994)

The selection of a modelling strategy to fulfil all these modelling features is most of the time complicated. For many years different simulation techniques have been applied extensively to the modelling of water resource systems, but a little portion could meet all the above stated needs. Most models have been developed using a decision tree style. Decisions on the allocation of inflow and storage start at the top of the tree (system) and proceeds downstream. The simulation models HEC-3 and HEC-5 (nowadays HEC-ResSim) are examples of this style. Other simulation models have been developed using simulation languages. These models are quite useful for modelling problems which are extremely dynamics in nature but for monthly response of complex configuration and operating strategies are less effective. For this reason, in this thesis, HEC-ResSim was chosen among the other techniques. (Basson et al. 1994)

On the other hand, once a reasonable operating strategy has been reached through simulation analysis based on the historic inflow sequences, applying an optimization technique could be useful to obtain an “optimal” operation. It should be noted that this model will provide a solution based on the complete foreknowledge of the inflow sequences, which in most cases is not possible for real situations. However, this solution can be useful in order to compare and judge between the “optimal” solution and the simulated one, and to try to emulate these optimal operating strategies. As simulation models has no foreknowledge of future events and the calculation process is as if in real time, it is unlikely to have the same operations and results. (Basson et al. 1994)

More generally, optimization techniques consist in finding the best possible values of some objective function given a defined domain (or input), under certain specified circumstances. Typical objective functions in water resource management, are minimizing costs or maximizing benefits, maximizing system yield, etc. (Basson et al. 1994)

An optimization technique provides the best solution having complete foresight of all future events, thereby, the results can resolve the dilemma of the operators of when to meet the objectives taking into account the risk of not meeting objectives in the future due to an erroneous forecast of inflow for example.

This technique is used by the water resource planner to investigate many of the different challenges that water resource management present, such as optimal system development planning, optimal system yield, optimal benefits, optimal operating policies. In this case, it will be used for the analysis of the effectiveness of the simulated operating rules by comparing them. Many different algorithms are available as well as different software. In this case, Aquarius is used because is driven by an economic efficiency operational criterion that provide an intelligent use of the reservoir storage which delivers the maximum yield capacity and has a level of complexity according to the needs.

3.3.1. Modelling San Roque Dam in HEC-ResSim

To begin with, every simulation analysis must follow the next steps:

1. Define study objectives
2. Develop Data sets

    - Physical, operational, flows
3. Validate data and operations
    - Compare simulation to historic data
4. Perform simulation with specified demands
5. Evaluate output and performance
6. Compare output with evaluation criteria

In this section, the first 3 items are developed and in the next chapters the performance, evaluation and comparison of the output are completed

3.3.1.1. Define study objectives

As mentioned before, the objective is to diminish as much as possible the operator uncertainty in the decisions and provide a support tool for the optimization and simulation in case needed. Questions such as store or pass inflows, release water from storage or save, allocation of release water or from what level in reservoir make releases, are usually present so having a model to assist is always necessary.

The operational goals depend on what is being prioritized in that moment. For example, for flood control the operator`s decisions aim is to not endanger the dam, to not contribute to downstream flooding, to not unnecessarily store water in the flood pool and to evacuate flood storage as quickly as possible. In case of water supply decisions, they must consider conflicts between the flood and supply storage, this is saving space for future floods and save water for future supply, and to satisfy the demand for water (varies with seasons, over the years, costumers, etc). And in case of hydropower, they must meet the demand and use efficiently the releases.

3.3.1.2. Develop Data sets

The availability of comprehensive and reliable information of a water resource system and the meaningful representation thereof, is the cornerstone of any operational decisions. Optimal use of simulation model can only be achieved if the specific variables which influence the behaviour and supply capabilities of a water resource system, are well represented.

To begin with, for the Watershed Setup Module, International System was chosen together with the time zone of Córdoba, GMT-3. Afterwards, shape files of the basin, rivers and reservoir were downloaded from the official website of the IGN (Instituto Geográfico Nacional) and added as a map layer. Then, with the help of the stream alignment and reservoir tool, the Watershed Setup Module was completed.

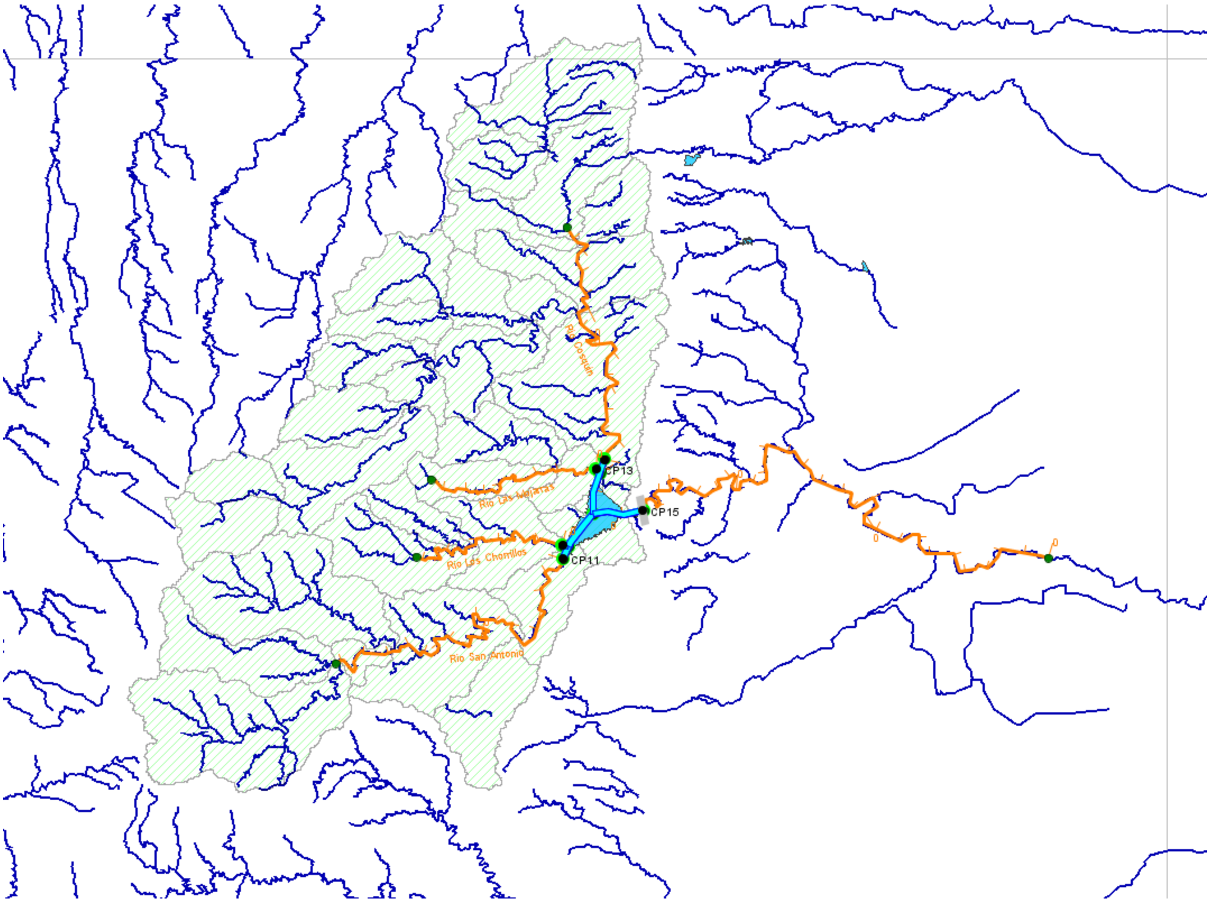

Figure 25 : Watershed Setup Module

In the following module, the Reservoir Network Module, the Reservoir Network is created. With the junction tool the connectivity is established, and each computational point is defined. In the Reservoir tool, the physical and operational data is specified. With the help of the Ministerio de Agua, Ambiente y Servicios Públicos from Córdoba Province, all the data was fulfilled representing the reservoir. The relation Storage-Elevation and Surface Elevation with a step of 10 cm was introduced for the reservoir (introduced in section 2.3). Regarding the Dam, Controlled outlet, Uncontrolled Outlet and Power Plant were defined as stated in section 2.2. The following image summarizes the release capacity of the dam,

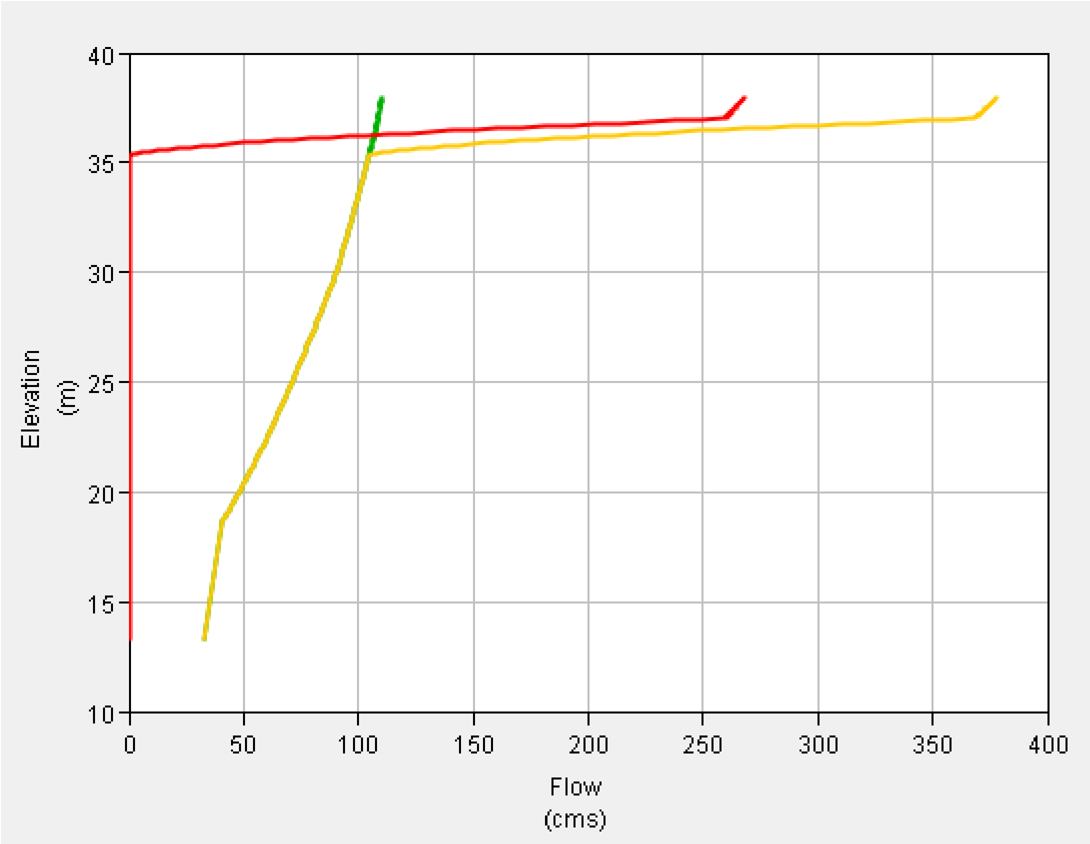

Figure 26 : Elevation vs Flow

This image demonstrates the release capacity of the dam according to the elevation. The red line is the Uncontrolled Outlet capacity which starts at the spillway level at 35.3 m and increases correspondingly to the equations mentioned in section 2.2. The green line and the yellow line represent the Controlled Outlet capacity and the Total Outlet capacity respectively. From 13.2 m (death storage level) till 35.3 m (spillway level), the total outlet capacity of the dam is equal to the controlled outlet capacity, and that is the reason of the overlapping. For levels higher than the spillway level, the total outlet capacity will be the sum of both lines (green one and red one) which will be led mainly by the uncontrolled outlet.

Operational data consists in the definition of different zones and operational rules that will control the simulation, thence this is described in detail when a concrete simulation is going to be performed.

3.3.1.3. Validation of the model

After modelling the dam, in order to be sure that the results are going to represent the real situation, it is necessary to check the physical and operational data previously inserted in HEC-ResSim. So before testing new alternatives, a calibration is carried out by setting historical events in the model (with their respective inflows, outflow and operating policies) and testing the correlation between the elevation results of the model with the measured elevations in that events. In order to guarantee representativeness, the model will be calibrated with two different events with different time scales and purposes.

To establish the degree of correspondence between observed and modelled values, there are several statistical indicators, within which the Nash-Sutcliffe efficiency index is selected among others. The Nash formula is:

$$NSE = 1 - \frac{\sum_{t=1}^{T}(E_m^t - E_o^t)^2}{\sum_{t=1}^{T}(E_o^t - \overline{E_0})^2}$$

where E_0 is the mean of observed elevation, and E_m is modeled elevations. $E_0{}^t$ is observed elevation at time *t*. (Nash, J., & Sutcliffe n.d.)

Nash–Sutcliffe efficiency can range from −∞ to 1. An efficiency of 1 (NSE = 1) corresponds to a perfect match of modelled elevation to the observed data. An efficiency of 0 (NSE = 0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero (NSE < 0) occurs when the observed mean is a better predictor than the model or, in other words, when the residual variance (described by the numerator in the expression above), is larger than the data variance (described by the denominator). Essentially, the closer the model efficiency is to 1, the more accurate the model is. Threshold values to indicate a model of enough quality have been suggested between 0.5 < NSE < 0.65. (Nash, J., & Sutcliffe n.d.)

Nash–Sutcliffe efficiency can be used to quantitatively describe the accuracy of model outputs other than elevation. This indicator can be used to describe the predictive accuracy of other models as long as there is observed data to compare the model results to.

Firstly, data of the real flood event **between 07 May 2018 and 14 May 2018** is used. Operations were set as told by the operators and data collected, outflow was imposed in the model so that releases where the same at the exact time in all the event. After 30m of elevation valves were closed so that the spillway took all the flood. This was forced by the Zone Flood Control which imposed a rule of 0 m^3/s called “ValvulasCerradas” after the Zone named “Valvula” as shown in Figure 27.

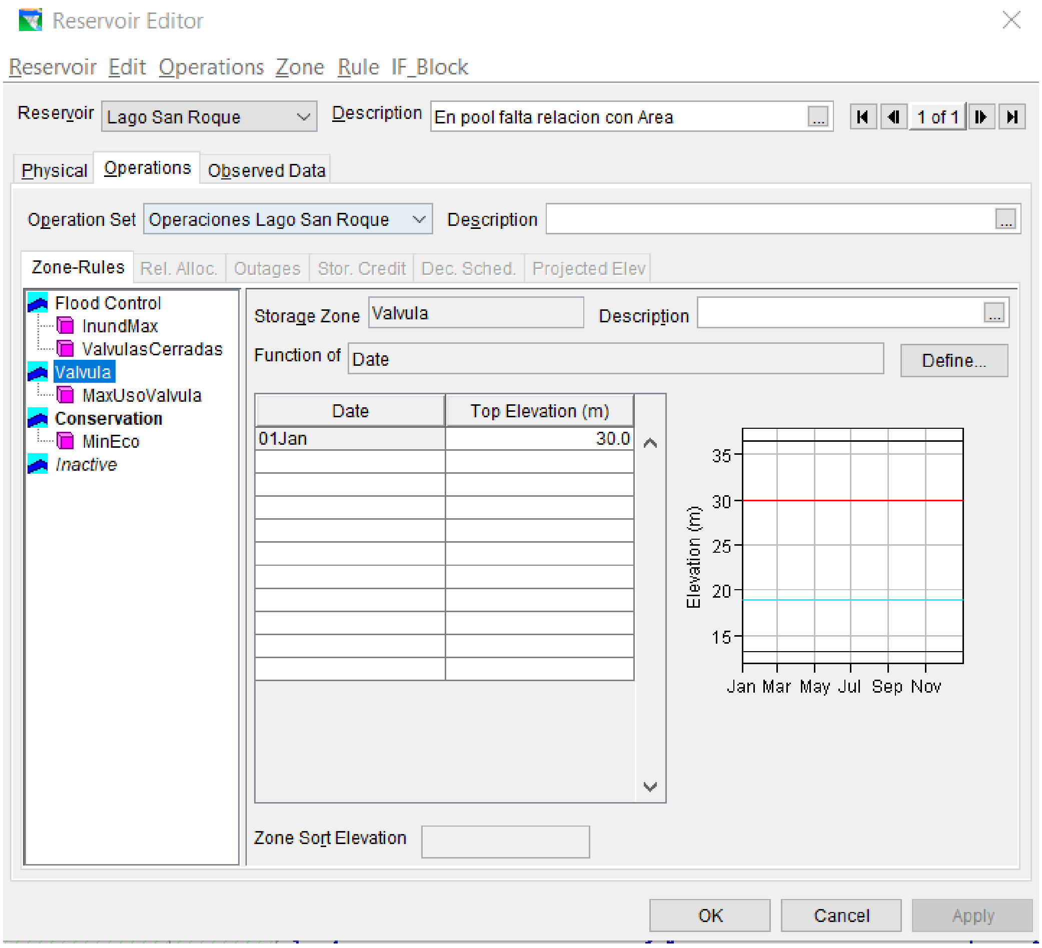

Figure 27 : Operations

For the inflows, historic (gauged) events were used with an hourly time step, these were introduced in the program HEC-DSSVue, which is the only way to use it in the HEC-ResSim.

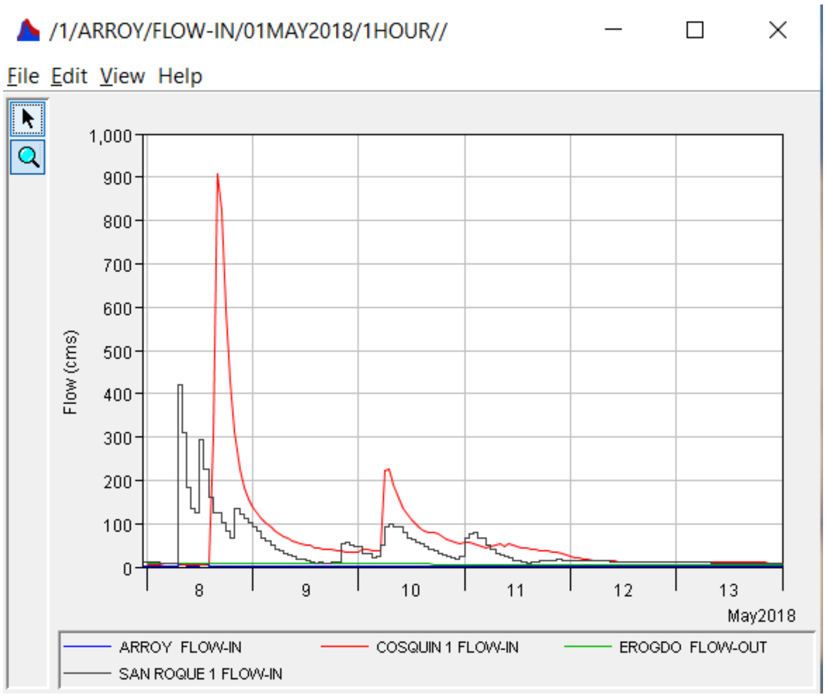

Figure 28 : HEC-DSSVue

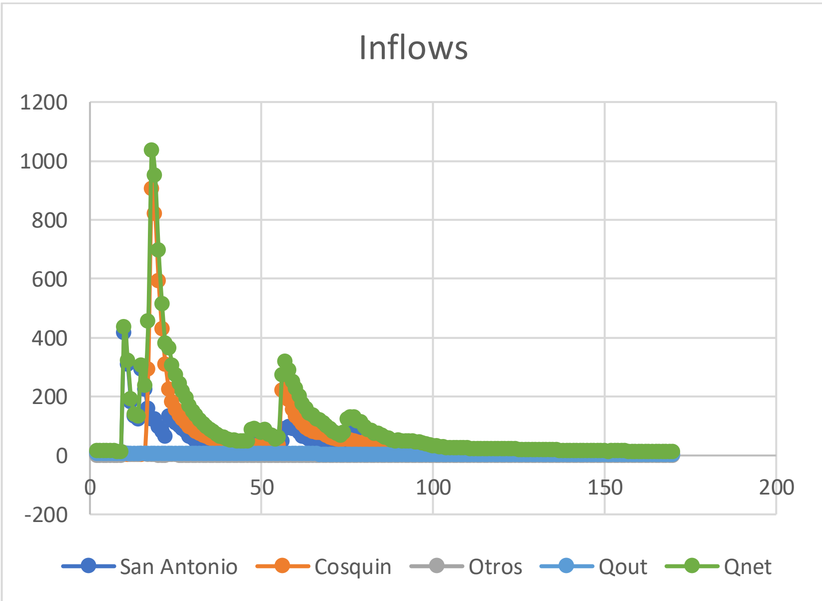

Figure 29 : Inflows Data

Afterwards, initial conditions were set as measured in the dam.

Location	Variable	Type	Default Value
Lago San Roque-Pool	Lookback Elevation	Constant	32.95
Lago San Roque-Pool	Lookback Storage	Computed	
Lago San Roque-Cont...	Lookback Release	Constant	0.0
Lago San Roque-Unc...	Lookback Spill	Constant	0
Lago San Roque-Pow...	Lookback Release	Constant	0

Figure 30 : Initial Conditions

Time step chosen was 1 hour, as the inflow data, and then computed in the same lapse of time. Results are presented in the following, together with the real ones:

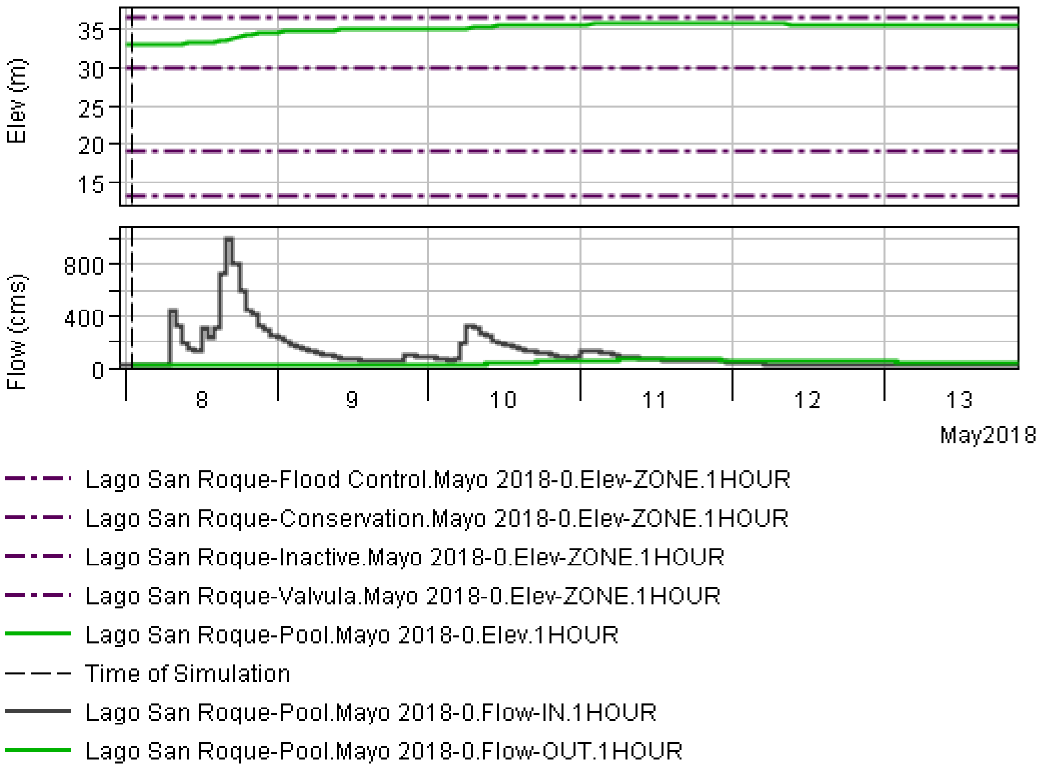

Figure 31 : Output of HEC-ResSim

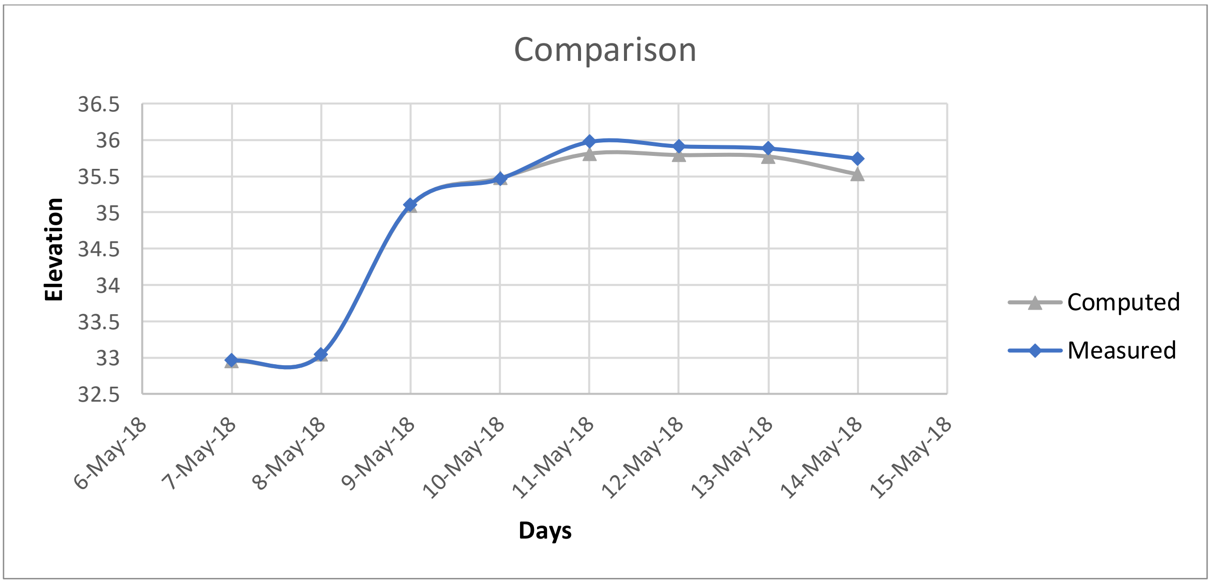

Figure 32 : Elevation Measured vs Computed

It can be easily observed that with the shape and the results, the model represents the real situation, however, the NASH coefficient is tested, and the result is 78% which is a high value and can be consider as representative. Differences come since the measures are with a daily step and the calculation is with an hourly step coinciding with the step of the inflow.

Secondly, a drought event **between April and November 1995** for water supply was modelled. Operations were set as told by the operators and data collected, outflow was imposed in the model so that releases where the same at the exact time in all the event. During all the months releases were from 6 m^3/s from the power plant. This was imposed by the Zone Flood Control which imposed a rule of Qplant=6 up to the Conservation Zone.

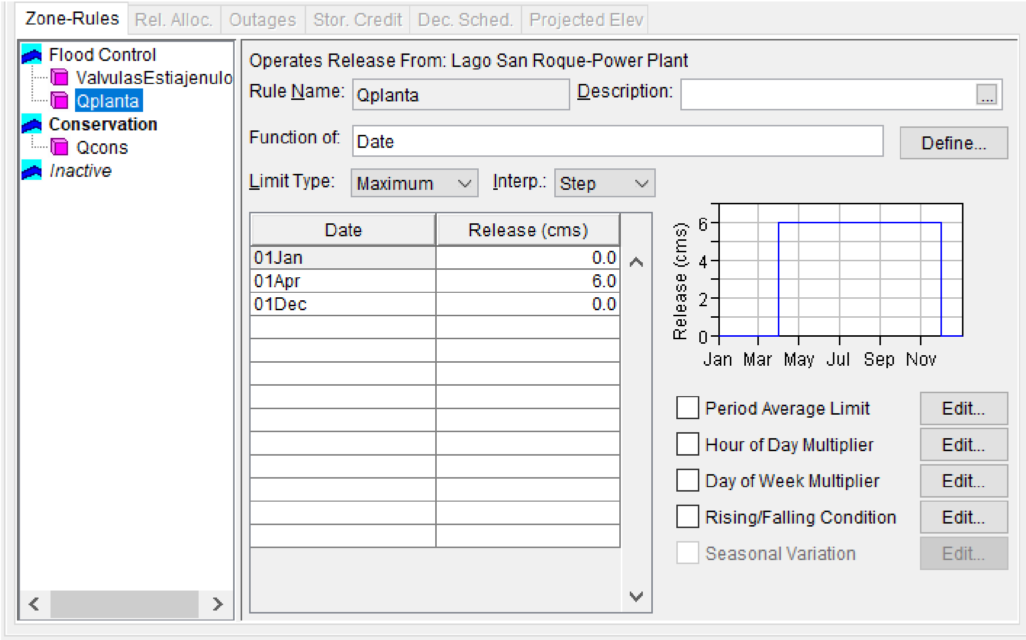

Figure 33 : Operations between Apr and Nov

For the inflows, historic (gauged) events were used with a monthly time step, these were introduced in the program HEC-DSSVue and then HEC-ResSim.

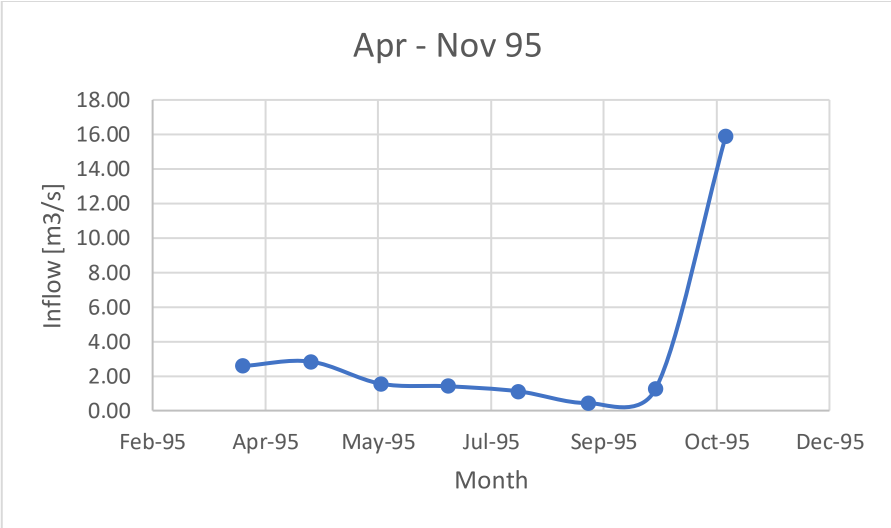

Figure 34 : Inflow data 95

Afterwards, initial conditions were set as measured in the dam.

Location	Variable	Type	Default Value
Lago San Roque-Pool	Lookback Elevation	Constant	31.14
Lago San Roque-Pool	Lookback Storage	Computed	
Lago San Roque-Cont...	Lookback Release	Constant	0
Lago San Roque-Unc...	Lookback Spill	Constant	0
Lago San Roque-Pow...	Lookback Release	Constant	6

Figure 35 : Initital conditions Apr 95

Time step chosen was 1 day, which is the maximum step allowed and reduces the computational time. Results are presented in the following, together with the real ones:

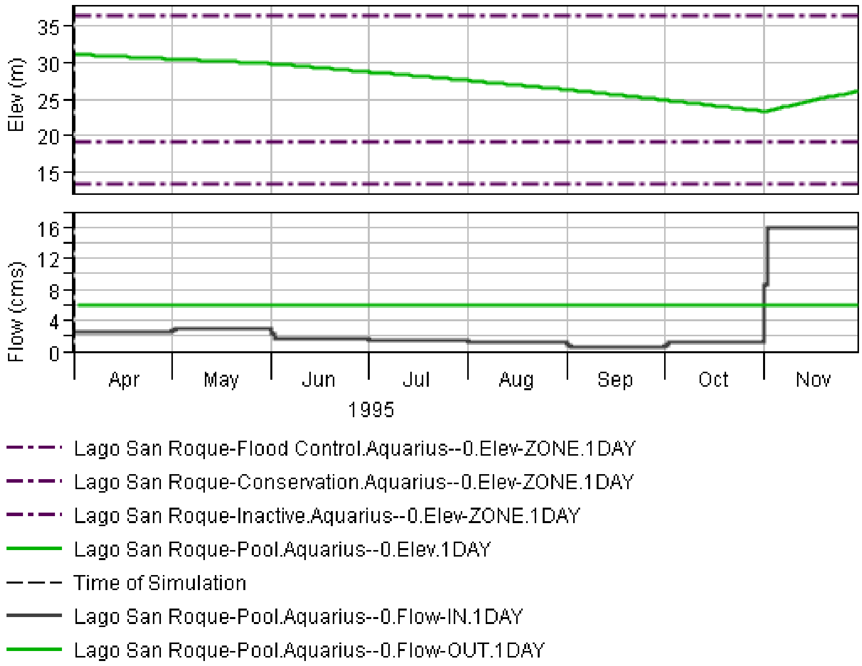

Figure 36 : Output of Hec-ResSim

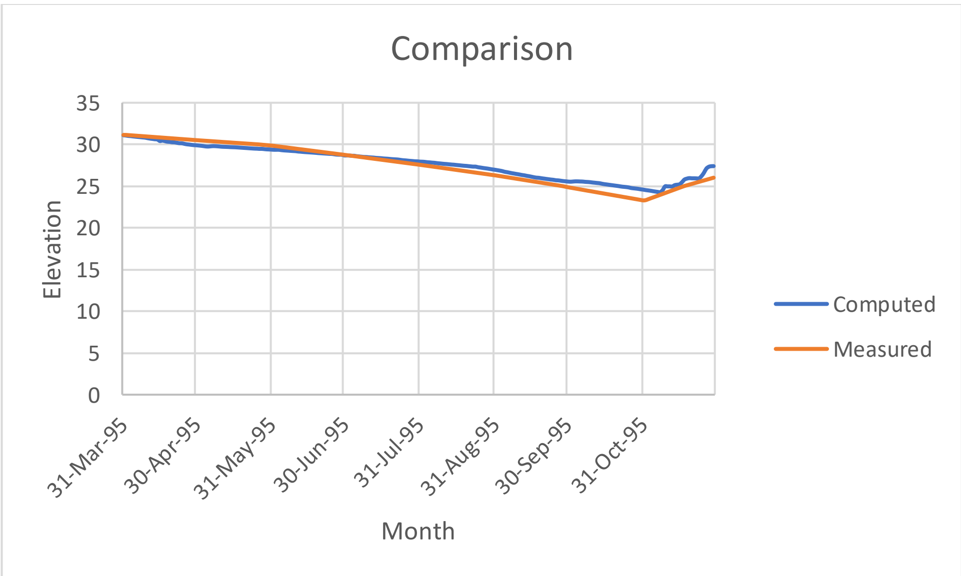

Figure 37 : Measured vs Computed

Again, here with the shape and the results, the model seems to represent the real situation, however, the NASH coefficient is tested, and the result is 89%. This can be considered as representative.

3.3.2. Modelling San Roque Dam in Aquarius

The modelling in Aquarius is simpler as it is not divided in different modules and the network-worksheet screen interaction is mild. First, 4 Natural Flow Basin were created, one for each river, which leads to the Reservoir by 4 River Reaches, one for each river. Downstream from the reservoir, the power plant was inserted with the Hydropower tool connected by a River Reach and another River Reach continues downstream which will be connected with the hydropower outlets by a Left-Bank Junction. The purpose of the last river reach is to differentiate the controlled and uncontrolled outlet from the input of the power plant. The following figure illustrate the system,

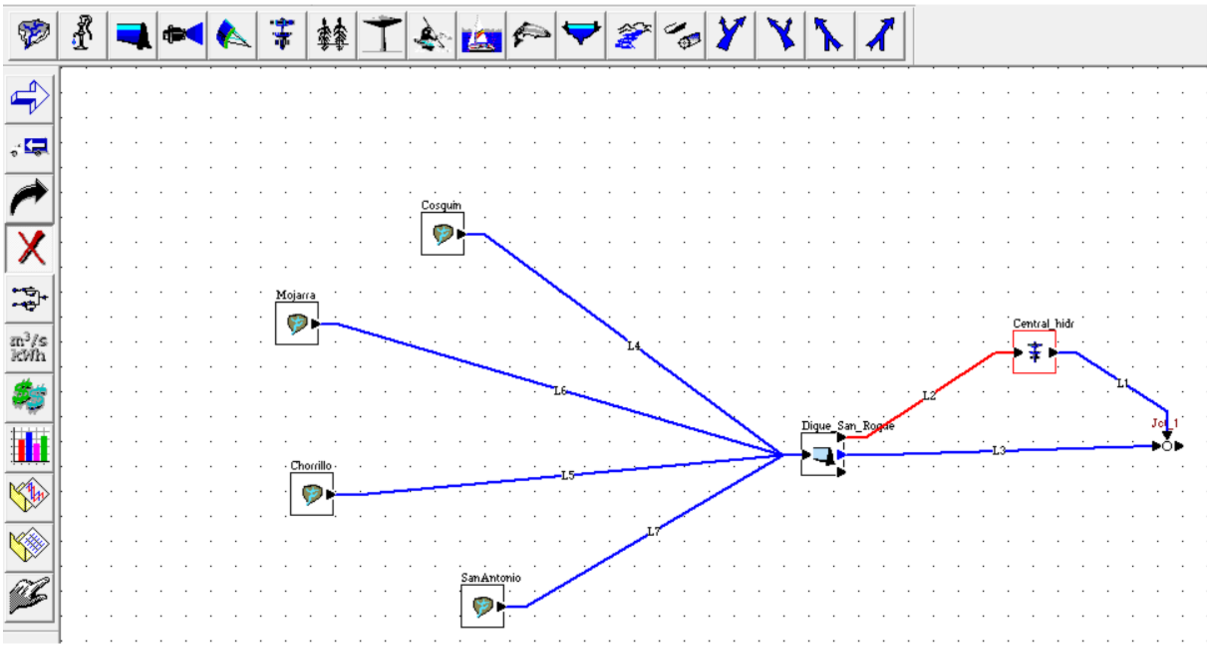

Figure 38 : Reservoir System in Aquarius

Afterwards, physical and economic input were defined. A limitation with respect to HEC-ResSim is that physical characteristics from the reservoir and for the power plant are define by equations relating the two variables, and non with tabulate data as in HEC-ResSim. Hence, an interpolation of the data was performed, although small differences are present.

For the reservoir, Physical Characteristic and Outlet Work are introduce defining Elevation vs Storage, Area vs Storage, Spillway and Valves characteristics, and maximum and minimum reservoir water surface elevation. Also, Operational Characteristics that define Initial Storage and Final Storage (in Mcm) are inserted, together with Minimum and Maximum Storage which can be used as Operational Constraints for the optimization. The inflow to the reservoir is put in each Natural Flow Basin using a specific format (.INF) and in Mcm/month. Illustrations with the data are presented in Appendix A

To conclude, for the power plant, physical characteristics are defined similarly to the reservoir, minimum release is also defined with maximum releases and operational constraints. Illustrations with the data are presented in Appendix A. Finally, for the Economic Input, a constant price of 75 U$D/MWh was calculated from past years prices, although they are not perfectly well adjusted due to the latest fluctuations in the country's economy.

4. DRAFT-YIELD ANALYSIS

The draft-yield analysis studies the yield behavior of a reservoir given a target draft. This analysis provides a graphical summary which is a very useful presentation to improve the understanding of the yield characteristics as well as being an operational guide.(Basson et al. 1994)

Yield analysis can be conducted in two stages, the first based on historical sequence and the second on stochastic sequences. In this study, just the historical study is performed and the stochastic one is for future research. The key aspect of this analysis is the draft-yield response diagram, with its various definitions of yield such as base, firm, total, average, secondary and non-firm yield. To make aware of these concepts, in the following a brief description of each term will be presented:

- Target Draft: Is the volume of water that the operator intends to withdraw from the reservoir over a specified period of time.
- Yield: Is the volume of water which is abstracted over a specific period of time. Although it is desirable that the yield should be the same as the target draft, this is not always possible.
- Base Yield: Is the lowest volume of water abstracted over a specific period of time to satisfy a given target draft under a specific operating policy. That is to say, the minimum possible yield that was abstracted, in this case, in the hole historical sequence, for the desirable target draft. This period normally coincides, logically, with dry periods. When the target draft is low, the reservoir will generally be able to provide the same volume that is requested. In these cases, the base yield equals the target draft. But as target draft increases, the reservoir begin to lose the ability to supply continuously the target draft, so the yield for a given period will be lower than the requested.
- Firm yield: Is defined as the maximum base yield that can be abstracted over a specific period of time. This is an important concept, because it determines the critical target draft that causes the reservoir trajectory to touch the minimum operating level. In other words, is the maximum possible volume of water that can be abstracted without reducing the yield below the target draft, and is unique for the historical sequence.

Up to this yield, the reservoir is able to provide always, in all the historical sequence, the target draft (this mean base yield equal to target draft). Afterwards, for higher target drafts, base yield decrease and the reservoir will not be able to reach the volume needed in all the sequence.

- Secondary yield: Is the yield that can be abstracted in excess of the target draft. This value provides a valuable measure of the potential for further development of a system. It is important to differentiate instantaneous and average secondary yield. The instantaneous value can fluctuate within the draft-yield line (imaginary line of yield=target draft) and the maximum possible installed abstraction. In contrast, the average secondary yield, is the average value of all these instantaneous values taken over the full period under consideration. This value is important because it indicates the storage in exceeds for export.
- Non-Firm yield: Is the yield above base yield to meet the target draft. Clearly, this concept is not present up to the firm yield where all the volume requested is provided. The Non-Firm yield can be seen as a measure of the magnitude by which the system may fail to meet the specific target draft during dry periods. Similarly to the secondary yield, Non-Firm yield can be stated with instantaneous o average values. Instantaneous values cannot exceed the difference between target draft and base yield. Instead, the average value would be the average of all these instantaneous values in the period of time considered. If the average value is added to the base yield, the average value is defined. And if the secondary yield and non-firm yield are added to the base yield, the total average yield is determined.
- Average yield: Is the arithmetic average yield released to meet the target draft. For target drafts less or equal to the firm yield, average yield is equal to the base yield (and target draft). For higher target drafts, average yield is always less than target draft, and is the sum of average non-firm yield and base yield. Hence, average yield provides a measure of the ability of the reservoir to meet the target draft.
- Total Yield: Is the sum of the yield to meet the target draft and the yield in excess of the draft. So, is the sum of the average yield and the secondary yield. It will always be less than the mean annual runoff, as spillage and evaporation are present. This value may exceed the target draft in certain cases and lower in others.

In the case study, the analysis is based on historical inflow records, with the initial storage as it was measured at that time and the given river flow variability. The simulation was performed from 1977 till 2019 with a daily step which is the maximum time step available in HEC-ResSim. Time-Series were prepared with the help of HEC-DSSVue 2.0.1 an introduced when creating the alternative. Apart from this, the initial elevation was 32.87m and the flow computation method was chosen as Period Average.

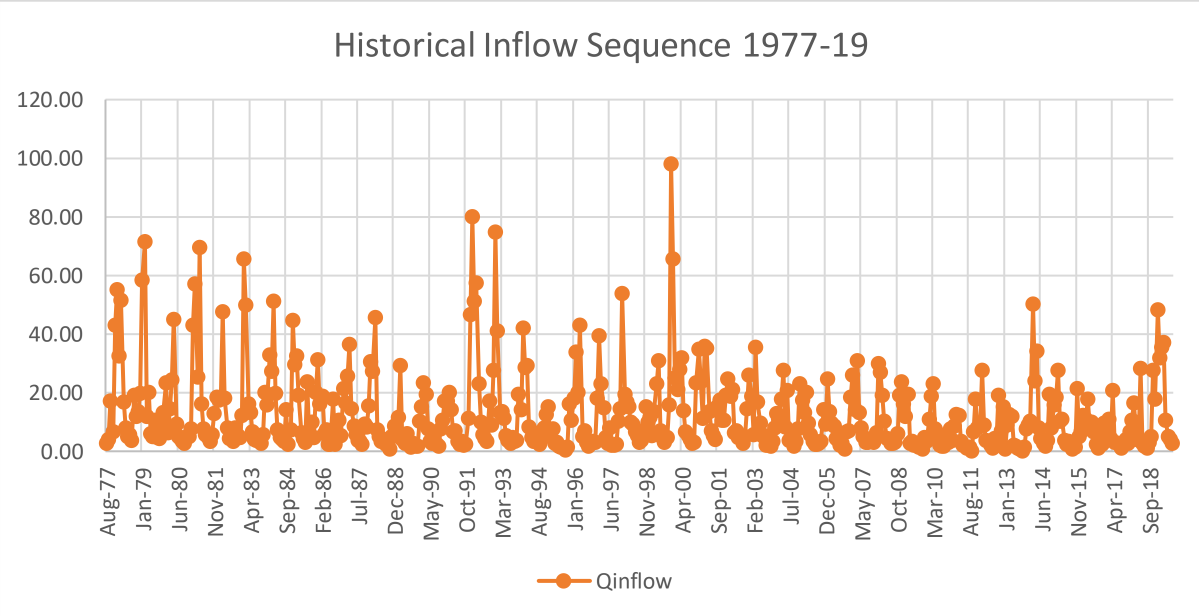

Figure 39 : Historical Inflow Sequence 1977-19

Regarding the operation set, constraints mentioned in chapter 2 were inserted (maximum discharge, minimum operating level, maximum operating level) as operational rules.

With reference to the draft-yield response diagram, in this case study, it is important to understand that the yield behavior of the reservoir will represent the performance of the power plant. Other demands are guarantee with the discharge of the power plant, so target draft will depend just on the plant. Having said that, in the operation set, an operation rule is added with the maximum possible abstraction which is 24 m^3/s. Also, another operation rule is created, which will only release from the power plant and in this case is a minimum release function, and will be run for 4 m^3/s, 6 m^3/s, 7 m^3/s, 7.5 m^3/s, 9 m^3/s, 10 m^3/s, 12 m^3/s, 18 m^3/s, 24 m^3/s. It is important to remind that the power plant present 4 turbines of 6 m^3/s each with an installed capacity of 6MW each.

During the simulations, the firm yield is identified for 7 m^3/s, as it can be seen in the following figure;

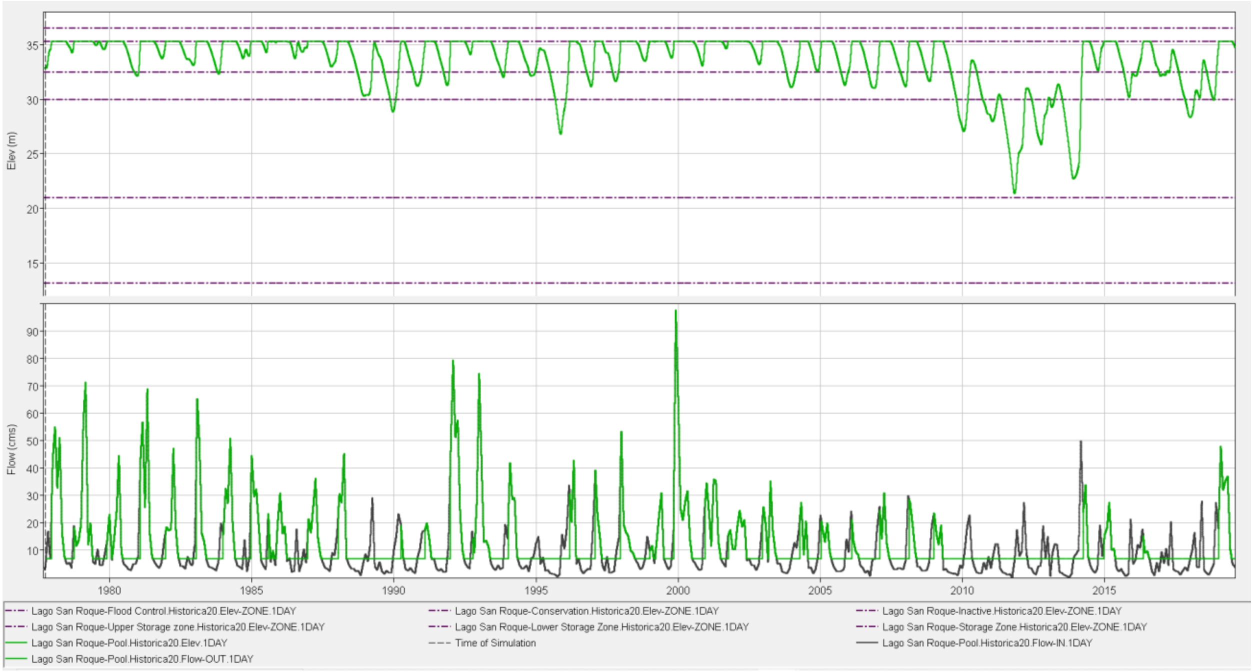

Figure 40 : Firm Yield

Reminding the concept of firm yield, it is when the critical target draft causes the reservoir trajectory to touch the minimum operating level (Basson et al. 1994). Once this is identified, it is expected that the storage o elevation trajectory touches the minimum operating level one or several times. This can be easily check with a simulation with a target draft equal to 7.5 m^3/s.

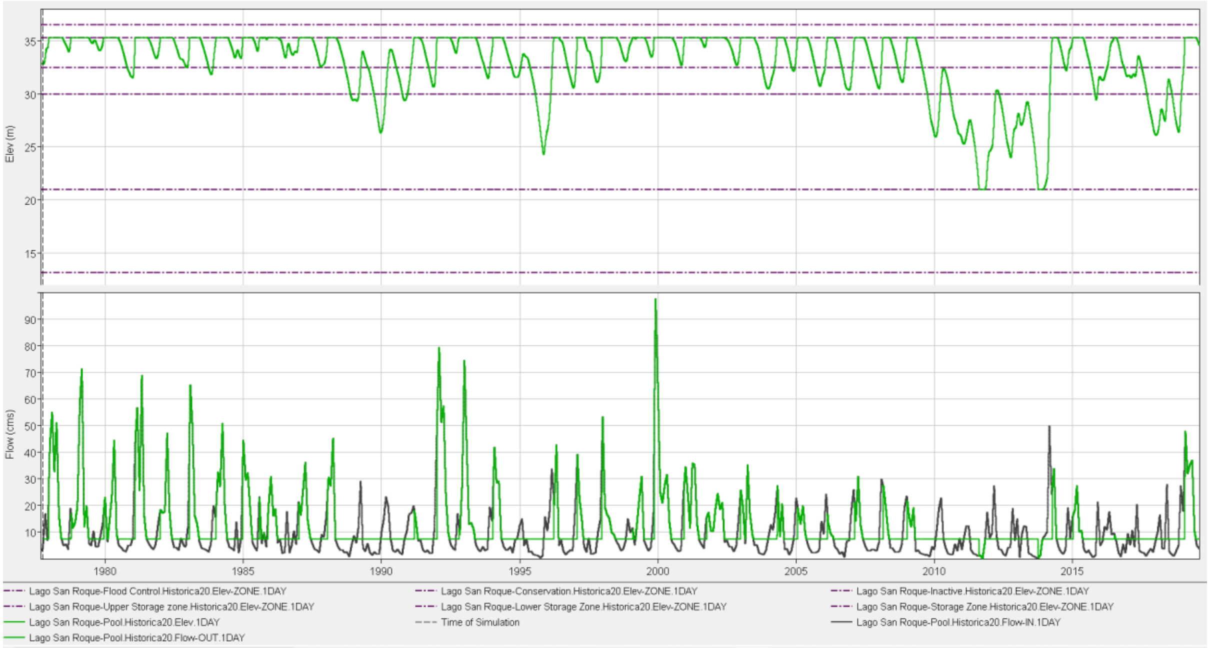

Figure 41 : Elevation and Flow for 7.5m3/s

Not just with the elevation, but the minimum flow which was set equal to 7.5 m^3/s, was not able to be provided by the reservoir in all the historical sequence. Between 2010 and 2015 the discharge from the plant was reduced to 0 due to the minimum operating level rule set in the software.

Instead, for target draft below 7 m^3/s, the reservoir is able to provide the requested volume in all the time-series. The following figures is for a target draft of 6 m^3/s, and it is possible to identify that the level does not reach 21m and the minimum flow abstracted is always the target draft.

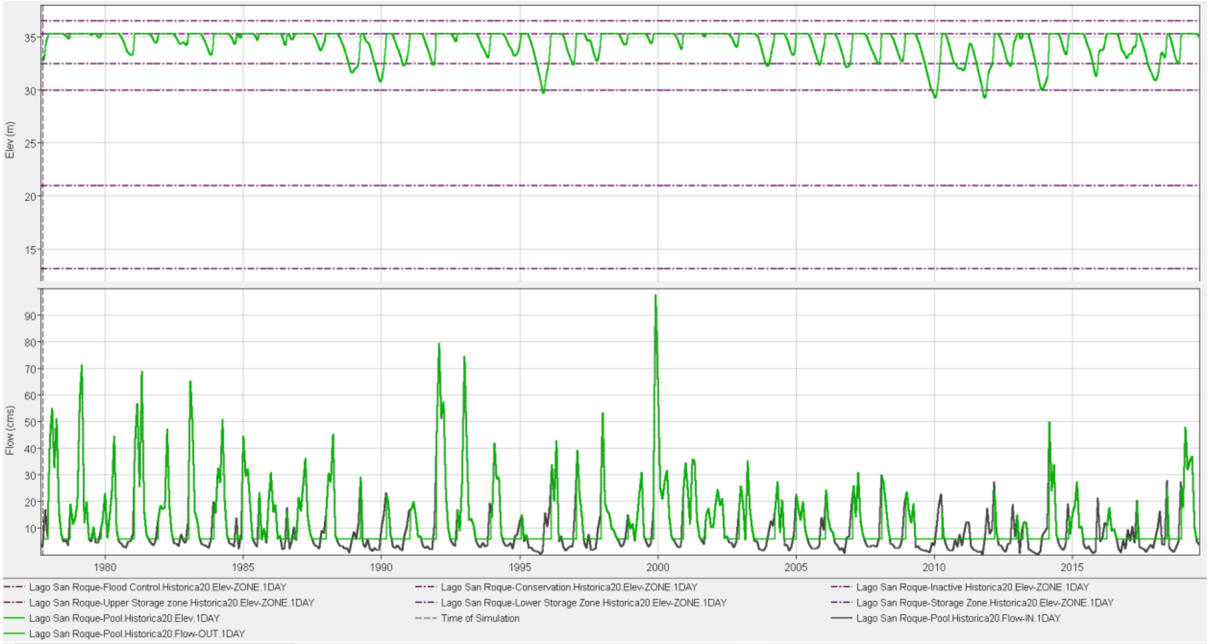

Figure 42 : Elevation and Flow for 6m3/s

Therefore, running HEC-ResSim with every target draft mentioned before, the draft-yield response diagram is created.

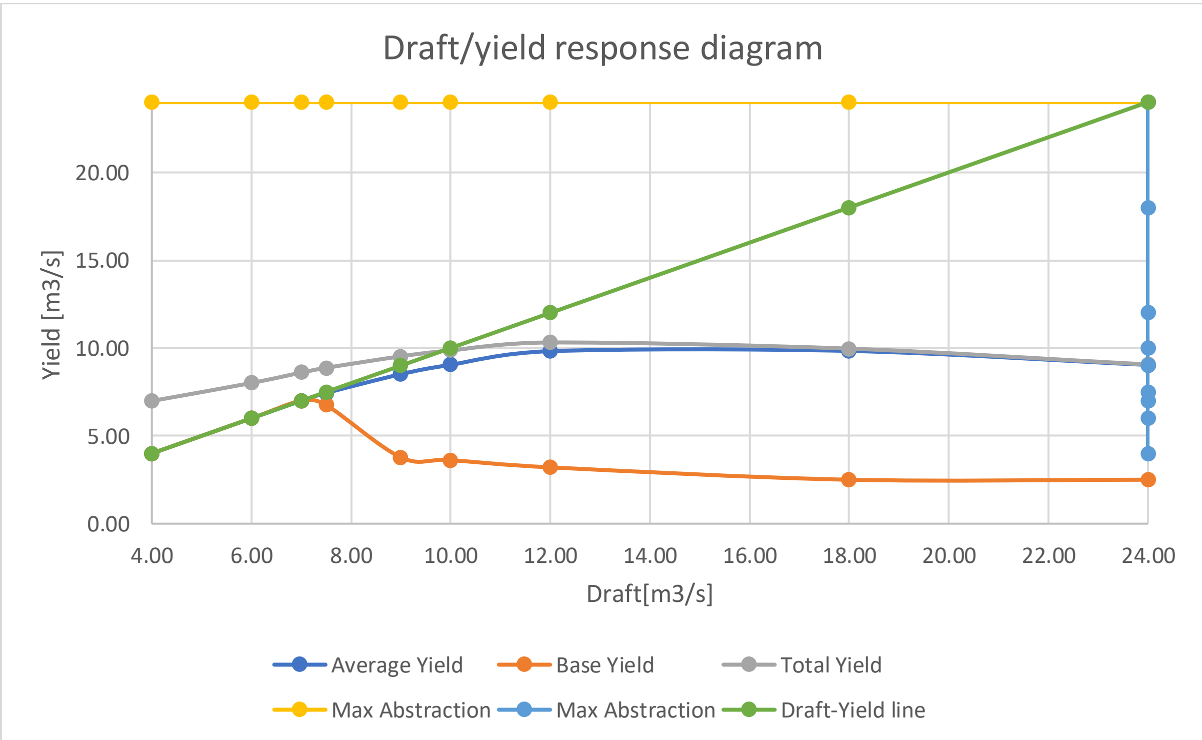

Figure 43 : Draft-Yield Response Diagram in m3/s

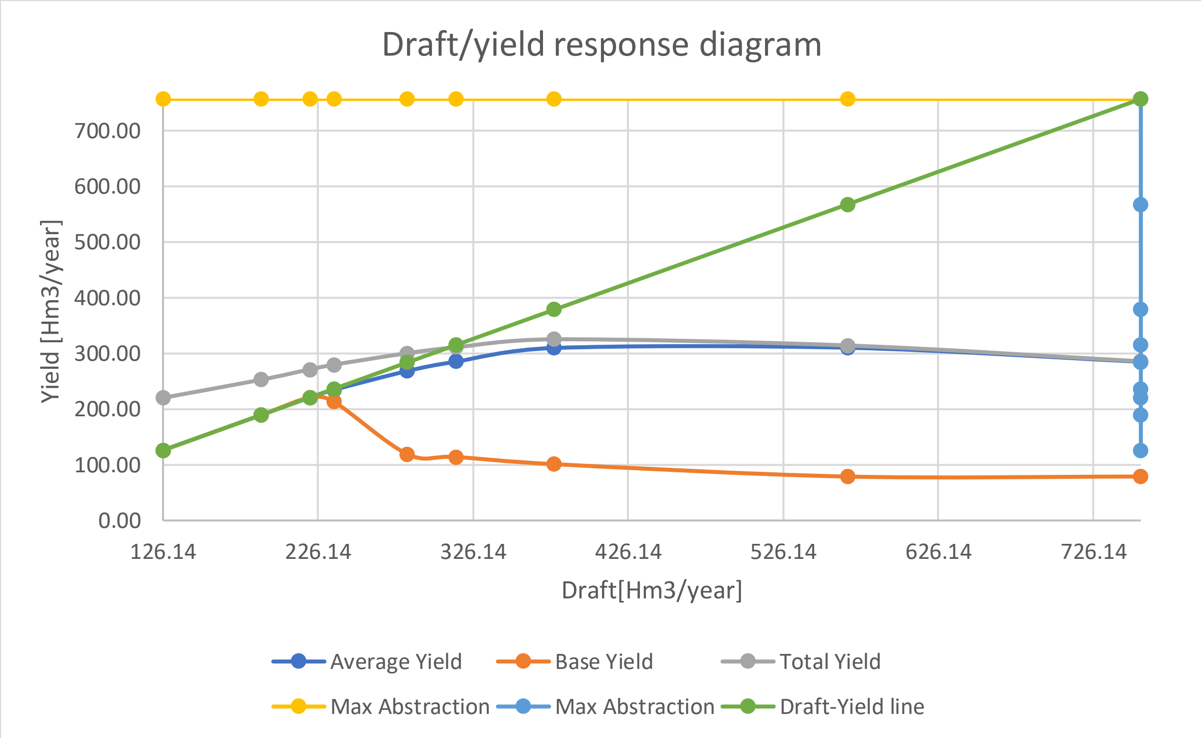

Figure 44 : Draft-Yield Response Diagram in Hm3/year

These diagrams are Average draft-yield response diagram, they were obtained by calculating the mean of all instantaneous values which are also annual mean values of the daily release from the power plant calculated by HEC-ResSim. In order to understand these values, some results of the simulation are presented below.

The values were calculated with the help of MATLAB and it was necessary to separate the calculation for target drafts lower and higher than the firm yield. Hence, results of 4 m^3/s and 9 m^3/s are given.

We can see in Figure 45, that for a minimum target draft of 4 m^3/s, the yield was always higher than this value. In fact, Figure 46 shows that the year with lowest yield also presented values higher than the target draft. This shows that the reservoir is able to provide permanently 4 m^3/s and more.

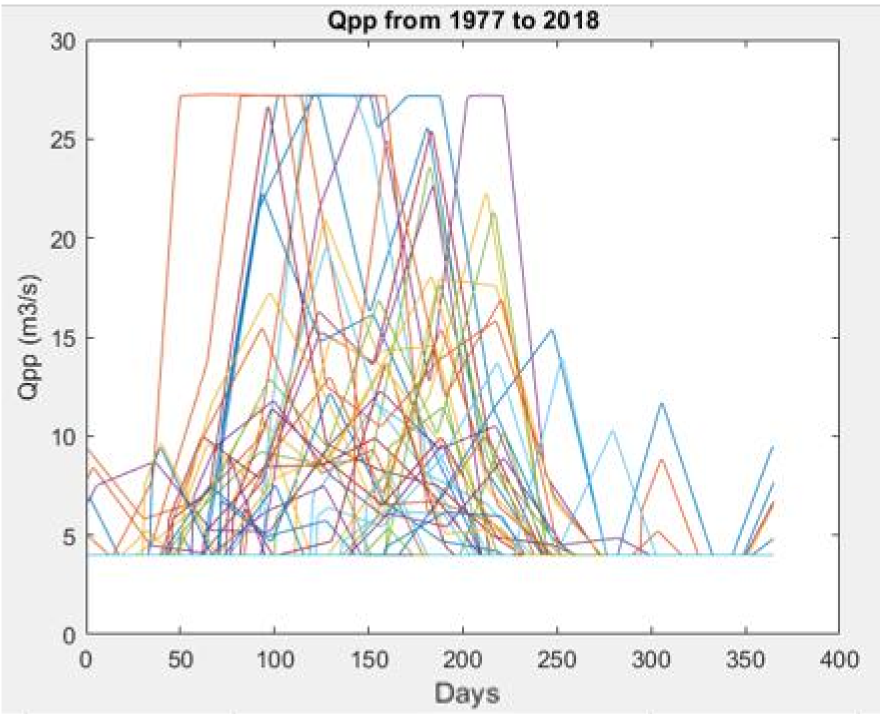

Figure 45 : Power Plant daily releases for 4m3/s

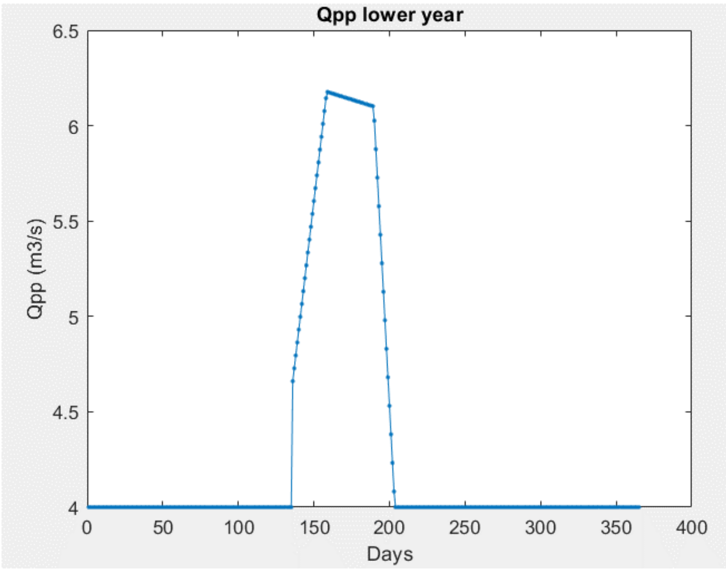

Figure 46 : Year with Lowest Yield

So, the base yield will obviously be 4 m^3/s, and the total average yield is the average of the average yield of each year.

In addition, for 9 m^3/s, which is higher than the firm yield, the non-firm yield concept appears, and it can be easily seen in Figure 47 that the reservoir fails to provide $9m^3/s$ permanently.

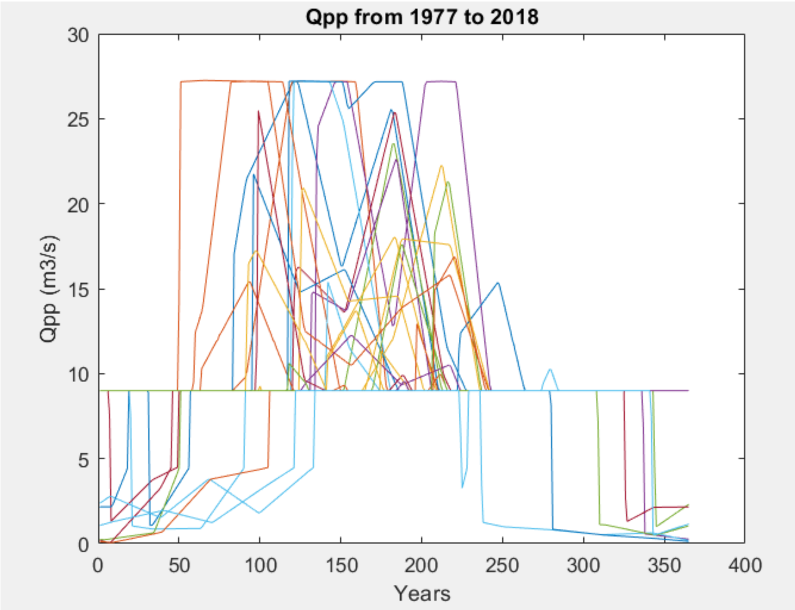

Figure 47 : Power Plant daily releases for 9m3/s

And now, the base yield will not be equal to the target draft, and it is shown in Figure 48.

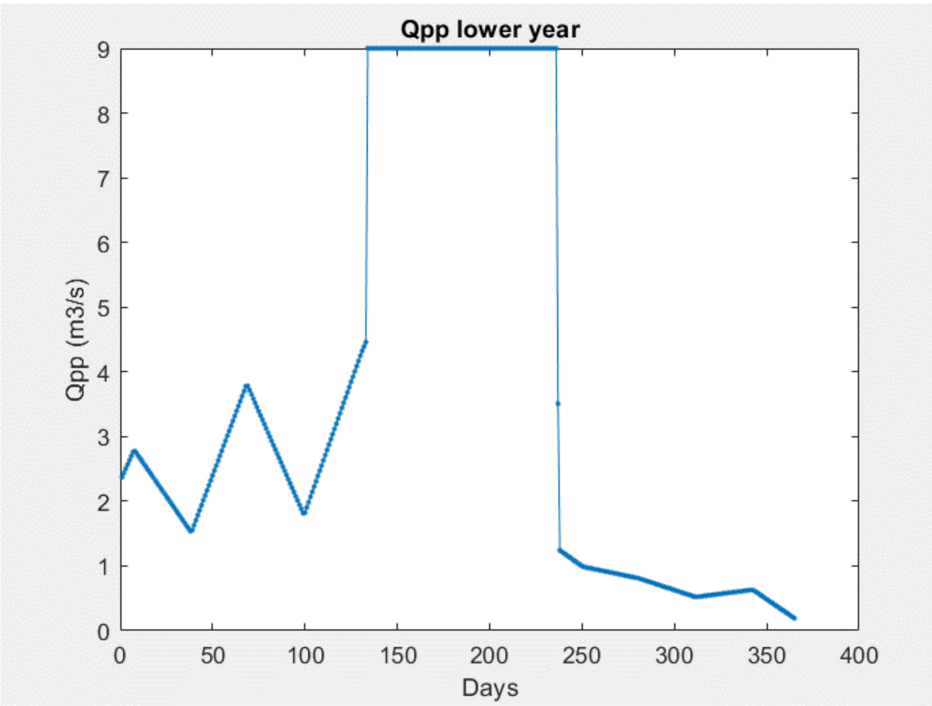

Figure 48 : Year with Lowest Yield

The average of this year will be the base yield presented in the draft-yield response diagram, which is 3.78 m^3/s or 119.12 $Hm^3/year$. Although, in average, the reservoir was able to supply 8.51 m^3/s to meet the target draft, and with a total average yield of 9.53 m^3/s.

In the process to create the draft-yield response diagram, other useful diagrams are performed which provide utile information. These can be, for example, the instantaneous values of secondary yield and non-firm yield for each target draft, which statistically furnish profitable outcomes.

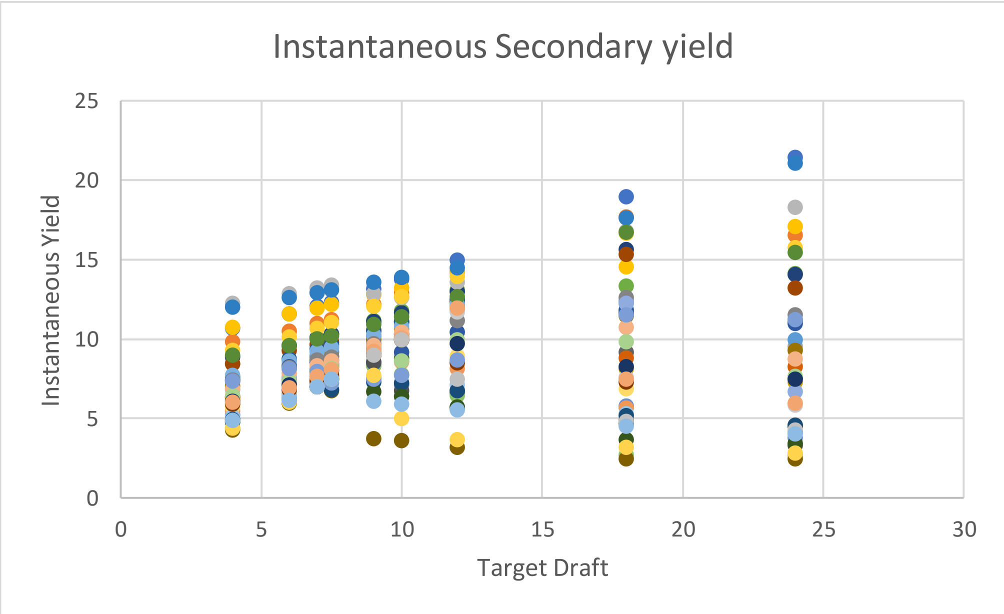

Figure 49 : Instantaneous Secondary Yield Diagram

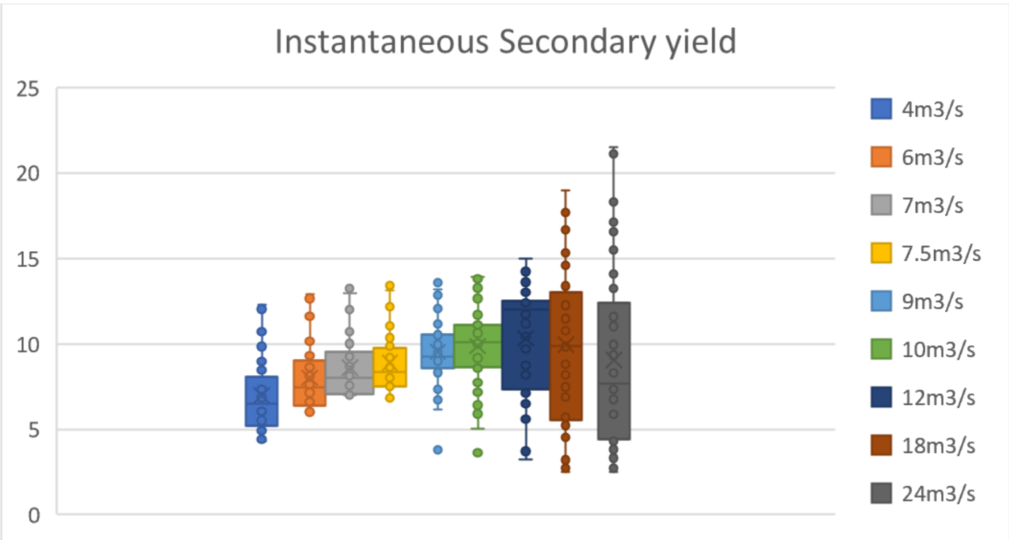

Figure 50 : Instantaneous Secondary Yield Boxplot

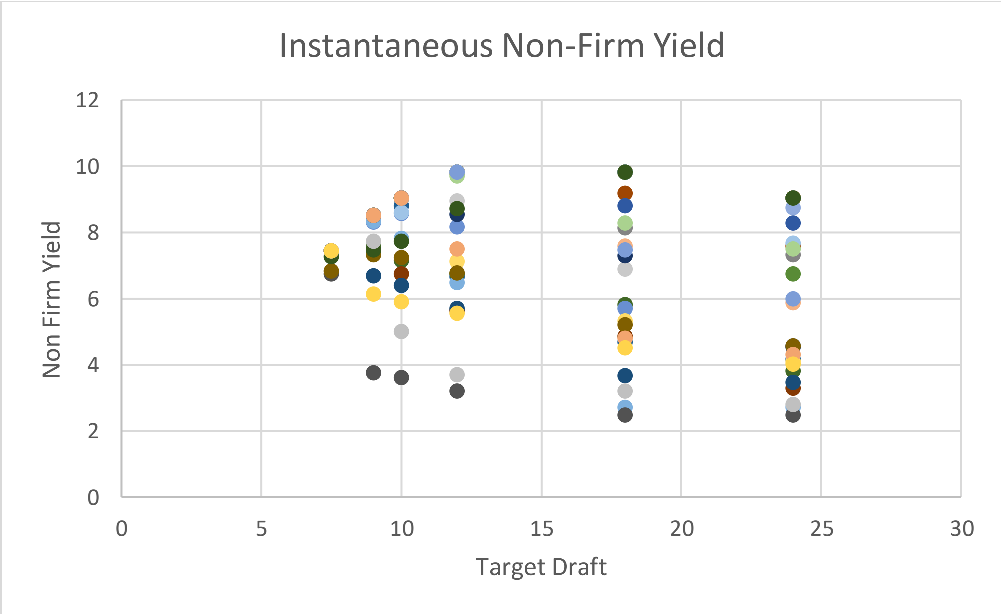

Figure 51 : Instantaneous Non-Firm Yield Diagram

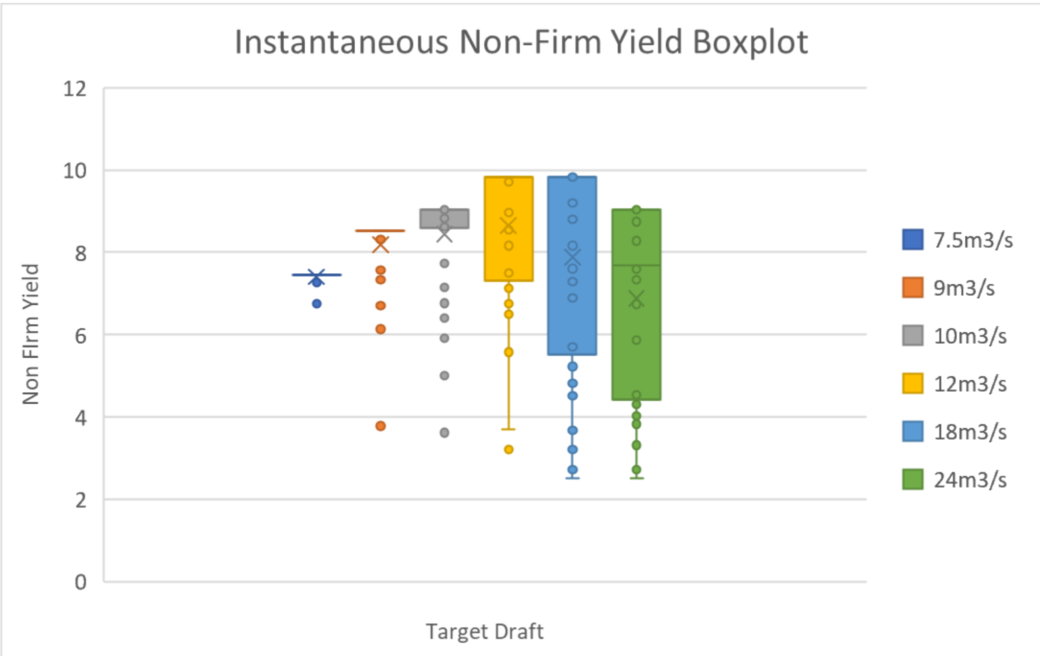

Figure 52 : Instantaneous Non-Firm Yield Boxplot

As stated before, these diagrams are relevant, and several conclusions can be withdrawn. In the case of the secondary yield, those values indicate the average secondary yield of each year and this is helpful to understand statistically the level of support available for export from a reservoir/system. And, in the case of the instantaneous non-firm yield, again, the diagram indicates the average non-firm yield of each year, and statistically can be viewed as a measure of the degree by which the reservoir may fail to meet a specific target draft.

Apart from these diagrams, another statistical analysis is provided by HEC-ResSim with the help of the tool HEC-DSSVue for each simulation. This statistical analysis is composed by several math functions that can calculate and plot different statistical parameters, in particular, the Duration Analysis is performed. This analysis provides a summary indicating the percent chance of a variable (in this case releases from the power plant, elevation and storage) to be equal or above a certain value during the time-series. *"The Duration Analysis function computes the duration curve for a regular interval time series data set and stores the results in a new paired data set."* (CEIWR-HEC 2009)

"The x-values represent the percent of time exceeded computed by:

*E = 100 * [M /(n+1)] (Weibull plotting positions), percent of the time the value is equaled or exceeded.*

M = the rank position of the value.

n = number of values."(CEIWR-HEC 2009)

Each target draft has different graphs, so the simulation and the analysis are computed for every target draft. Exporting the output to Excel, the results for 12 m^3/s are presented below with a description of the interpretation of these graphs (other results are presented in the appendix B).

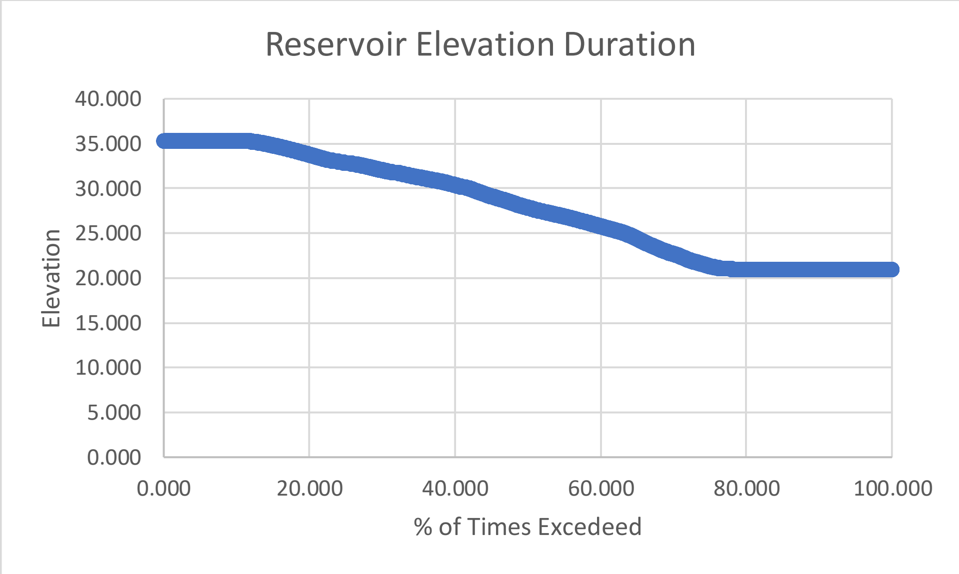

Figure 53 : Reservoir Elevation Duration for 12m3/s

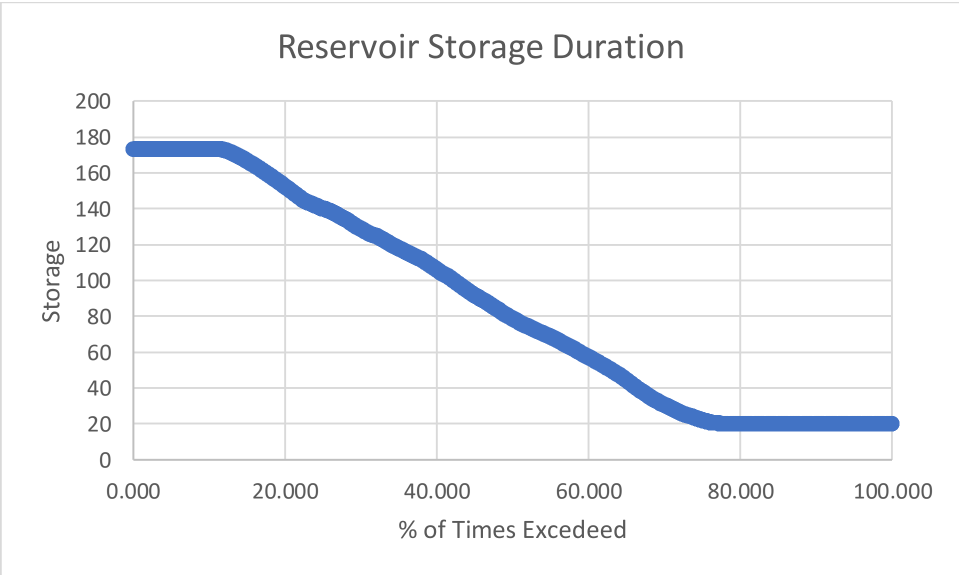

Figure 54 : Reservoir Storage Duration for 12m3/s

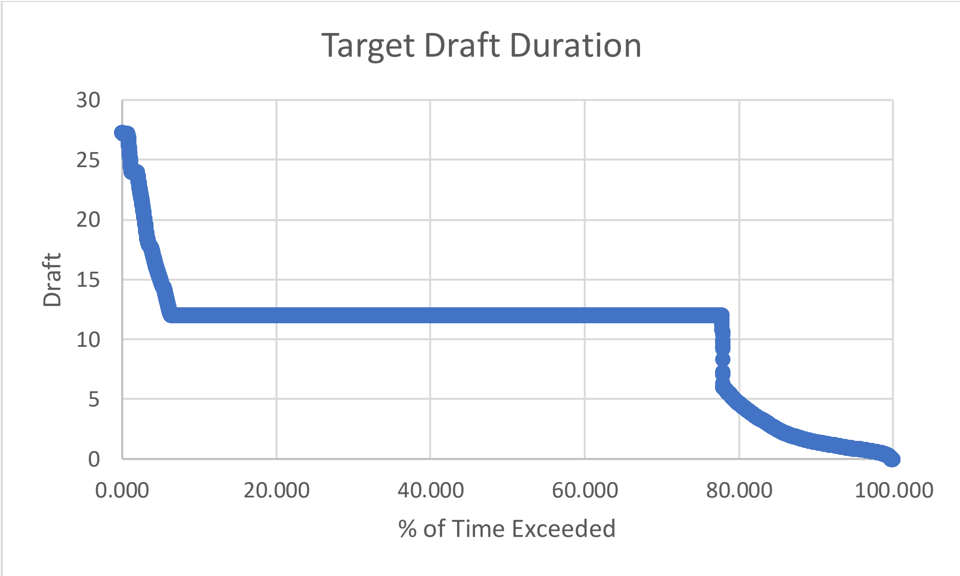

Figure 55 : Reservoir Target Draft Duration for 12m3/s

The concept is the same for each variable, so the explanation is referred to the last graph. For a target draft of 12 m^3/s, the percentage of times that the power plant releases more than 12 m^3/s is approximately 7%. So, it means that from the whole sequence, just 7% of the times the target draft was exceeded, which can be interpreted as the times the reservoir was able to release as a secondary yield. This percentage obviously, will be higher for lower target drafts and lower for higher target drafts. This is shown in the following figure:

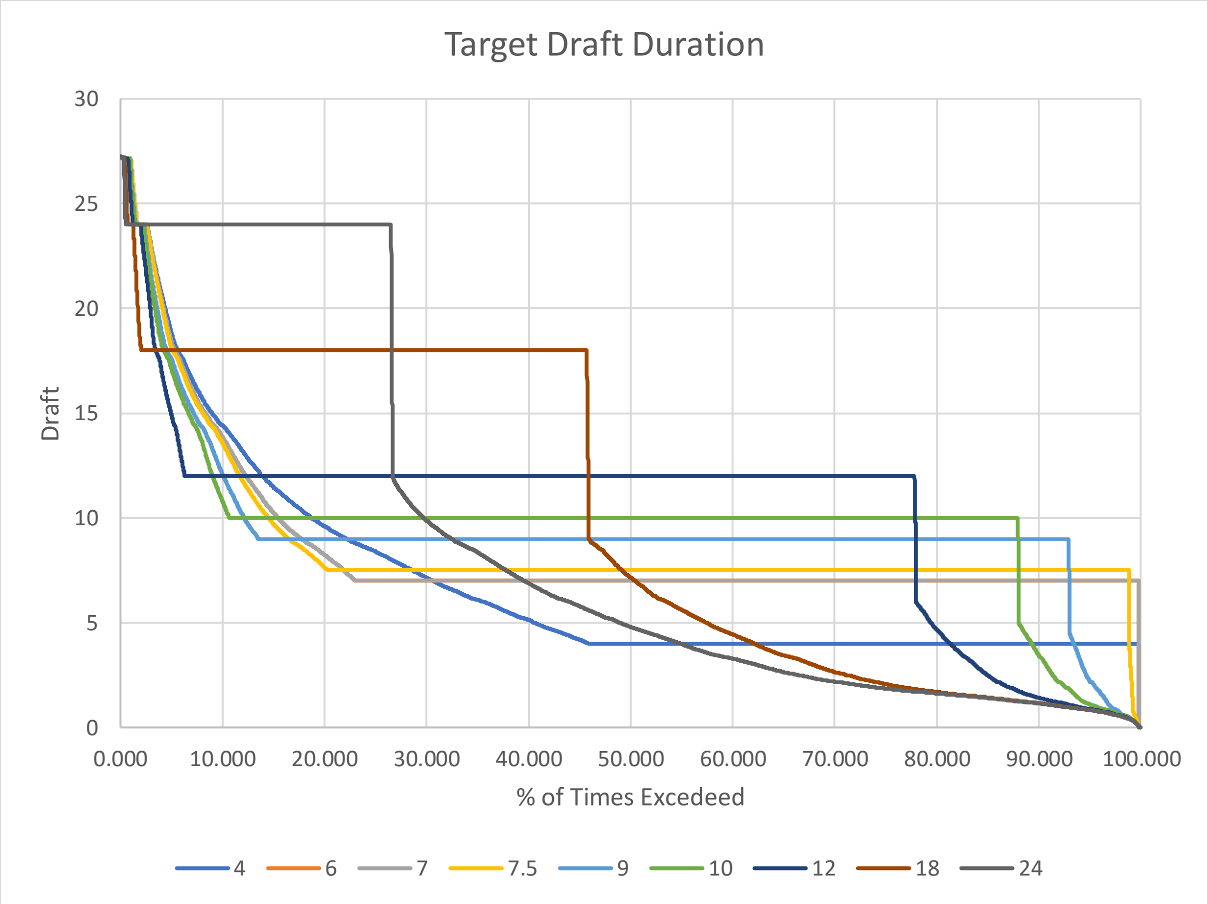

Figure 56 : Target Draft Duration Comparison

Another key aspect that can be obtained from this analysis, is the percentage of times that the reservoir was able to release the target draft or more, and it can be visualized as the point break of the constant line. For example, again for 12 m^3/s, the percentage of times that the reservoir provided 12 m^3/s or more is approximately 78%, which is an indication of the reliability of supply. Obviously, for 7 m^3/s, the percentage is 100% as it is the firm yield.

Hence, as an aid to the draft-yield diagram, these graphs give a statistical meaning which can be useful for the operator to understand the risk of releasing more than the firm yield as well as the reliability of releasing more.

5. MODEL APPLICATION

In this chapter, several sections will be developed, with different applications of the simulation model. First of all, a comparison with the optimization model done with Aquarius is faced which shows the applicability of the models. Secondly, some indexes are defined and presented to show dissatisfaction and satisfaction indicators. And finally, an operational analysis is performed for short and medium-term decisions that serves as a guide for future decisions.

5.1. Optimization

To begin with, as stated before, once a reasonable operating strategy has been reached through simulation analysis based on the historic inflow sequences, applying an optimization technique could be useful to obtain an "optimal" operation. Despite not getting the same results, the comparison is useful because is a guide to judge if the simulation strategy "follows" the optimal operations. It is important to remember the fact that the optimization model have complete foreknowledge of the future events, this mean that decisions will be held knowing all the inflows till the end. As a consequence of this, the calculation process will not face the risk of, for example, empty the reservoir for a future rain that may not come. Instead, the simulation model act as in real life, and the calculation is done with a fixed time step and the decisions will follow different rules and guide curves. (Basson et al. 1994)

Therefore, it is interesting to compare the result of both models to judge similarity, and specially in critical periods, which decision are the best possible.

In order to compare, both models are, obviously, run with the same inflow and same constraints. In Aquarius, minimum storage and maximum storage are operational constraints for the reservoir, and minimum release is put as a constraint for the power plant. In the first place, minimum release will be 7 m^3/s, which in Aquarius is set with the units requested, 18.14 Mcm. The figures below, shows the storage variation in all the time series (remember that Aquarius uses a monthly time step) and the power plant flow from Aquarius:

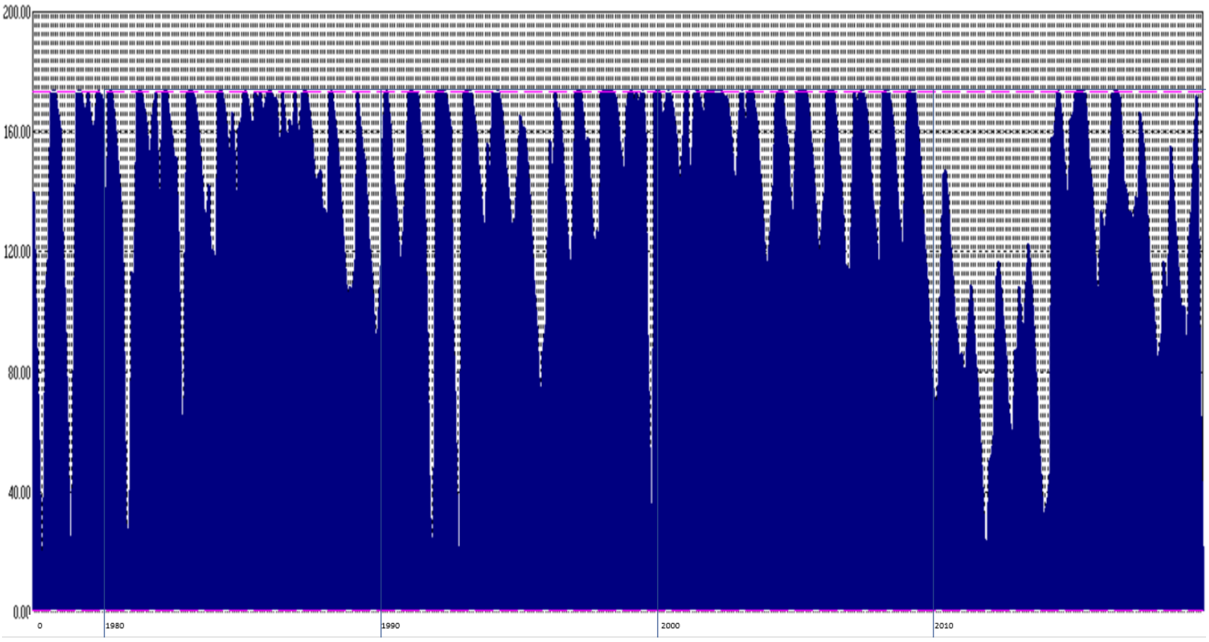

Figure 57 : Storage Computed with Aquarius

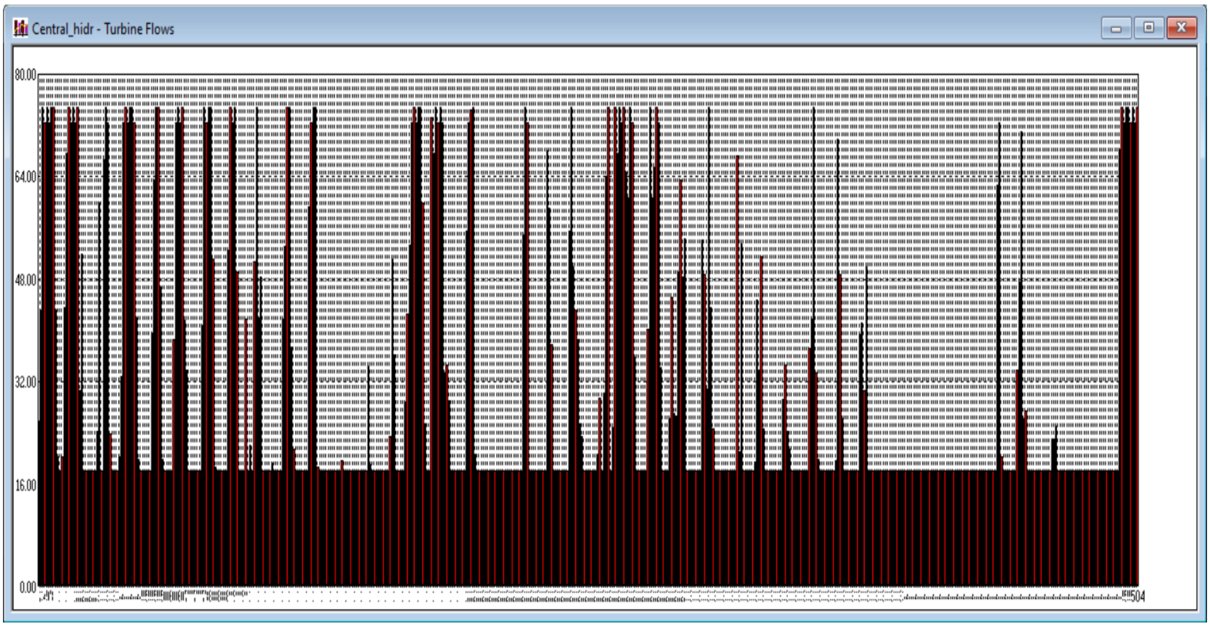

Figure 58 : Turbine Flows Computed with Aquarius

On the other side, for HEC-ResSim same operational constraints were inserted, and minimum release from the plant equal to 7 m^3/s as a operation rule. The following figure show the output:

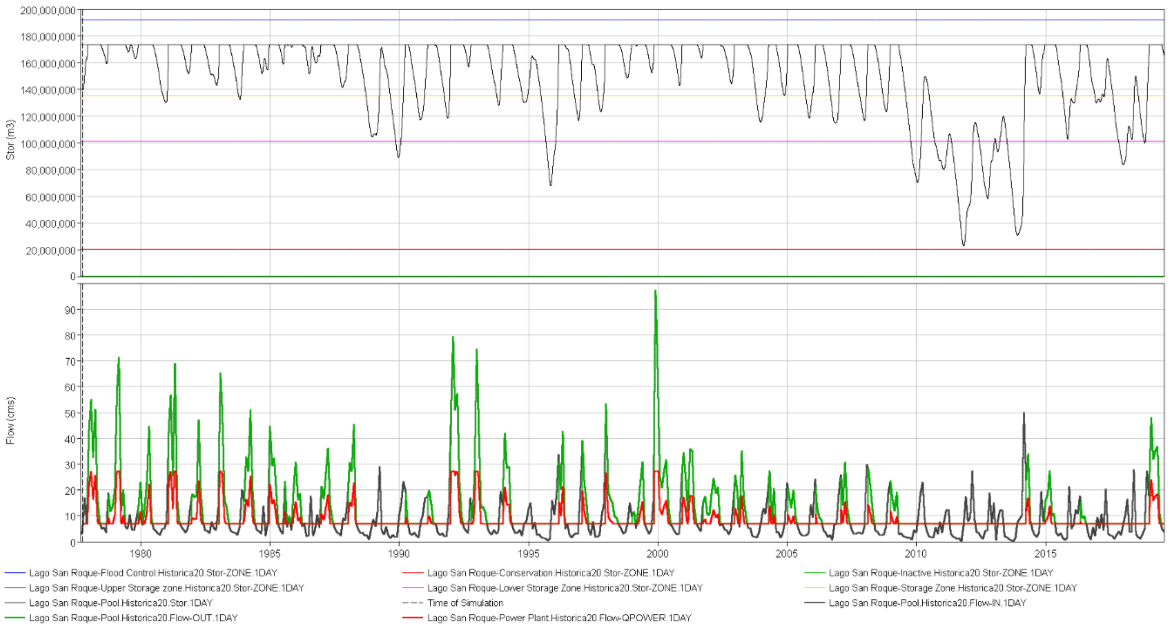

Figure 59 : HEC-ResSim Output

From these graphs, it is possible to arrive to the conclusion that both models operate with similar criteria. It is easy to compare for example, in the critical period between 2010 and 2015, that both models follow the same values, with the same shape at the same time. Unfortunately, both software have different time step in the calculation so it is difficult to perform a more deeply analysis with parameters that can express correlation.

Anyway, peak values and shape can express similarity. As said before, the periods between 2010 and 2015 shows the same shape and peak values differ from few meters. Also, between 1995 and 2000 is easy to observe concordance. However, it is also true that there are some peak values in the optimization output, that are not present in the simulation output. For example, in 2000, in HEC-ResSim the green line in the flow diagram shows a release of approximately 100 m^3/s, which is not withdrawn completely from the power plant but most of it by the valves. This mean energy that could have been produce which is translated in economic losses. In contrast, Aquarius in the same period, as it has complete foreknowledge of what inflows are arriving, produces energy as much as possible withdrawing everything with the turbine, and when the inflow arrived, it fulfills the reservoir. Simulation model will not reproduce this ever due to the risk of not knowing what is coming as the calculation window is shorter.

5.2. *Performance Assessment Indexes*

In this section, some indexes will be presented as a result of the historical simulation. It is important to mention that there are not universal indexes, but each reservoir, according to the aim of the analysis, will have their own representative indexes. Moreover, these indexes should not be many, but a reasonable number that describes what it is being searched. Owing to this, the indexes should meet the following characteristics (Ronnie de Camino V. y Sabine Müller Proyecto IICA/GTZ n.d.):

- Their definitions should be practical
- They should be measurable and easily measurable
- They should be tangible
- They should be significant
- They should be able to be reproduce for other simulations
- They should express pragmatic and clear information
- They should be sensitive for changes in the system

Having clarified this, the definition of the indexes is presented below:

1. **Ld**: Is defined as the maximum period with deficit for all the simulation. So is a measure of the historical longest shortage for that operating policies. Its units are days
2. **Lcd**: This index quantifies the percentage that represent the Ld with respect to the total numbers of days with deficit. Obviously, is a dimensionless index.
3. **Md**: Is defined as the maximum deficit recorded in all the time series for a given period, in this case a year. This can be intended as the year with less yield, same values with the base yield, and its units are Hm3/year
4. **Mcd**: This index evaluates the ratio between Md and the annual target draft, giving a perception of how far was the maximum deficit from the actual demand for that operating policies.
5. **CDV**: This index provides the concrete deficit of volume accumulated in all the time sequence for a target draft. Its units are m3

6. **Vr**: This is the historical volumetric reliability of the reservoir for a given operating policy. That is to say, the relation between the total volume of water supplied to meet the demand with respect to the total water demanded.
7. **R**: The resilience index, indicates the number of times that the deficit was null in proportion to the number of times that there was deficit. Gives a measure of the capability of the reservoir to adapt to stress situations and the probability of non-deficit.
8. **V**: The vulnerability index, represent the proportion of days with deficit related with the whole number of days of the series. This value should be equal to $1 - \frac{\%\, of\ times\ of\ excedeed}{100}$ seen in chapter 4.

In contrast with the indexes defined before, which measure dissatisfactions, the following indexes represent the satisfaction or advantages of operating above the target draft whenever is possible.

9. **Lcs**: This index quantifies the percentage that represent the historical longest surplus with respect to the total numbers of days with surplus. Obviously, is a dimensionless index.
10. **Mcs**: This index evaluates the ratio between the maximum surplus recorded in all the time series for a given period and the annual target draft, giving a perception of the highest benefit the reservoir can reach in all the sequence for that operating policies.
11. **CSV**: This index provides the concrete surplus volume accumulated in all the time sequence for a target draft. Its units are m3
12. **S**: Sustainable index provides an idea of how much does this operating policies are profitable. That is to say, the relation between the total volume of water supplied with respect to the total water demanded
13. **B**: The benefit index, represent the proportion of days with surplus related with the whole number of days of the series
14. **A**: The aid index, indicates the number of times with surplus in proportion to the number of times that the surplus was null. Gives a measure of the capability of the reservoir to increase its production and the probability of succeeding.

The purpose of this section is to analyze, primarily, the performance of the reservoir after the firm yield. Thence, the indexes will be computed with the help of MATLAB for simulations results with target drafts higher than 7 m^3/s. Anyway they can be determined, in particular the surplus indexes, for target drafts lower than the firm yield.

In Table 2, a summary of the indexes for different target drafts is exhibit:

	7.5	9	10	12	18	24
Ld	80.000	191.000	243.000	276.000	655.000	1409.000
Lcd	0.576	0.182	0.134	0.082	0.079	0.126
Md	213.038	119.117	114.140	101.158	78.919	78.919
Mcd	0.901	0.420	0.362	0.267	0.139	0.104
CDV	1161051	10085143	19438533	43798060	162952039	298501863
Vr	0.992	0.945	0.904	0.820	0.553	0.385
R	108.921	13.565	7.437	3.539	0.843	0.361
V	0.009	0.069	0.119	0.220	0.543	0.735
Lcs	0.065	0.093	0.113	0.117	0.250	0.470
Mcs	1.183	1.059	0.986	0.860	0.554	0.378
CSV	28812928.8	11082619.6	-2352857.9	-33467558.9	-160356992.5	-298026696.1
S	1.190	1.061	0.988	0.862	0.560	0.386
B	0.203	0.135	0.107	0.063	0.021	0.009
A	0.255	0.157	0.120	0.067	0.021	0.009

Table 2 : Indexes

5.3. Operational Analysis

In the present section, an operational analysis is accomplished to complement the operational strategies of the reservoir. As an aid for the reservoir operators in evaluating the reservoir performance, operational guidelines are set. These operational guidelines give an idea of whether the reservoirs level (or storage) is within the historical levels and maintain predetermined reliabilities of supply. There are several operational guidelines with different purposes that can be performed with stochastic sequences or with historical sequences. In this case, a short-term and medium-term probabilistic behavior operational guidelines are implemented with the historical sequence from 1977 to 2019.

On one hand, for short-term operational guidelines, a simple and effective way of calculating them is through the probabilistic performance of the reservoir level under a specific operating policy for the period of operation before the next decision date. In other words, this is done by simulating the reservoir level under projected demand conditions, based on the historical inflow sequence, and then bring all the simulated years together. This is done for different target draft starting and finishing in April, hence a superposition of all the years simulated will be presented for each target draft. The following figures condense this process,

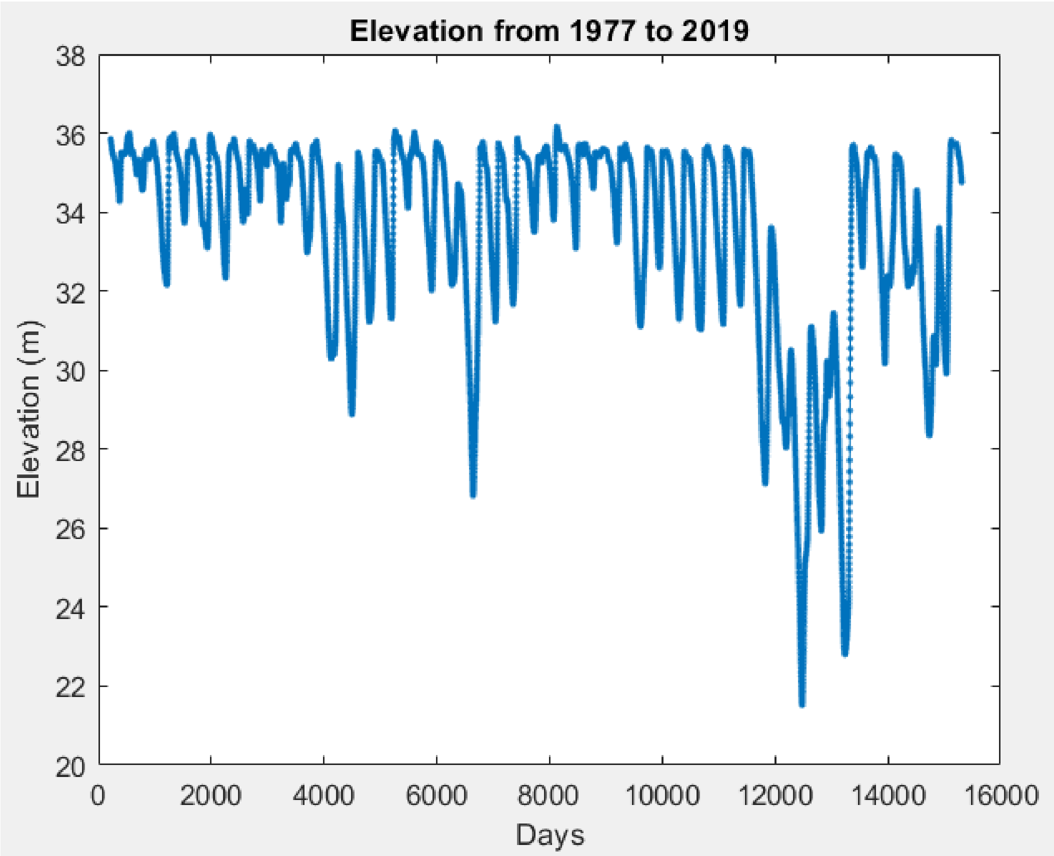

Figure 60 : Elevation from 1977 to 2019

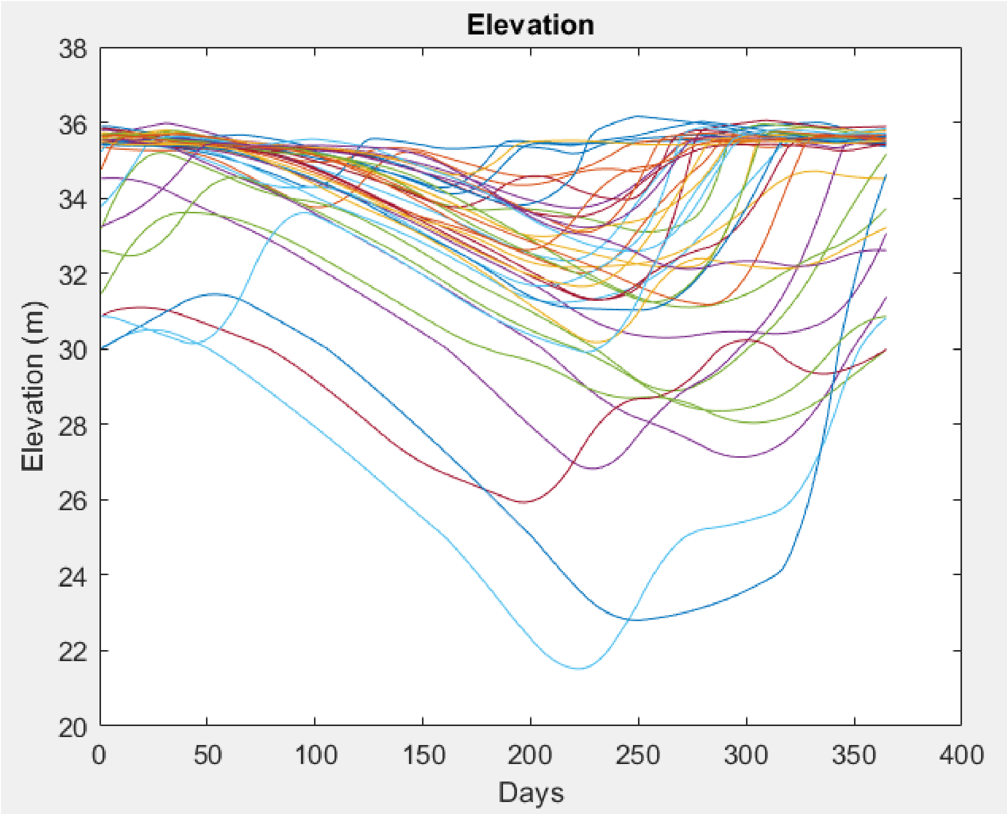

Figure 61 : Elevations from April to April

Figure 60 and Figure 61 are showing the simulated elevation for a target draft of 7 m^3/s. In the same way, simulations with a target draft of 9 m^3/s, 10 m^3/s, 12 m^3/s, 18 m^3/s and 24 m^3/s were performed. Special attention should be placed on the non-regularity amongst sequences as well as the different final elevations level resulting from many of the sequences.

Afterwards, as these diagrams does not give any practical information, boxplots of probable reservoir level can be created. These boxplots display the range of elevation level on a monthly basis, which can be expected to experience with different levels of probability. As awaited, the probable range of elevation level will be increased progressively in the wet months, from November to April, and progressively decrease for the dry moths, April to October. Figure 62 show the boxplot for a target draft of 7 m^3/s,

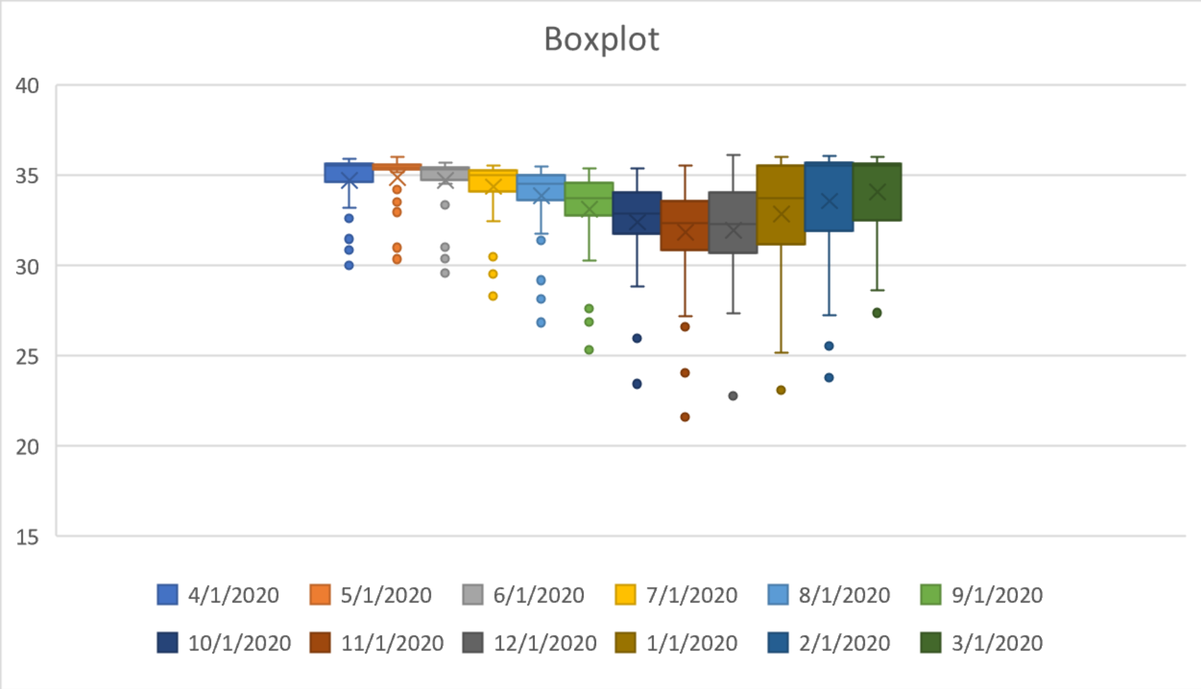

Figure 62 : Boxplot Elevation per Months

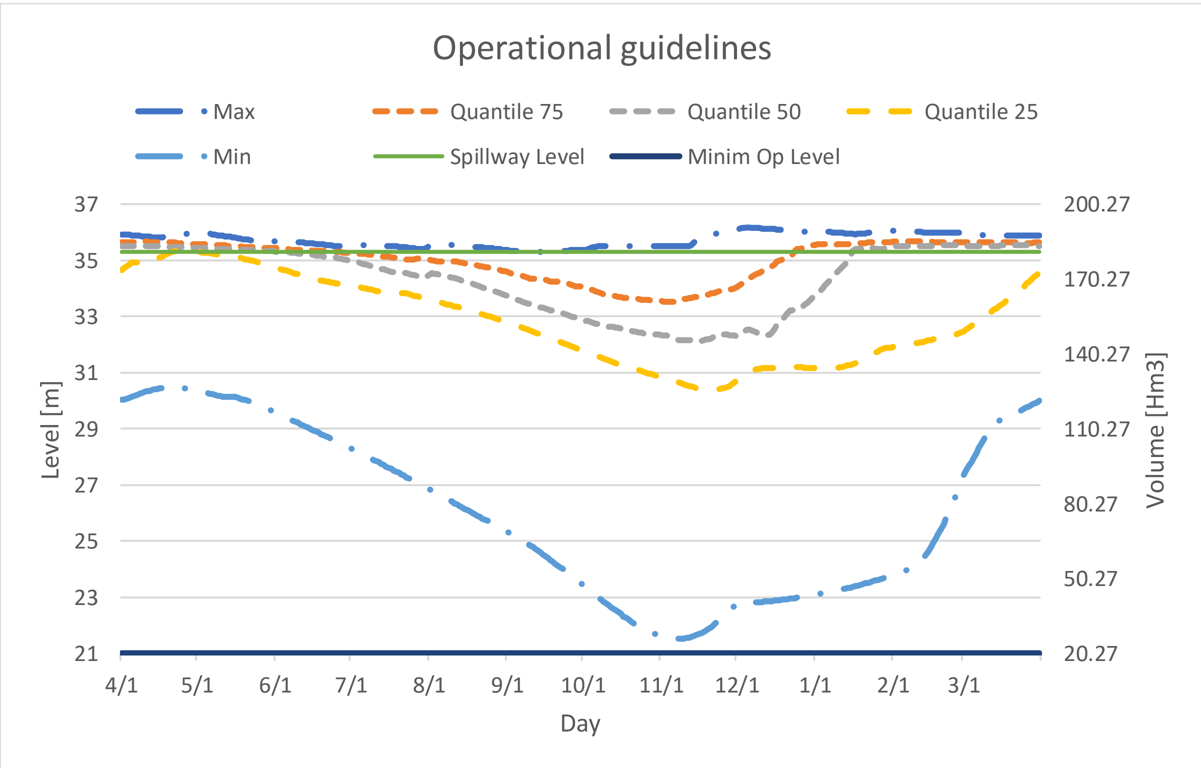

Figure 63 : Operational guidelines

And Figure 63 summarizes the boxplot into lines that represent the boxplots through the whole year, starting and finishing April 1st, for a given operating policy, and indicating Volumes at the end of the period. In this diagram, a follow-up of the current situation is necessary to illustrate the operator and allow him to judge based on the possible future results of any operation strategy. Hence, over the decision period, the operator can plot the actual reservoir level and by comparing, he can review the expected state of the reservoir with the actual state of the same. This will help him to evaluate whether the reservoir level is decreasing more than expected or whether the reservoir level is higher than expected and an increase in production can be evaluated (Basson et al. 1994). Also, it is important to clarify that the volumes are indicated in the diagram are approximate since elevation and volume relationship is not linear, so a scale error is present. The operational guidelines for other target drafts are presented on the appendix

On the other hand, in addition to the annual operational guidelines to assist the operator during decision dates, it is also important to have a perspective of how the decisions taken in the present will jeopardize the performance in the next years. Again, as in this study simulations are being held just with historical sequences and not stochastic sequences, the same output elevations that were used in the short-term guidelines are employed. However, the calculation procedure changes, considering that if a superposition of series of 3 years simulated in the entire simulation is used, the number of series superposed will be just 14 and will not be representative probabilistically. In the interest of increasing the number of superposed results, the approach proposed is to hold a time window of 3 years and move it every 1 year, increasing the number to 39 series of simulations superposed. Figure 64 shows the results of this approach, again for 7 m^3/s,

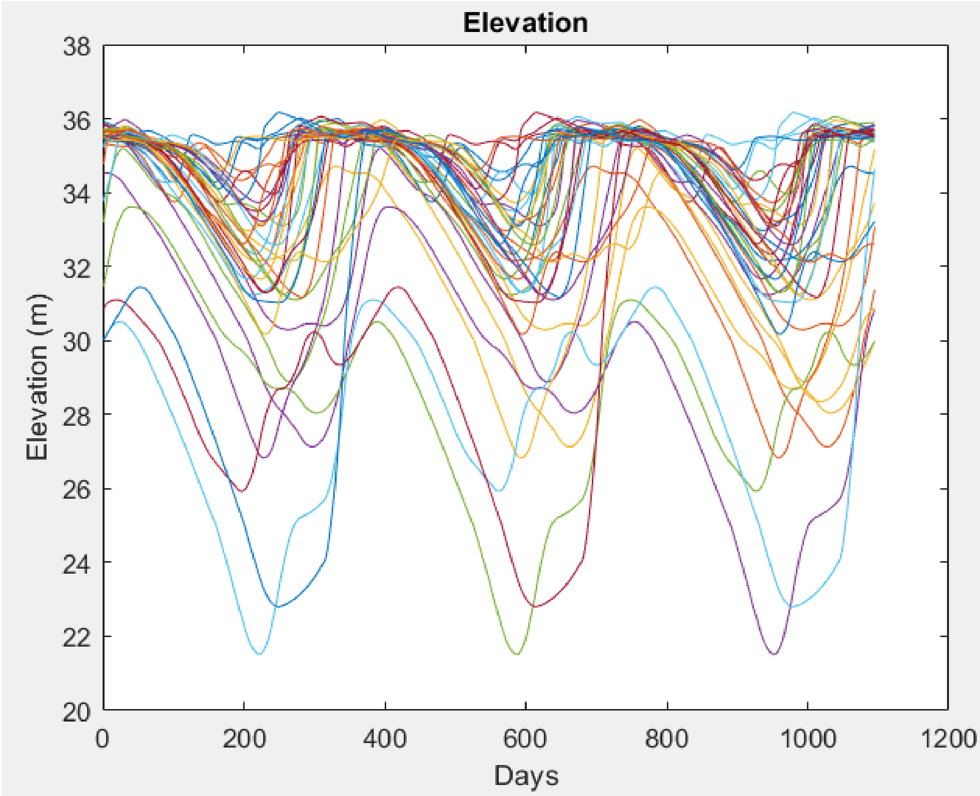

Figure 64 : Elevation simulation for 3 years

Again, as these diagrams does not give any practical information, boxplots are calculated and summarized into operational guidelines, starting April 1st and finishing April 1st but 3 years later, for a given operating policy, and indicating Volumes at the end of the period. One more time, it is important to remember that the volumes in the diagram are approximate. Figure 65 show the medium-term operational guidelines,

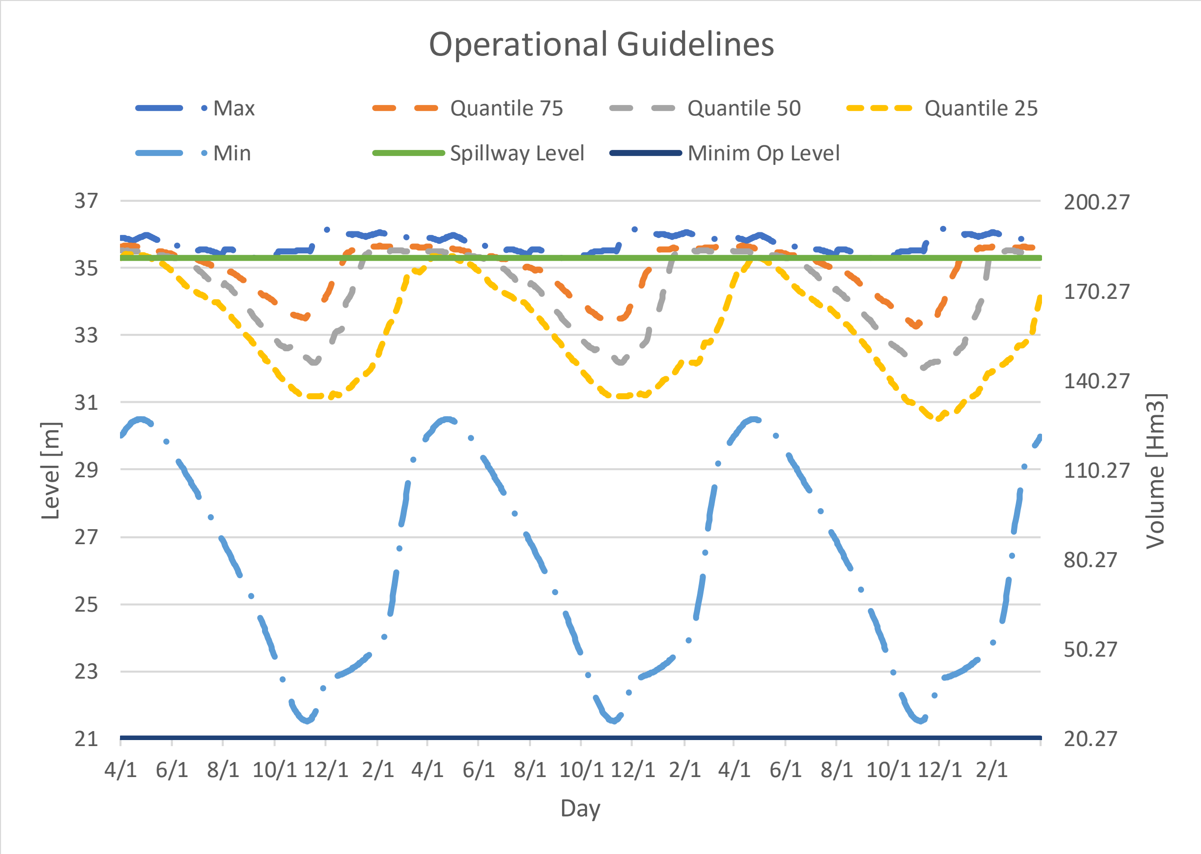

Figure 65 : Medium-Term Operational Guidelines

These operational guidelines show projected elevation levels as well as the minimum levels which should be observed to avoid water curtailment. It is important to note how quartile 25 and quantile 50 perceives a progressive reduction over the years which can threaten the reservoir performance. The operational guidelines for other target drafts are presented on Appendix C and it is necessary to warn that they will be more chaotic because they are target drafts which are higher than the firm yield, so they may not be sustainable for 3 years or even a year.

6. SENSITIVITY TO INITIAL CONDITIONS

In order to measure the sensitivity or reliability of the draft-yield analysis and the indexes performed, variations in the initial conditions are computed and, with the new results, new draft-yield diagrams and new indexes will be calculated. There are several criteria that could be considered when varying the initial conditions, using the average level observed $\pm$ standard deviation, using the median level of all the history with its 1st and 3rd quartile or, the approach that is selected, for different percentages of storage within the limits. A part from this method, monthly variations in the target draft is also impose as another way of analyzing sensitivity.

With the intention of reproducing this sensitivity to different initial conditions together with describing severe initial conditions, two different values were chosen. In a practical way, it is considered the values of storage between the minimum operating level and the spillway level, 21 m and 35.3 m respectively, as the operational range. Therefore, the levels which correspond to the 20% and 100% of storage between that ranges were chosen.

Percentage	Storage	Corresponding level
100%	173.576670	35.30
70%	127.585162	32.50
50%	96.924156	29.60
20%	50.932648	25.89
0%	20.271642	21.00

Table 3 : Storages within the range

The calculation process for the diagrams and indexes are the same mentioned in the respective chapters, just a change in the alternative from HEC-ResSim is done in the lookback elevation putting 25.89 m and 35.3 m.

Afterwards, with the aim of reproducing the sensitivity to monthly variations in the demand, dimensionless coefficients for each month were calculated considering the monthly variations in the demand of the water treatment plant with respect to the average demand throughout the year. With this dimensionless coefficients and different target drafts proposed, monthly variations per each target draft is calculated. A summary is presented in Table 4,

	TargetDraft	4	5	6	7	7.5	8	9	12	18	24
Months	Coefficient	m3/s	m3/s	m3/s	m3/s	m3/s	m3/s	m3/s	m3/s	m3/s	m3/s
January	1.03	4.11	5.14	6.17	7.19	7.71	8.22	9.25	12.33	18.50	24.66
February	0.98	3.93	4.91	5.90	6.88	7.37	7.86	8.84	11.79	17.69	23.58
March	1.02	4.09	5.12	6.14	7.16	7.67	8.19	9.21	12.28	18.42	24.56
April	0.96	3.85	4.82	5.78	6.75	7.23	7.71	8.67	11.56	17.34	23.13
May	0.97	3.87	4.84	5.81	6.77	7.26	7.74	8.71	11.61	17.42	23.22
June	0.93	3.71	4.64	5.57	6.49	6.96	7.42	8.35	11.13	16.70	22.27
July	0.96	3.85	4.81	5.77	6.73	7.21	7.69	8.66	11.54	17.31	23.08
August	1.01	4.04	5.05	6.06	7.07	7.57	8.08	9.09	12.11	18.17	24.23
September	0.99	3.95	4.94	5.92	6.91	7.41	7.90	8.89	11.85	17.77	23.70
October	1.03	4.11	5.13	6.16	7.19	7.70	8.21	9.24	12.32	18.48	24.64
November	1.01	4.05	5.06	6.08	7.09	7.60	8.10	9.11	12.15	18.23	24.30
December	1.11	4.44	5.55	6.66	7.77	8.32	8.88	9.99	13.31	19.97	26.63
Average	1.00	4.00	5.00	6.00	7.00	7.50	8.00	9.00	12.00	18.00	24.00

Table 4 : Monthly variation

The calculation process will change in the rule of minimum release imposed in HEC-ResSim. A function date rule is created and the target draft in table 4 is imposed for each month as shown in the following figure.

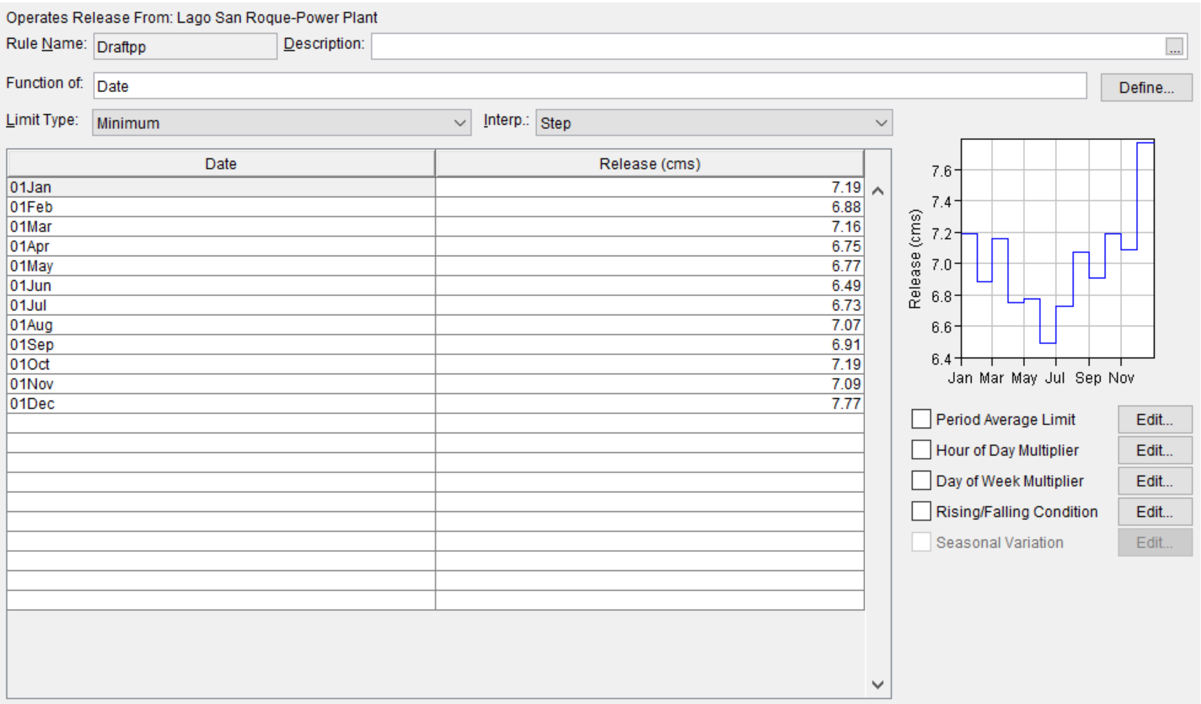

Figure 66 : Monthly variations in HEC-ResSim

6.1. First Alternative: $S_0 = 20\%$

Firstly, draft-yield Diagram and indexes calculated for the initial conditions of 25.89 m was computed, and results are presented below.

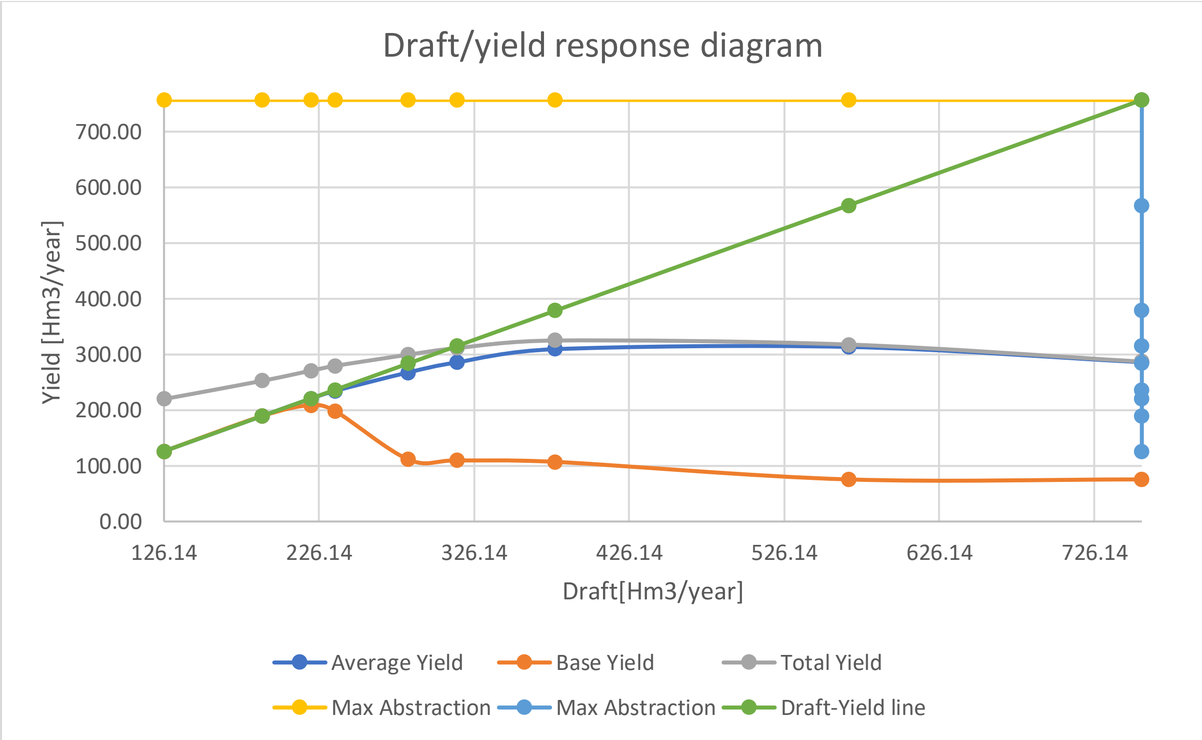

Figure 67 : Draft-Yield Diagram for 25.89 in [Hm3/year]

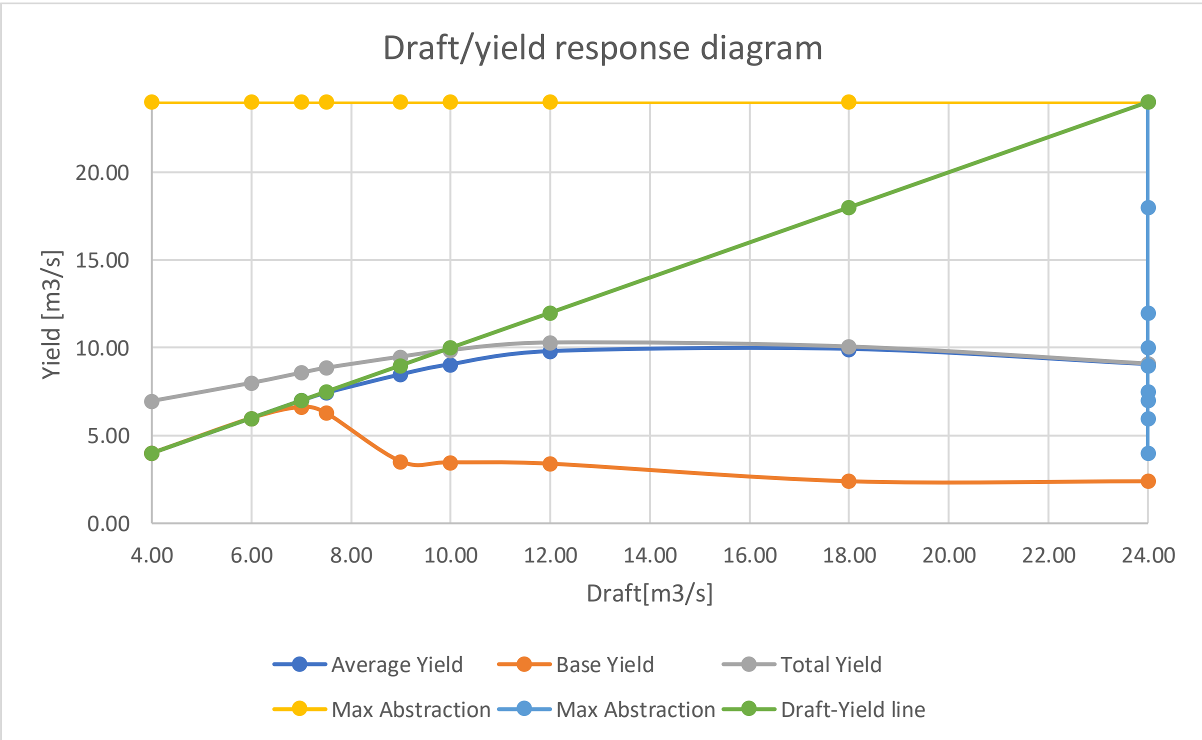

Figure 68 : Draft-Yield Diagram for 25.89 m in [m3/s]

	7	7.5	9	10	12	18	24
Ld	34	102.000	195.000	227.000	276.000	656.000	1394.000
Lcd	1	0.689	0.181	0.132	0.083	0.081	0.126
Md	208.968107	198.251	111.264	109.611	107.097	75.533	75.533
Mcd	0.94661931	0.838	0.392	0.348	0.283	0.133	0.100
CDV	180647.086	1263980	10473049	18961801	43900624	160624250	297411487
Vr	0.99872479	0.992	0.942	0.906	0.819	0.559	0.388
R	448.382353	102.236	13.160	7.888	3.573	0.898	0.378
V	0.00222528	0.010	0.071	0.113	0.219	0.527	0.726
Lcs	0.0558111	0.063	0.090	0.124	0.100	0.267	0.385
Mcs	1.22610367	1.181	1.055	0.987	0.859	0.560	0.379
CSV	33306799.2	28567422.5	10630748.9	-1987538.8	-33520904.2	-157923644	-296775038
S	1.235117	1.188	1.058	0.990	0.862	0.566	0.389
B	0.2134302	0.188	0.131	0.094	0.058	0.019	0.012
A	0.27134299	0.232	0.150	0.103	0.061	0.019	0.012

Table 5 : Indexes for 25.89 m

It is important to notice that the yield for 7 m^3/s , in this alternative, present 34 day of deficit. So, the firm yield is lower than 7 m^3/s as in the standard initial conditions. The following tables represent clearly these changes by the ratio between Standard initial condition and the Alternative condition.

Standard Initial Condition / Alternative Condition				
Draft	Base Yield	Non firm yield	Average yield	Total Yield
4	1	0	1	1.00210567
6	1	0	1	1.00088906
7	1.0563909	0	1.00130361	1.00236787
7.5	1.07458734	0.59669261	1.00069848	1.00151815
9	1.07057827	0.95426683	1.00260058	1.00313244
10	1.04131607	0.9706252	0.99773074	0.99895395
12	0.94454098	1.03096515	1.0010529	1.00118235
18	1.04482285	0.97206834	0.98959983	0.98927375
24	1.04482285	0.97951405	0.99676105	0.9958785

Table 6 : Draft-yield diagram comparison

Standard Initial Condition / Alternative Condition							
	7.5	9	10	12	18	24	Average
Ld	0.784	0.979	1.070	1.000	0.998	1.011	0.974
Lcd	0.835	1.007	1.016	0.993	0.970	0.999	0.970
Md	1.075	1.071	1.041	0.945	1.045	1.045	1.037
Mcd	1.075	1.071	1.041	0.945	1.045	1.045	1.037
CDV	0.919	0.963	1.025	0.998	1.014	1.004	0.987
Vr	1.001	1.002	0.997	1.001	0.989	0.994	0.997
R	1.065	1.031	0.943	0.990	0.939	0.956	0.987
V	0.939	0.972	1.054	1.007	1.030	1.012	1.002
Lcs	1.032	1.035	0.916	1.173	0.935	1.220	1.052
Mcs	1.002	1.003	0.999	1.001	0.989	0.996	0.998
CSV	1.009	1.043	1.184	0.998	1.015	1.004	1.042
S	1.001	1.002	0.998	1.000	0.988	0.993	0.997
B	1.081	1.036	1.141	1.094	1.097	0.706	1.026
A	1.102	1.042	1.158	1.101	1.099	0.703	1.034
Average	0.994	1.018	1.042	1.018	1.011	0.978	

Table 7 : Indexes comparison

Through this tables it is easy to identify which indexes and yield suffer more changes between the two conditions, the closer to one, less changes have undergone. For the draft-yield diagram the more significant change is given in the firm yield which causes changes in the non-firm yield and base yield but just for the closer yields. For example, the non-firm yield of 7.5 m^3/s suffers an increase of 40% with respect to the standard simulations. Regarding the indexes, in average, there are not big changes. However, an increase in the index Ld for 7.5 m^3/s is seen, which means that there were more days with deficits and is not a factor that should be overlooked.

6.2. Second Alternative: $S_0 = 100\%$

This section provides the draft-yield diagram and indexes for the initial elevation of 35.3 m.

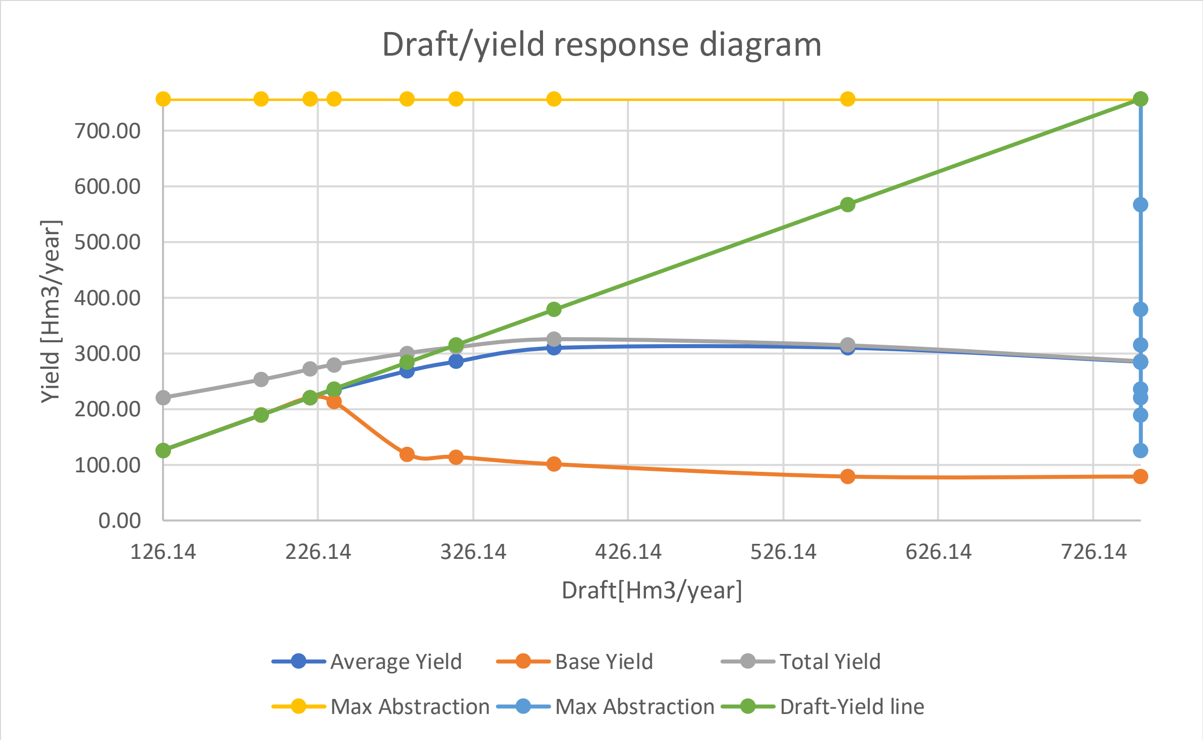

Figure 69 : Draft-Yield Diagram for 35.3 m in [Hm3/year]

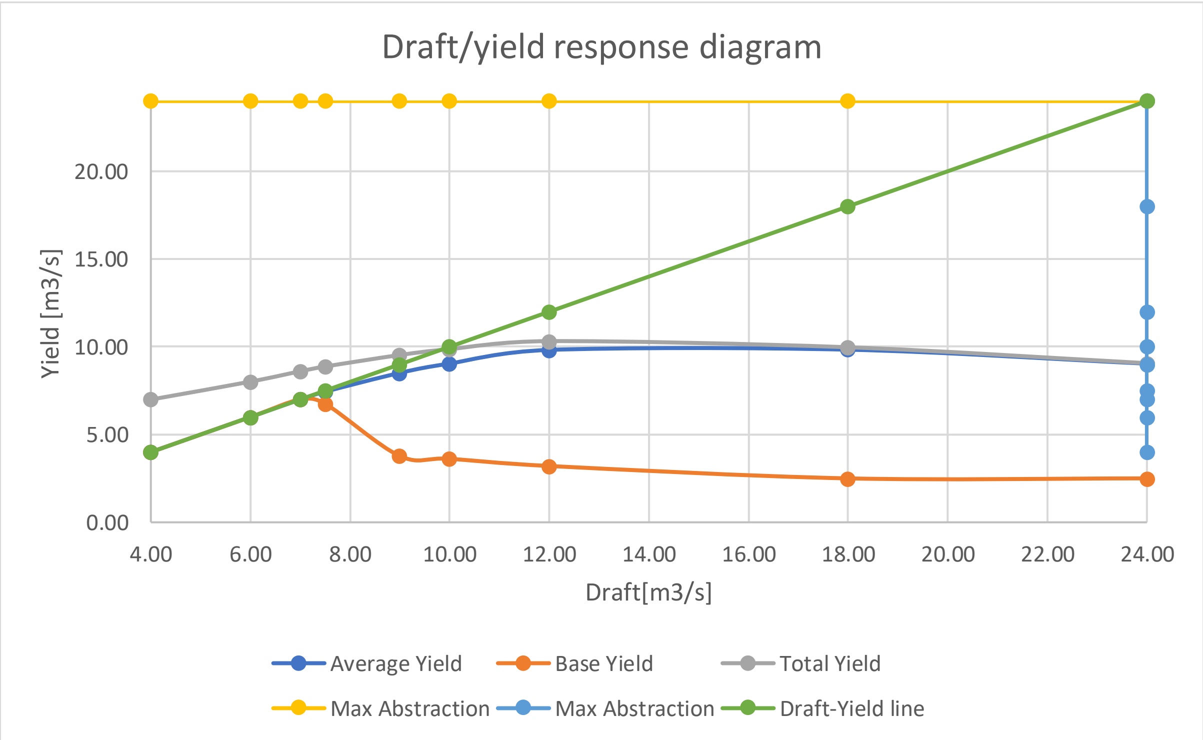

Figure 70 : Draft-Yield Diagram for 35.3 m in [m3/s]

	7.5	9	10	12	18	24
Ld	80.000	191.000	243.000	276.000	655.000	1409.000
Lcd	0.576	0.182	0.134	0.082	0.079	0.126
Md	213.038	119.117	114.140	101.158	78.919	78.919
Mcd	0.901	0.420	0.362	0.267	0.139	0.104
CDV	1161051	10085143	19438533	43798060	162952039	298501863
Vr	0.992	0.945	0.904	0.820	0.553	0.385
R	108.921	13.565	7.437	3.539	0.843	0.361
V	0.009	0.069	0.119	0.220	0.543	0.735
Lcs	0.065	0.092	0.112	0.133	0.241	0.437
Mcs	1.183	1.059	0.987	0.860	0.554	0.378
CSV	28860432.7	11150608.5	-2270947.4	-33353362.1	-160256708	-298002052
S	1.190	1.061	0.989	0.863	0.560	0.386
B	0.205	0.136	0.108	0.064	0.021	0.009
A	0.258	0.158	0.121	0.069	0.022	0.009

Table 8 : Indexes for 35.3 m

Standard Initial Condition / Alternative Condition				
Draft	Base Yield	Non firm yield	Average yield	Total Yield
4	1.0000	0.0000	1.0000	0.9990
6	1.0000	0.0000	1.0000	0.9996
7	1.0000	0.0000	1.0000	0.9997
7.5	1.0000	1.0000	1.0000	0.9997
9	1.0000	1.0000	1.0000	0.9996
10	1.0000	1.0000	1.0000	0.9996
12	1.0000	1.0000	1.0000	0.9994
18	1.0000	1.0000	1.0000	0.9995
24	1.0000	1.0000	1.0000	0.9999

Table 9 : Draft-yield diagram comparison

Standard Initial Condition / Alternative Condition							
	7.5	9	10	12	18	24	Average
Ld	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Lcd	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Md	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Mcd	1.000	1.000	1.000	1.000	1.000	1.000	1.000
CDV	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Vr	1.000	1.000	1.000	1.000	1.000	1.000	1.000
R	1.000	1.000	1.000	1.000	1.000	1.000	1.000
V	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Lcs	1.007	1.006	1.009	0.885	1.038	1.076	1.003
Mcs	1.000	1.000	1.000	0.999	0.999	1.000	1.000
CSV	0.998	0.994	1.036	1.003	1.001	1.000	1.005
S	1.000	1.000	1.000	0.999	1.000	1.000	1.000
B	0.993	0.994	0.991	0.983	0.963	0.930	0.976
A	0.992	0.993	0.990	0.981	0.963	0.929	0.975
Average	0.999	0.999	1.002	0.989	0.997	0.995	

Table 10 : Indexes comparison

Table 9 and Table 10 show that there are no symbolic differences between the two alternatives. This is important because it validates both models and exhibit that the initial condition is not causing any practical modifications in the simulation.

6.3. Third Alternative: Monthly Variations

To conclude this chapter, the third alternative results is presented in the following illustrations.

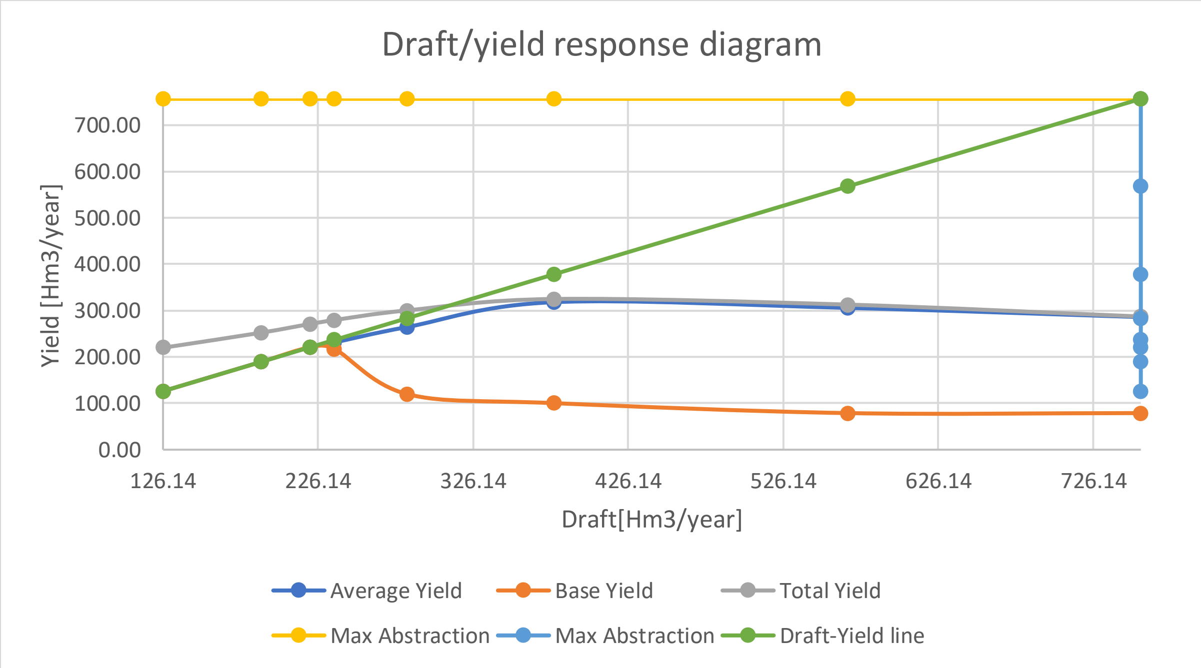

Figure 71 : Draft-Yield Diagram for variation in demand in [Hm3/year]

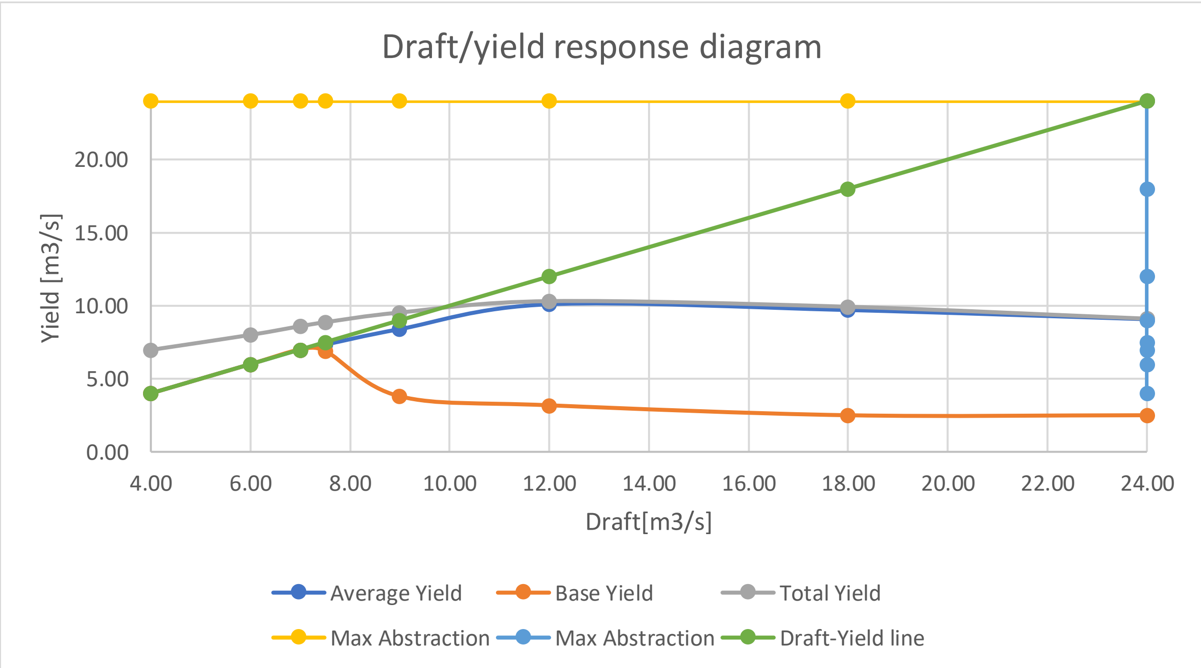

Figure 72 : Draft-Yield Diagram for variation in demand in [m3/s]

	7.5	9	12	18	24
Ld	75.000	296.000	726.000	1075.000	1430.000
Lcd	0.493	0.041	0.079	0.087	0.105
Md	217.598	119.714	100.379	78.919	78.919
Mcd	1.000	0.422	0.265	0.139	0.104
CDV	1074729	12469983	46818456	165803440	298054650
Vr	0.992	0.932	0.807	0.545	0.386
R	99.520	1.132	0.672	0.237	0.122
V	0.010	0.469	0.598	0.808	0.891
Lcs	0.818	0.029	0.033	0.050	0.147
Mcs	1.285	1.059	0.859	0.551	0.379
CSV	40746272.1	11100567.2	-33654677.0	-161232917	-297349519
S	1.292	1.061	0.861	0.557	0.388
B	0.990	0.531	0.402	0.192	0.028
A	99.520	1.132	0.672	0.237	0.029

Table 11 : Indexes for variation in demand

Standard Initial Condition / Alternative Condition				
Draft	Base Yield	Non firm yield	Average yield	Total Yield
4	1	0	1	1.0018942
6	1	0	1	1.001462
7	1	0	1	1.00096922
7.5	0.97904121	1.58917291	1.01496633	1.00116379
9	0.99500728	1.02971846	1.01402174	0.99982764
12	1.0077566	0.95713435	0.97309755	1.0008103
18	1	1.01906175	1.01414357	1.00439314
24	1	0.99511645	0.99646352	0.9952159

Table 12 : Draft-yield diagram comparison

	7.5	9	12	18	24
Ld	1.067	0.645	0.380	0.609	0.985
Lcd	1.166	4.409	1.032	0.908	1.196
Md	0.979	0.995	1.008	1.000	1.000
Mcd	0.901	0.995	1.008	1.000	1.000
CDV	1.080	0.809	0.935	0.983	1.002
Vr	1.000	1.014	1.015	1.014	0.998
R	1.094	11.985	5.266	3.557	2.964
V	0.914	0.146	0.368	0.671	0.824
Lcs	0.079	3.188	3.514	5.014	3.198
Mcs	0.921	1.000	1.001	1.004	0.995
CSV	0.707	0.998	0.994	0.995	1.002
S	0.921	1.000	1.001	1.004	0.996
B	0.206	0.255	0.157	0.108	0.308
A	0.003	0.138	0.100	0.089	0.302

Table 13 : Indexes comparison

To begin with, an interpretation of the draft-yield diagram in this case should be described as well as the indexes. For this alternative, the draft-yield response diagram is made with the average target draft, though the target draft in the simulation was not constant. Hence, each month will have a variation in the target draft as shown in Table 4, which increases or decreases the yield according to the month in issue. The same aspect is present for the calculation of the indexes, the deficit or surplus count is with respect to the average of target draft. As a consequence, Table 12 and Table 13 can give a false sense of increase or decrease in the performance, which is not in every month, so the analysis regarding those results should be thorough.

7. DISCUSSION OF RESULTS AND CONCLUSIONS

7.1. Discussion of Results

After the different analysis made and considering the objectives of this preliminary work, the most acceptable management configuration identified is a **minimum release** of 9 m^3/s. This selection will be justified by the considerations below.

In the first place, Chapter 4, in particular Figure 43 (which will be addressed below as Figure 73 for the benefit of the reader), gives positives conclusions regarding this **target draft** of 9 m^3/s. Even though the values of average yield and total yield are higher for 12 m^3/s for example, and this may suggest this target draft as preferred, the risk taken for that higher discharge is higher. The base yield is 15% lower, thus the non-firm yield is higher, which increases risks of failure. Instead for 9 m^3/s the non-firm yield is 30% lower than for 12 m^3/s which decreases the hazard.

Another positive aspect is that the average total yield is higher (9.53 m^3/s) than the draft-yield line, this demonstrates that the reservoir is able to provide more than what is being requested and does not fail to meet the demand. This is not true for 10 m^3/s or 12 m^3/s , which total values are 9.86 m^3/s and 10.32 m^3/s respectively, evidently failing in average to reach the requested yield. Instead, for lower target drafts, such as 7.5 m^3/s or less, which also present the average total yield higher than the draft-yield line, their values present losses compared to 9 m^3/s. Apart from the fact that 7.5 m^3/s is an impractical discharge value for the turbines, the average total yield is 7% lower and the average yield is 13% lower, presenting losses that, taking into account the low risks of 9 m^3/s, it seems unreasonable. These losses are aggravated for 7 m^3/s, which presents a decrease of 10% and 18% of average total yield and the average yield respectively.

Probabilistically speaking, also in Chapter 4, Figure 56 (which will be addressed below as Figure 74 for the benefit of the reader) shows that the percentage of times that 9 m^3/s was equaled or exceeded is 93.1%, which is extremely high. This means that just 6.9% of the times, in all the historical sequence, the target draft was not reached. In terms of performance, it is strongly safe. Moreover, the diagram shows that 18 m^3/s and 24 m^3/s are extremely dangerous, as their percentage of times exceeded do not reach 50%. Instead, evidence suggest a break point between those target drafts and 12 m^3/s, which is higher than 75%, which may seem acceptable. However, a present risk of 22% attempts on water supply, and this is not admissible. In this diagram, obviously, 7.5 m^3/s is a better choice, and even more 7 m^3/s which is the firm yield, but benefits are reduced just for 7% of risk of failure.

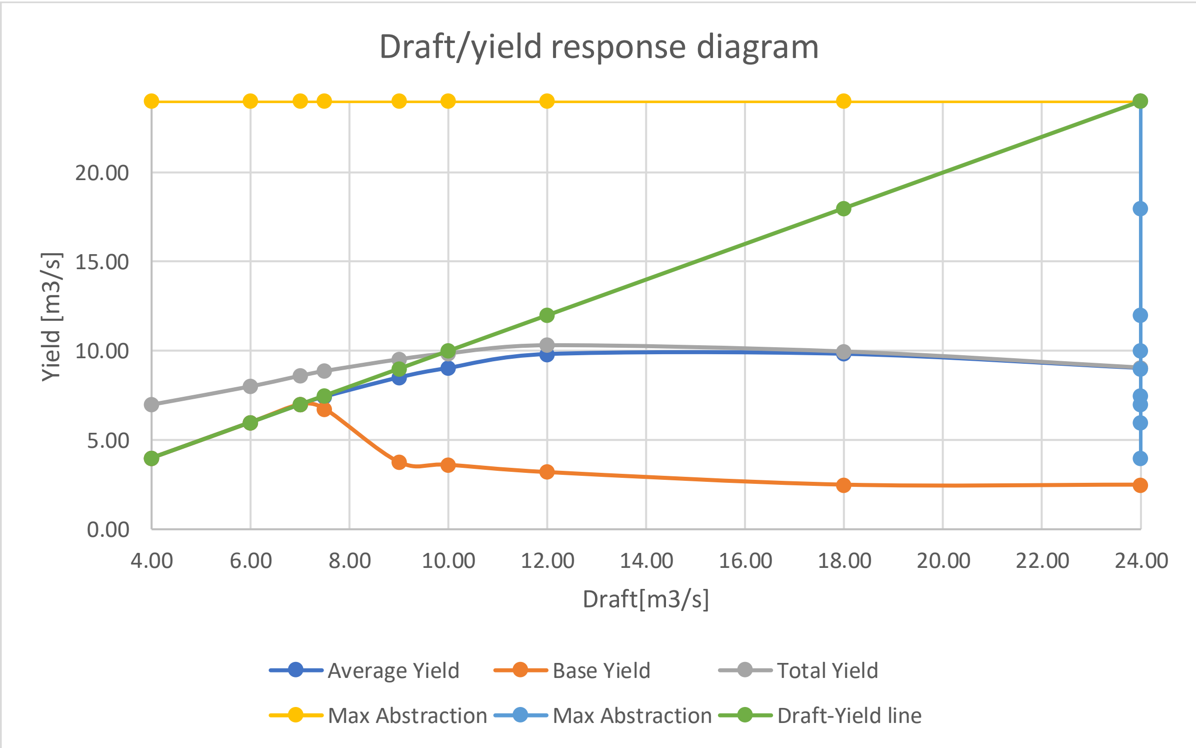

Figure 73 : Draft-Yield Response Diagram in m3/s

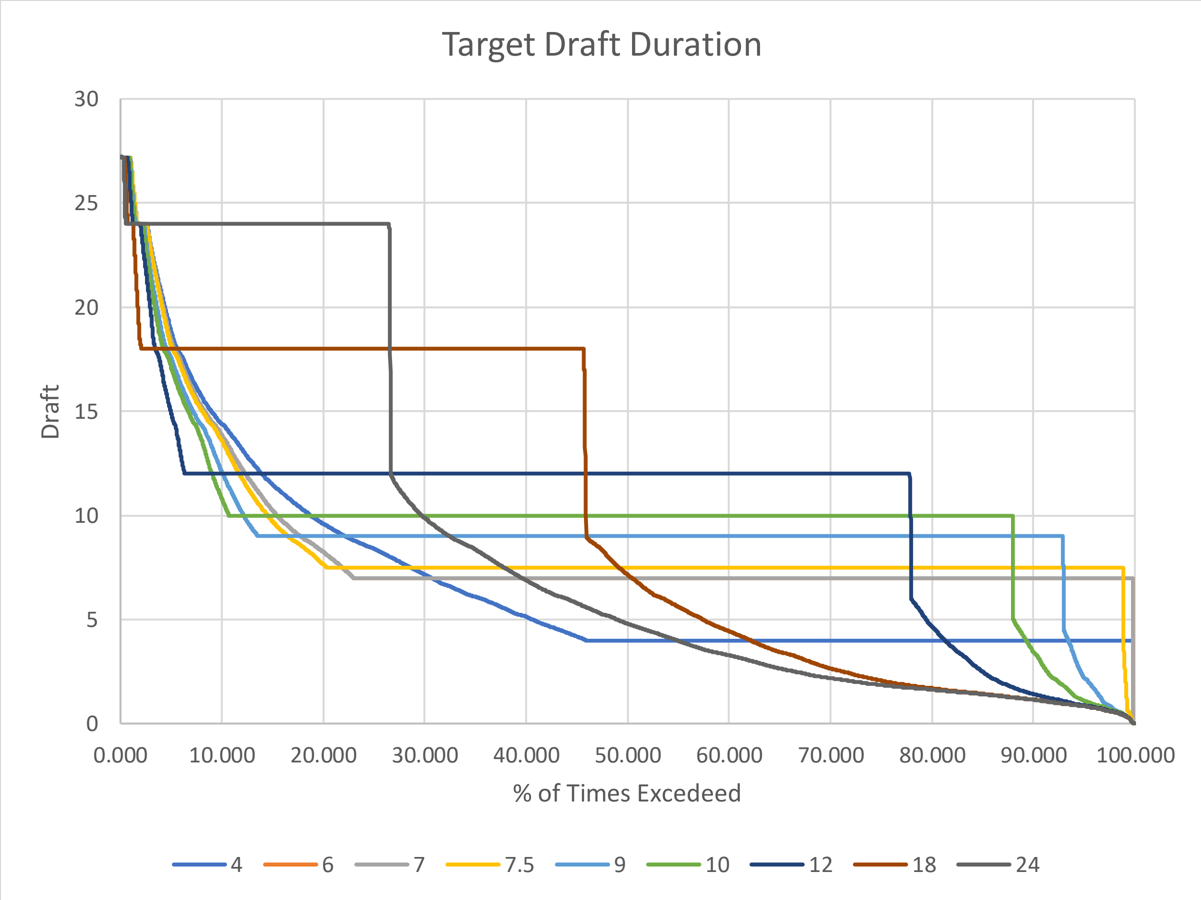

Figure 74 : Target Draft Duration

Regarding the indexes developed in Section 5.2, their values confirm that 9 m^3/s is the optimal management configuration. Table 2 (which will be addressed below as Table 14 for the benefit of the reader) shows that:

- **R** is 13.565 indicating that the proportion between days with deficits is equal to 13 times those that were null, which is a significative difference. This index is nearly the half for 10 m^3/s, 4 times less for 12 m^3/s and obviously, even less for higher target drafts. This time 7.5 m^3/s presents a great performance with 108.9, however, 13 times gives enough guarantee.
- As seen in Figure 74, **V** indicates, again, that just 6.9% of the whole simulation was with deficit. This value is considerably acceptable, and the same analysis can be made for other target drafts.
- **Mcs** shows that profits can reach up to 6% more than the target draft. This value is lower than 1 for target drafts higher than 10 m^3/s, which proposes an advantage for 9 m^3/s among higher values.

- **CSV** is positive as well as **S**. The cumulative volume in the end is profitable, and for values higher than 10 m^3/s, again, is not true. This statement also verifies that the total yield is higher than the target draft in average.
- **B** indicates that 13% of the time there was a surplus, which is twice the percentage for 12 m^3/s for example.

These are the main indexes that show advantages for 9 m^3/s.

	7.5	9	10	12	18	24
Ld	80.000	191.000	243.000	276.000	655.000	1409.000
Lcd	0.576	0.182	0.134	0.082	0.079	0.126
Md	213.038	119.117	114.140	101.158	78.919	78.919
Mcd	0.901	0.420	0.362	0.267	0.139	0.104
CDV	1161051	10085143	19438533	43798060	162952039	298501863
Vr	0.992	0.945	0.904	0.820	0.553	0.385
R	108.921	13.565	7.437	3.539	0.843	0.361
V	0.009	0.069	0.119	0.220	0.543	0.735
Lcs	0.065	0.093	0.113	0.117	0.250	0.470
Mcs	1.183	1.059	0.986	0.860	0.554	0.378
CSV	28812928.8	11082619.6	-2352857.9	-33467558.9	-160356992.5	-298026696.1
S	1.190	1.061	0.988	0.862	0.560	0.386
B	0.203	0.135	0.107	0.063	0.021	0.009
A	0.255	0.157	0.120	0.067	0.021	0.009

Table 14 : Indexes

Lastly, in Section 5.3, with the operational analysis others conclusion can be achieved. Figure 108 (which will be addressed below as Figure 75 for the benefit of the reader), in appendix C, shows that the Quantile 25, which is defined as the middle number between the smallest number and the median of the data set, is approximately 23.8 m for the 11/1, date that the dry season end. This determines that 75% of the data is above this value, which can be considered as a safety parameter. However, risks of drought are always present, so if the trace of the actual level is lower than the Quantile 25 a curtailment program is still possible to be implemented. This is not possible for 10 m^3/s (see Figure 110 or for the benefit of the reader Figure 76 which addresses below the same data) or higher because the Quantile 25 touches the minimum operating level, hence there is not a safety margin.

A similar interpretation can be done for a medium-term perspective, which in this case is very important because demonstrates that present decisions are not jeopardizing the reservoir performance in the future years. Although, the minimum level suffers a reduction which, one more time, has a safety margin that still allows a curtailment program to be implemented.

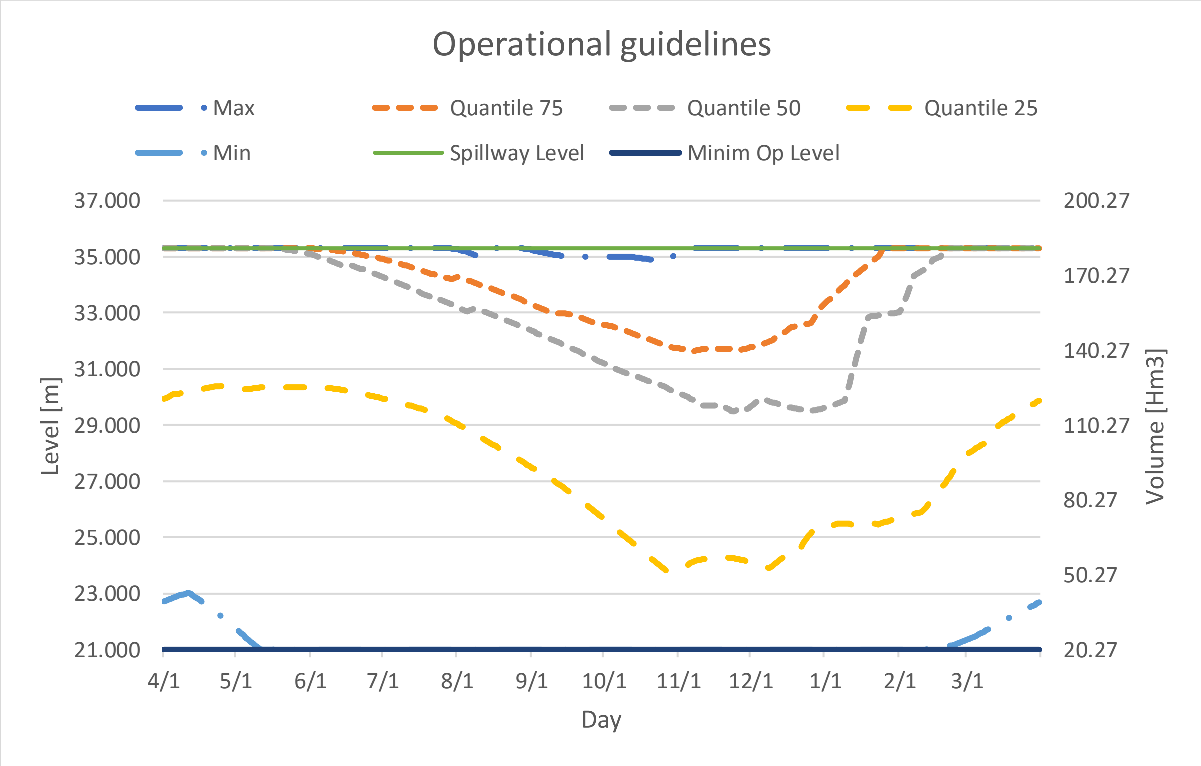

Figure 75 : Operational Guidelines for 9m3/s

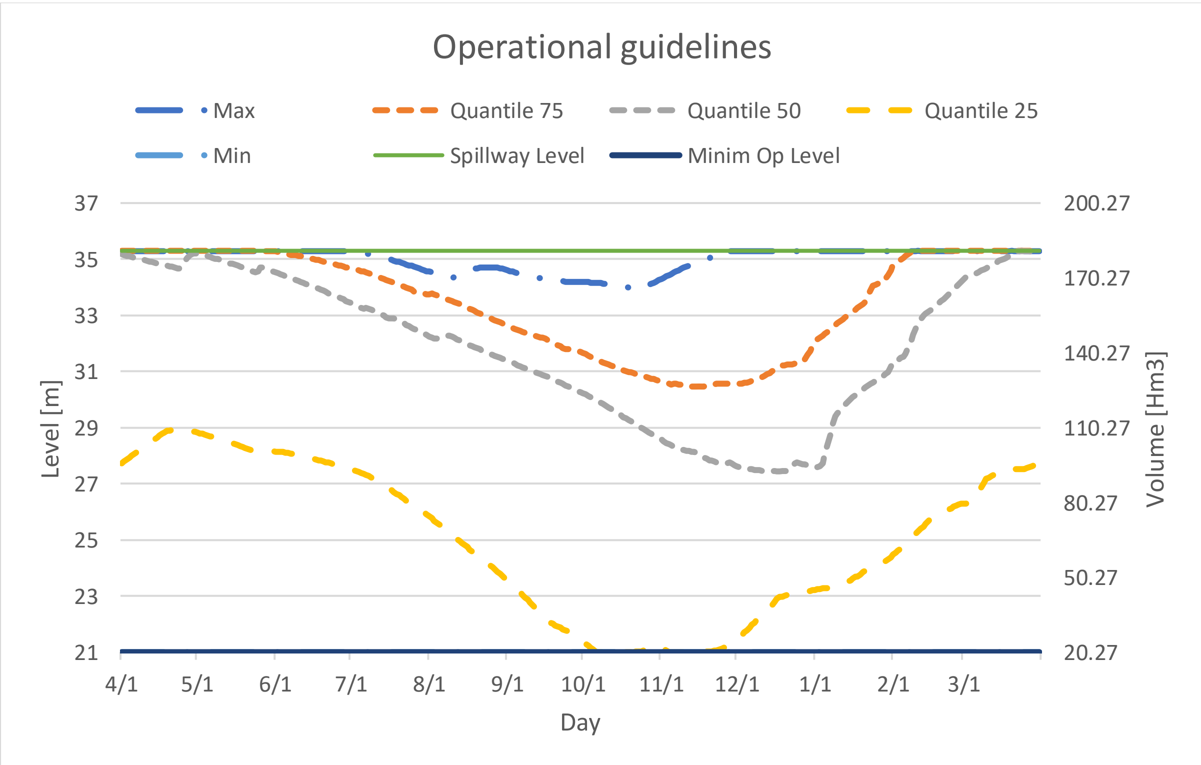

Figure 76 : Operational Guidelines for 10m3/s

7.2. Conclusions

The aim of this thesis has been to provide useful tools to reduce uncertainties in the water management in San Roque reservoir, as well as acting as a first guide and assistance to the operator's decisions. For this purpose, two different models were developed for the simulation and optimization of the reservoir, which can be widely used for different objectives. Based on these models and using the long historical inflow sequence, important approaches for the analysis of the reservoir performance were covered, with only short theoretical discussions and directed to a more practical application. Lastly, the most admissible management configuration was identified and discussed among other possibilities

First, with the draft-yield analysis the operator can evaluate the yield potential of the system subject to specific variables such as initial reservoir storage, historical inflow hydrology and target draft. A draft-yield response diagram is presented together with different statistical diagrams that give a panorama of the risks taken as well as the reliability of supply for different target drafts.

Secondly, several indexes were defined and calculated which serves to know or assess the characteristics and intensity of an event. These indexes describe different situations, unsatisfactory and satisfactory, which can lead the operator to know exactly how much is affecting or benefiting a certain decision.

Finally, an operational analysis was performed for short-term and medium-term perspective aimed at improving the operational strategy of the system. The operator can monitor the actual behavior of the reservoir and compare them with the operational guidelines, detecting changes in expected system performance. These will aid the operator to gauge whether the water storage is increasing or decreasing with respect to the historical sequence, and the future consequences of a decision.

It is important to highlight that a sensitivity test was held for different conditions to check the applicability of the draft-yield response diagram and for the defined indexes and the results were competent.

In line with all these analyses stated, the most acceptable management configuration would be to set a minimum release of 9 m^3/s presenting the highest “risk-profit” relation among other practicable target drafts.

Besides, future investigations are proposed to improve even more the management of the reservoir:

- No stochastic analysis was carried out, so adding stochastic sequences will complete the different analysis made, giving a more certain probabilistic behavior.
- This thesis investigated only water volumes and discharge and not the water quality aspects. Nowadays, environmental studies are gaining importance, so integrating the quality of the water in the simulations for the analysis achieved would improve them categorically. For example, after the allocation decision has been made, the performance of the system is simulated over the next decision horizon with the purpose of determining the resultant water quality concentration at key points in the system. If these values fall within certain limits, no adjustment need to be made. Instead, the water allocation should be iteratively adjusted till the quality specifications are met.
- Global warming is a fact and a future challenge for water resource managers, so projecting future sequences affected by the trend of the climate changes would be interesting to improve and anticipate the decisions taken.
- Evaporation from the lake should be considered into the models; supposedly it does not present high rates and as no accurate information was found, so the rate is presumed as null. However, different methods can estimate this rate, like Penman's method.
- As mentioned in section 2.1.1, Córdoba is located in one of the regions with the most severe storms on the planet and with the international research program called RELAMPAGO it is expected to achieve an improvement in the forecasts of these phenomena globally. It would be interesting to merge the above-mentioned improvements in the management of rainstorms and floods, in order to optimize at a higher time resolution the decisions in real time.
- Climate variability must be taken into account, as El Niño or La Niña, which are important climatic phenomena that causes an irregularly periodic variation in the

temperature, rain pattern, winds and other hydrological conditions. It is important to identify dry seasons, because as the indexes shows, for 9 m^3/s a deficit of 191 days could be present which is more than half a year. This value, as **Lcd** shows, represent 20% of the times that there was deficit. This can have social and economic consequences that are not desirable.

- The Rio Suquia must not dry up or be altered significantly in order to conserve the hydrological and ecological characteristics. For this purpose, an ecological quality of the river must be preserved by maintaining a minimum or ecological discharge. Nowadays, the regulations do not explicit this value, being left to the authority's criteria. This aspect must be borne in mind when managing the reservoir, especially in dry seasons, so an accurate value should be studied and added in the analysis performed as a physical constraint.
- The lack of any cost function associated with the benefit of users is a disadvantage for the optimal water allocation. An economic analysis for the decision making, especially in deficit, plays a major role in the management of a sustainable system. Ideally, all factors influencing the economy of the region under consideration need to be contemplated. It may include all operational costs associated with the supply of water together with the losses that may result from not meeting all demands. In addition, if water quality is being considered in the decision making, is of importance to be accounted if water supply does not satisfy required standards.

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Appendix A: Input Conditions Aquarius

- Reservoir Input Data

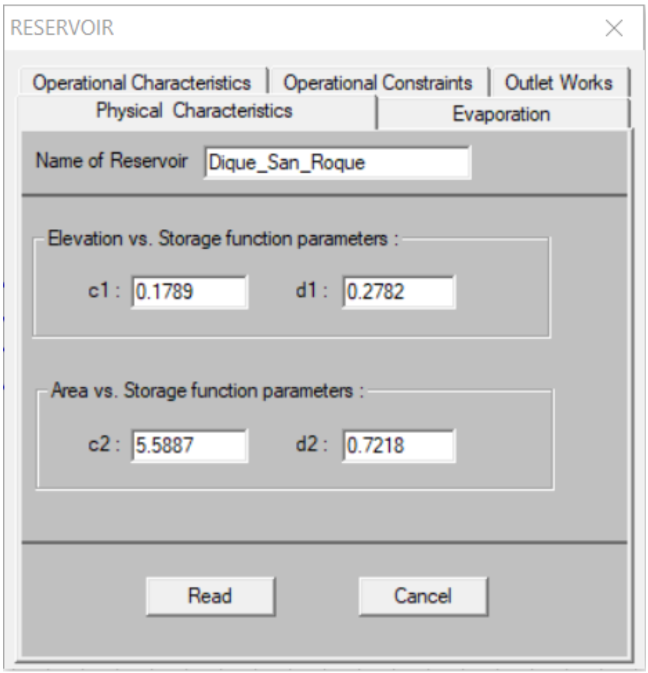

Figure 77 : Physical Characteristics

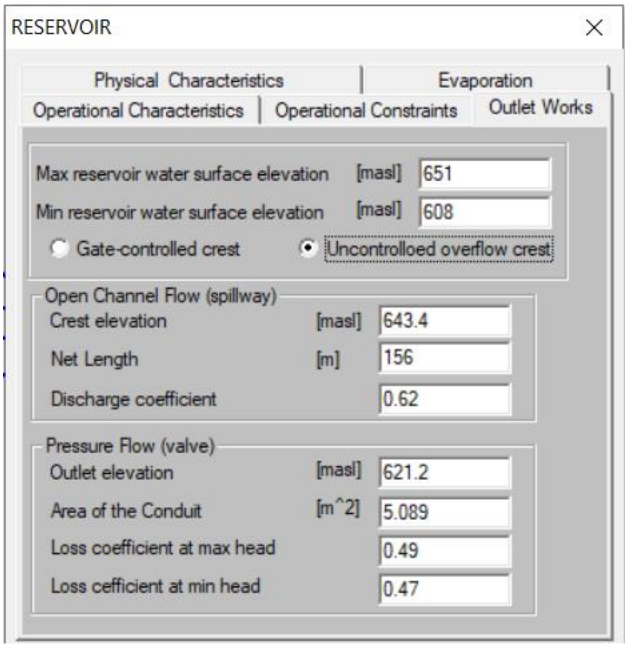

Figure 78 : Operational Characteristics

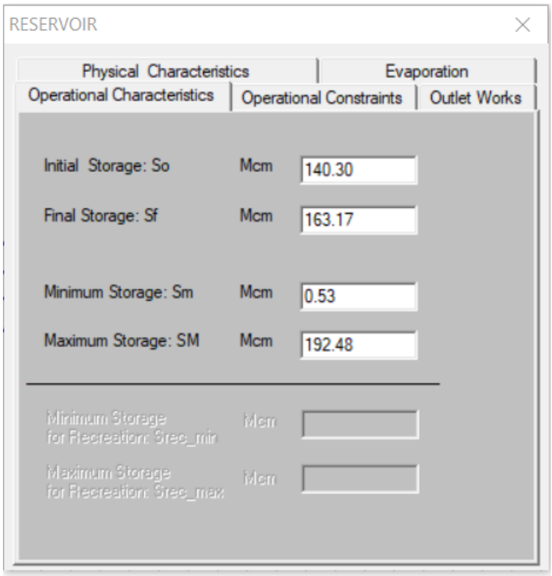

Figure 79 : Operational Characteristics

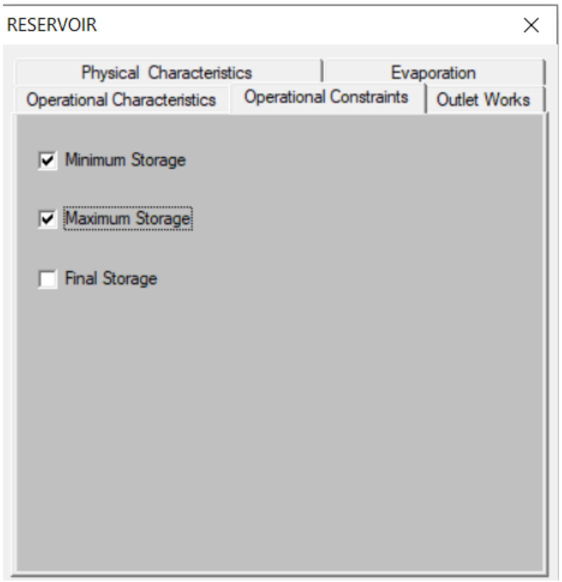

Figure 80 : Operational Characteristics

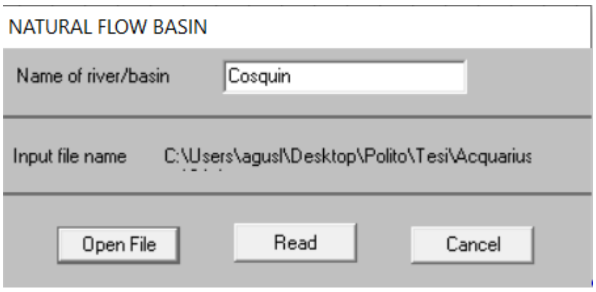

Figure 81 : Inflow Input

- Hydropower Input Data

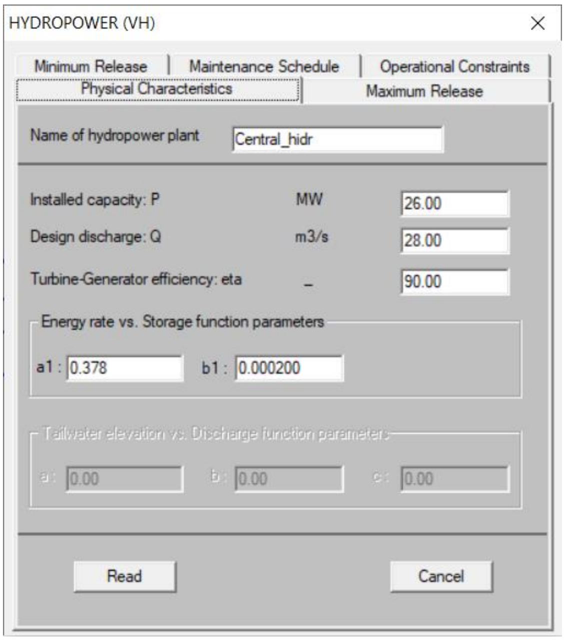

Figure 82 : Physical Characteristics Power Plant

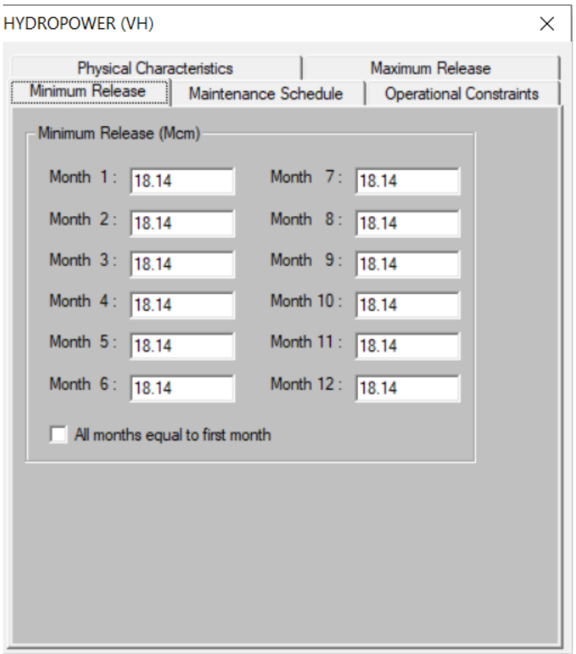

Figure 83 : Minimum Release Power Plant

Appendix B: Duration Analysis

- <u>Target Draft:</u> 4 m^3/s

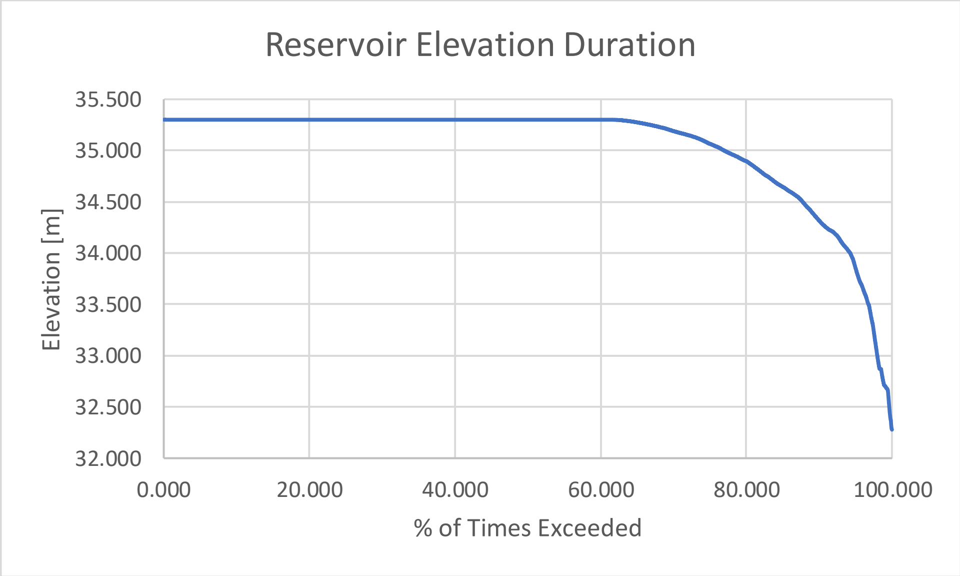

Figure 84 : Reservoir Elevation Duration 4m3/s

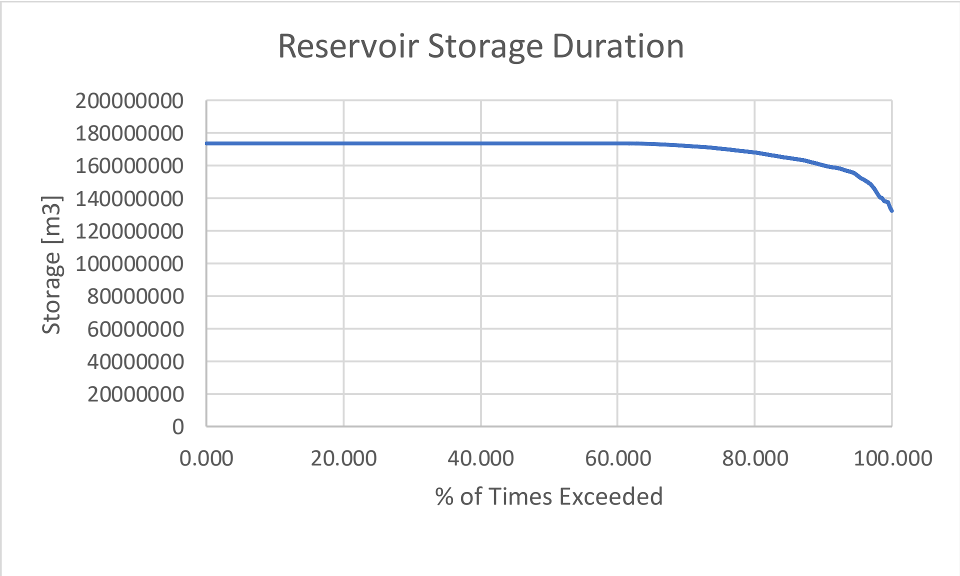

Figure 85 : reservoir Storage Duration 4m3/s

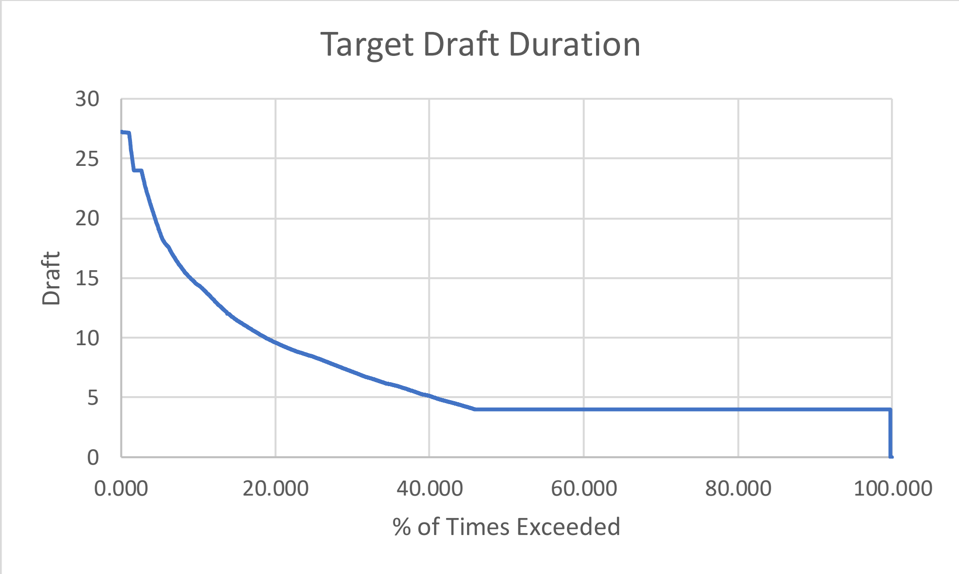

Figure 86 : Target Draft Duration 4m3/s

- <u>Target Draft:</u> 6 m^3/s

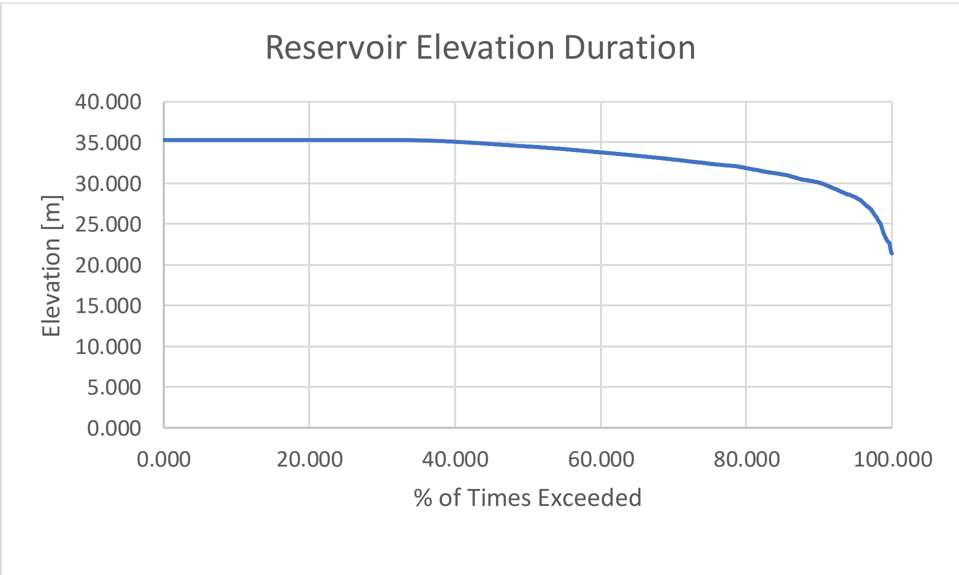

Figure 87 : Reservoir Elevation Duration 6m3/s

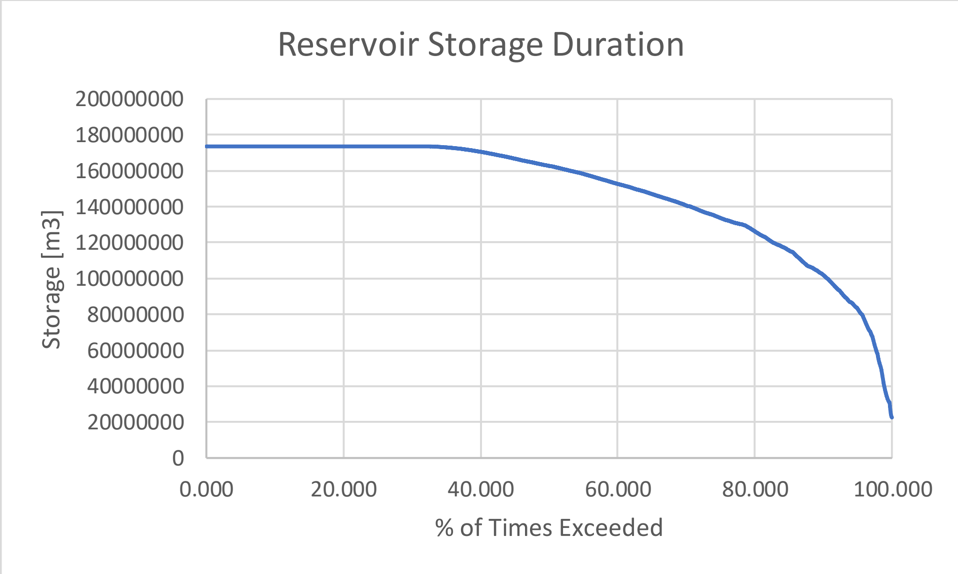

Figure 88 : Reservoir Storage Duration 6m3/s

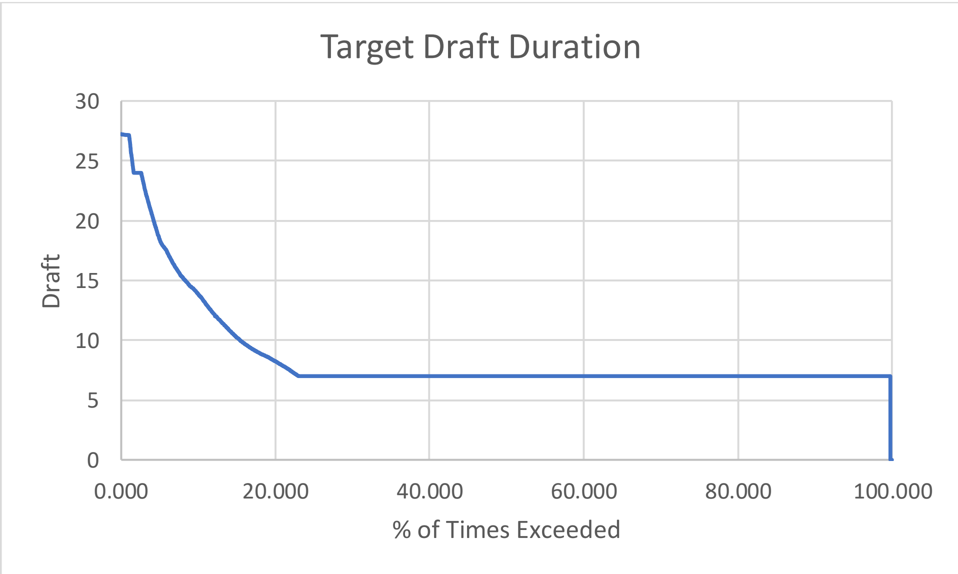

Figure 89 : Target Draft Duration 6m3/s

- <u>Target Draft:</u> 7 m^3/s

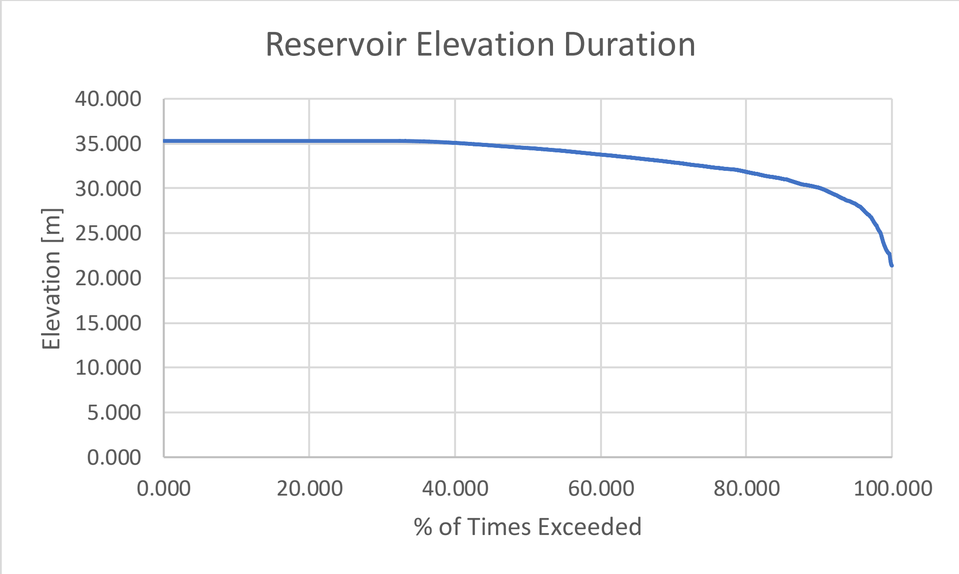

Figure 90 : Reservoir Elevation Duration 7m3/s

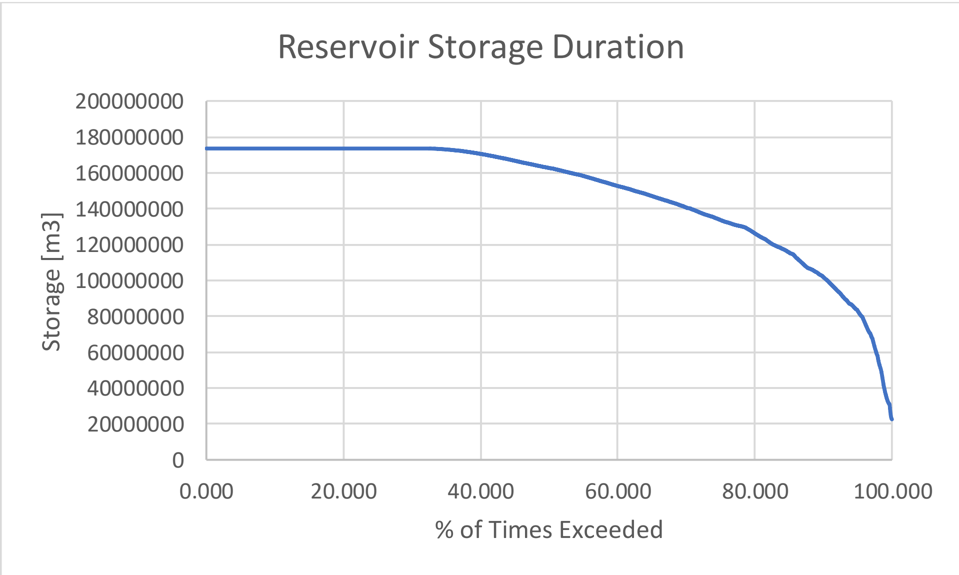

Figure 91 : Reservoir Storage Duration 7m3/s

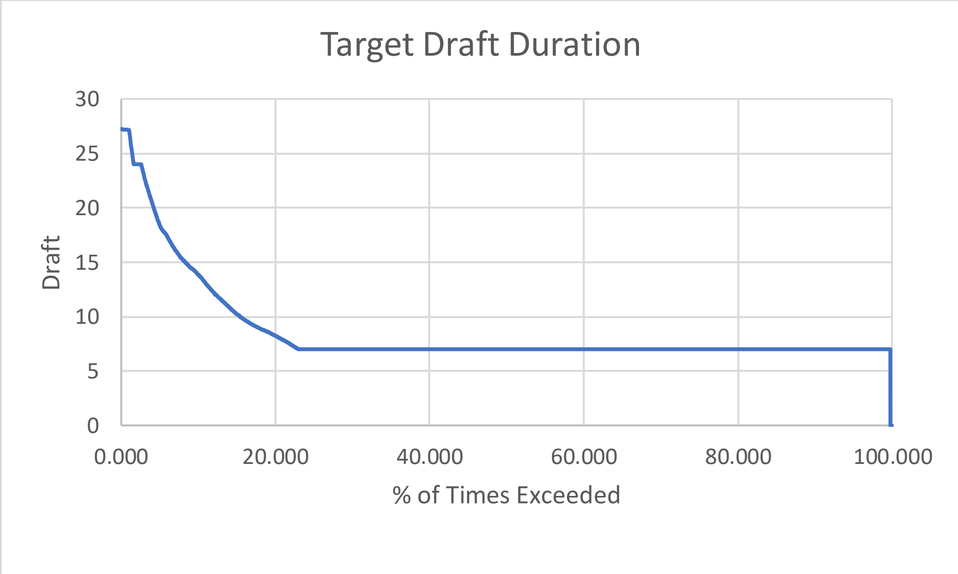

Figure 92 : Target Draft Duration 7m3/s

- <u>Target Draft:</u> 7.5 m^3/s

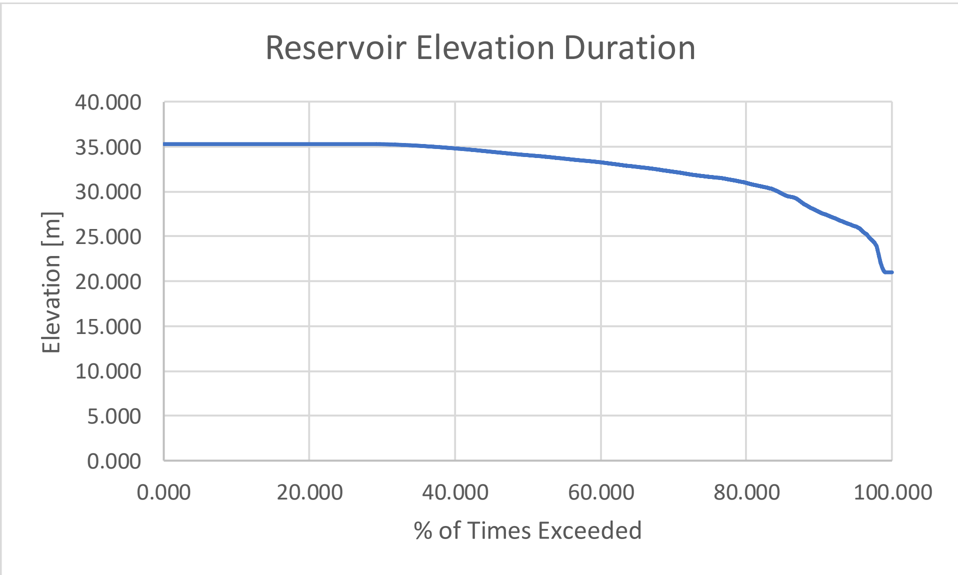

Figure 93 : Reservoir Elevation Duration 7.5m3/s

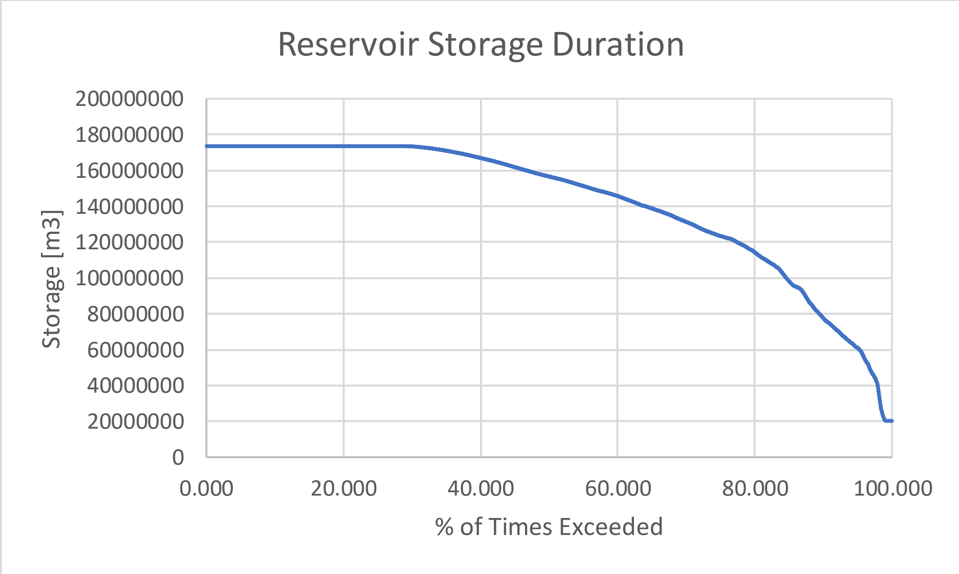

Figure 94 : Reservoir Storage Duration 7.5m3/s

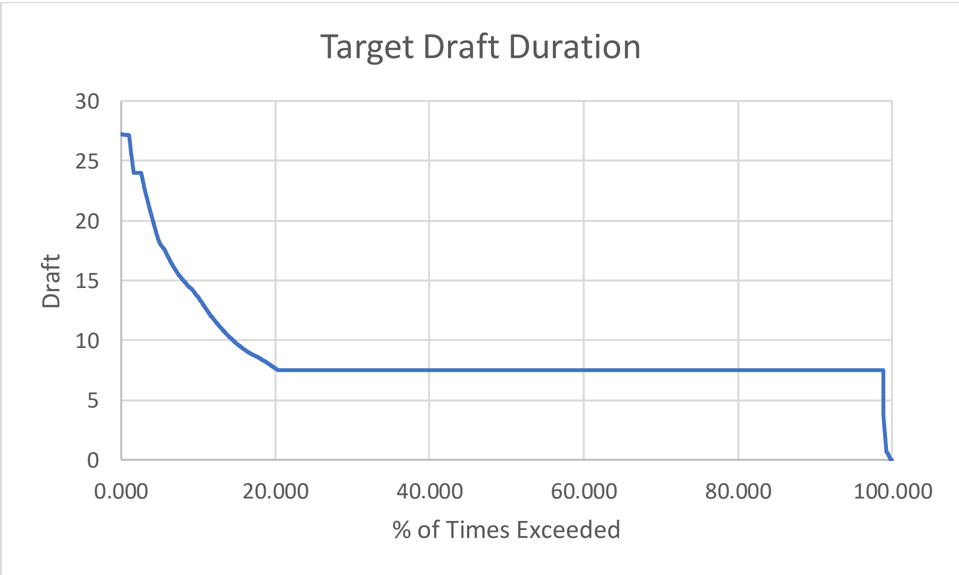

Figure 95 : Target Draft Duration 7.5m3/s

- <u>Target Draft:</u> 9 m^3/s

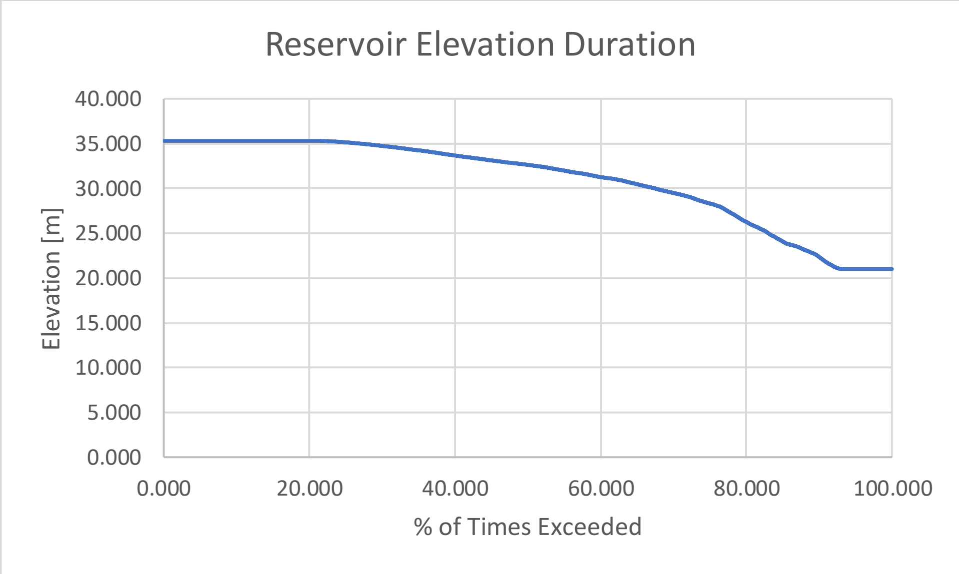

Figure 96 : Reservoir Elevation Duration for 9m3/s

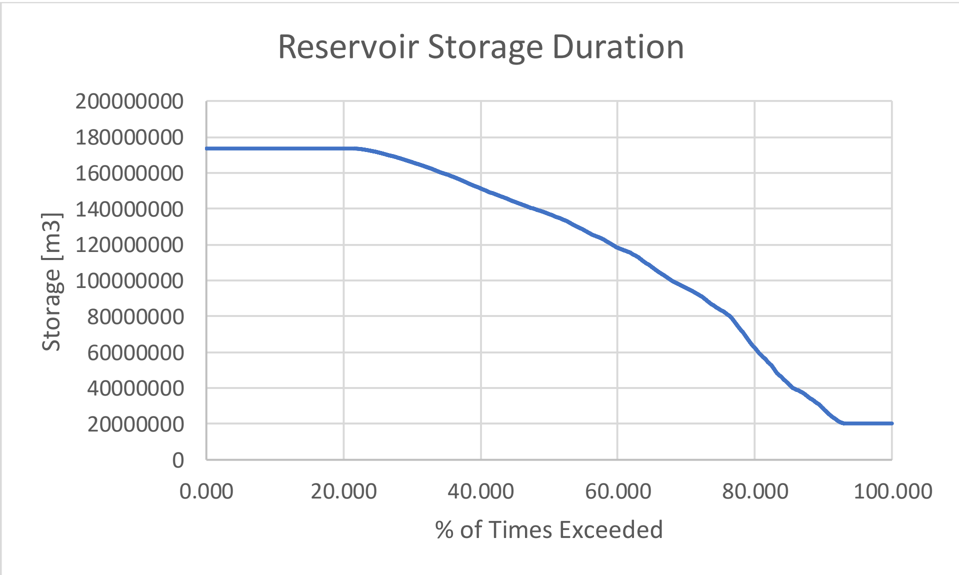

Figure 97 : Reservoir Storage Duration 9m3/s

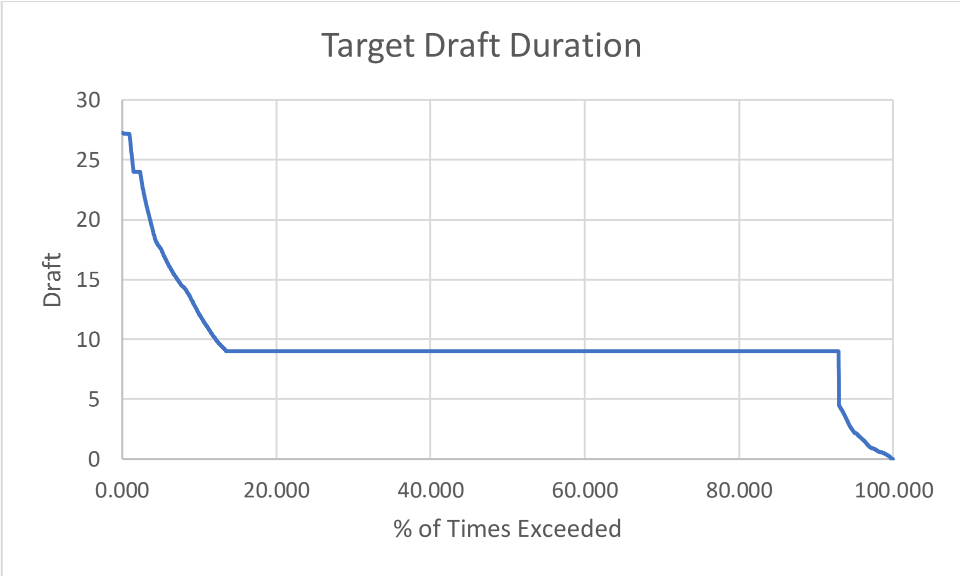

Figure 98 : Target Draft Duration 9m3/s

- <u>Target Draft:</u> 10 m^3/s

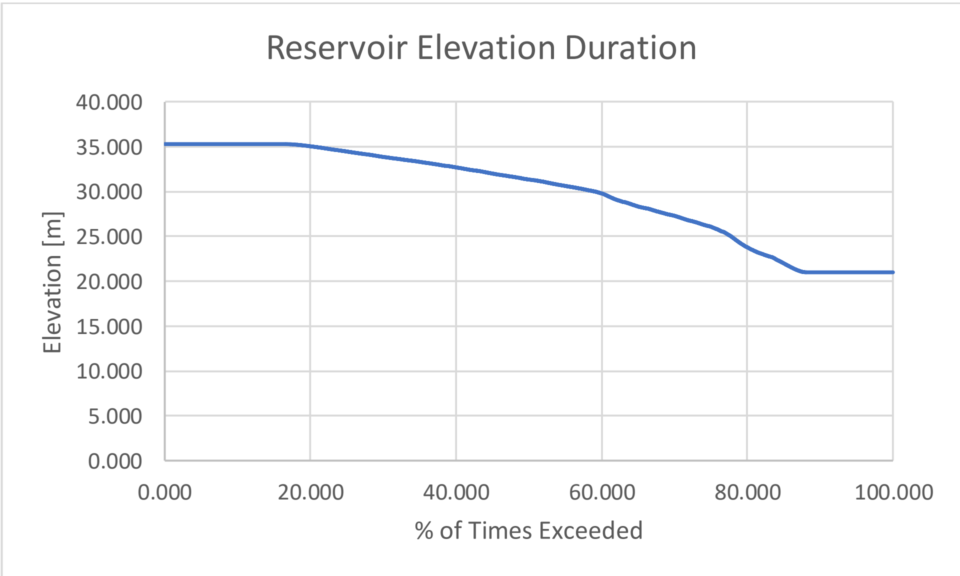

Figure 99 : Reservoir Elevation Duration 10m3/s

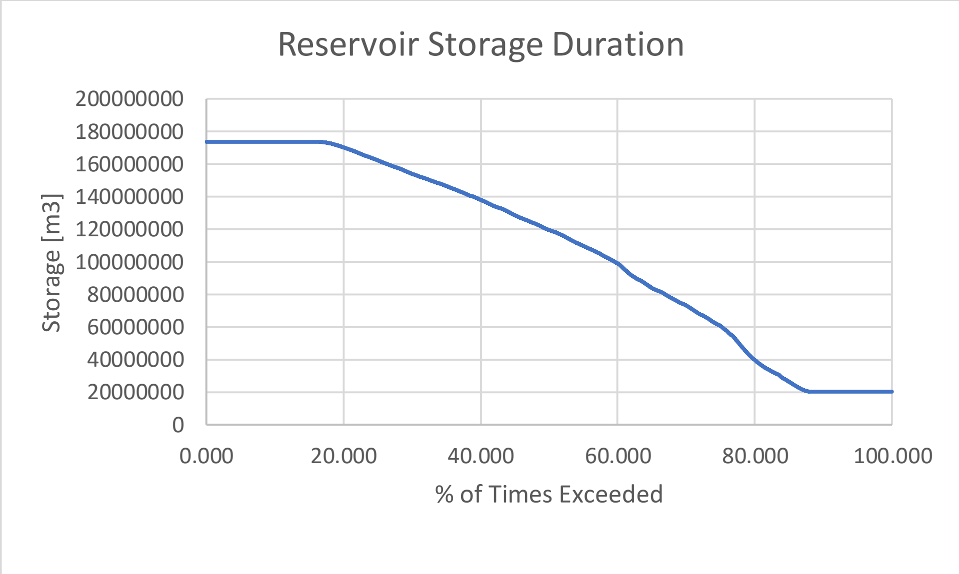

Figure 100 : Reservoir Storage Duration 10m3/s

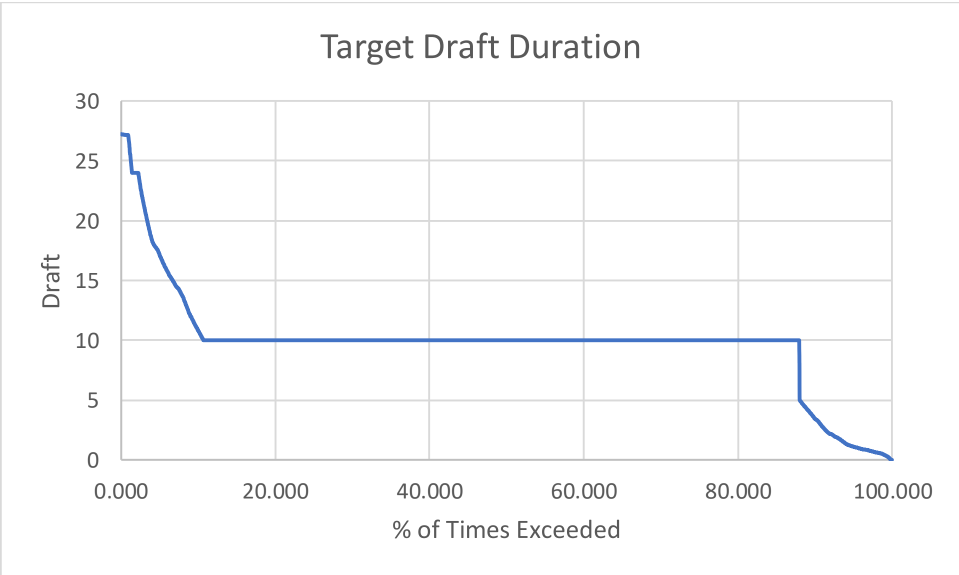

Figure 101 : Target Draft Duration 10m3/s

- <u>Target Draft:</u> 18 m^3/s

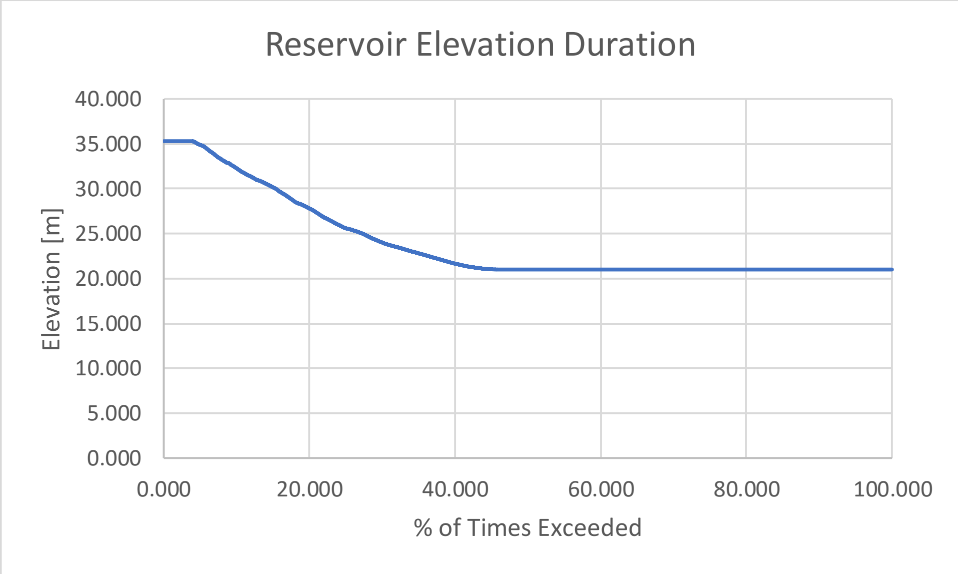

Figure 102 : Reservoir Elevation Duration 18m3/s

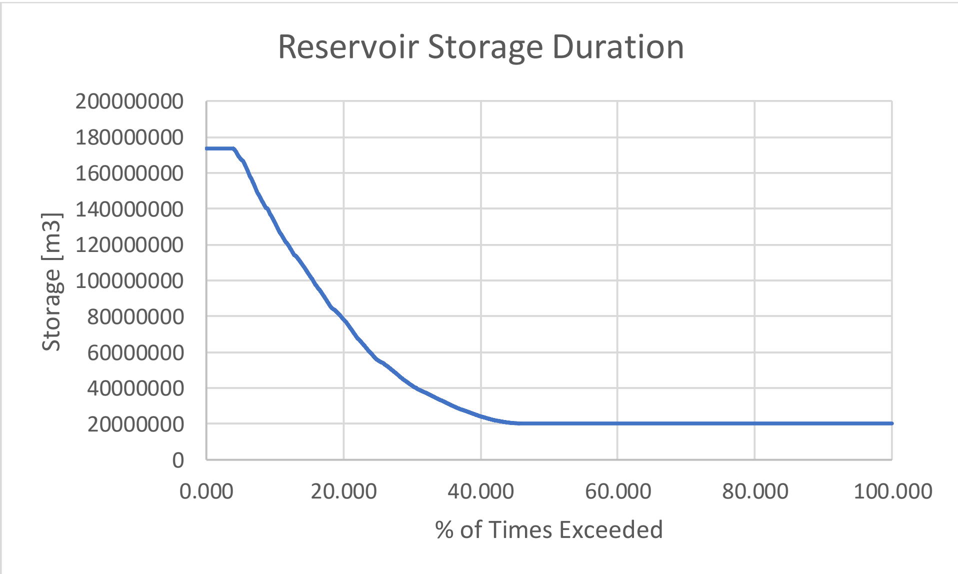

Figure 103 : Reservoir Storage Duration 18m3/s

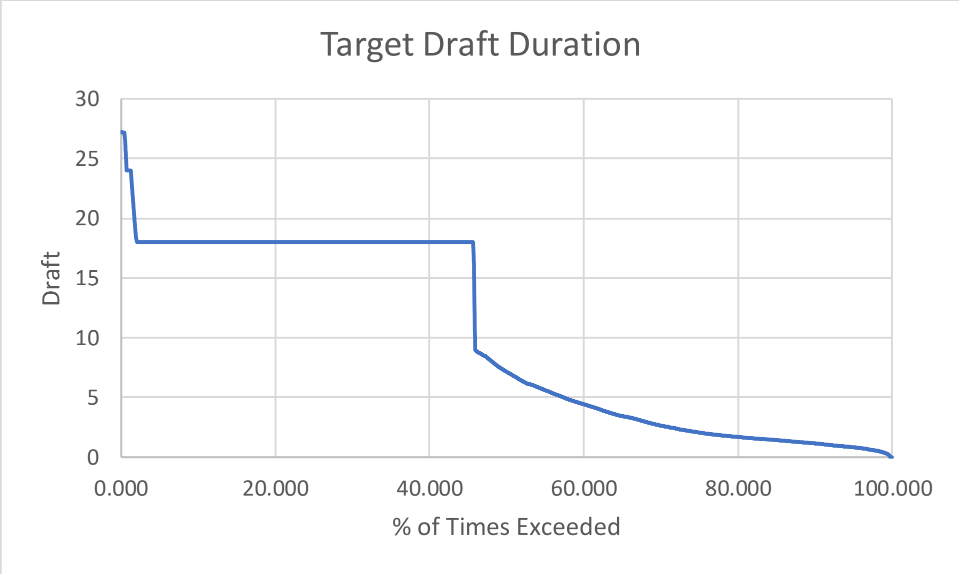

Figure 104 : Target Draft Duration 18m3/s

- <u>Target Draft:</u> 24 m^3/s

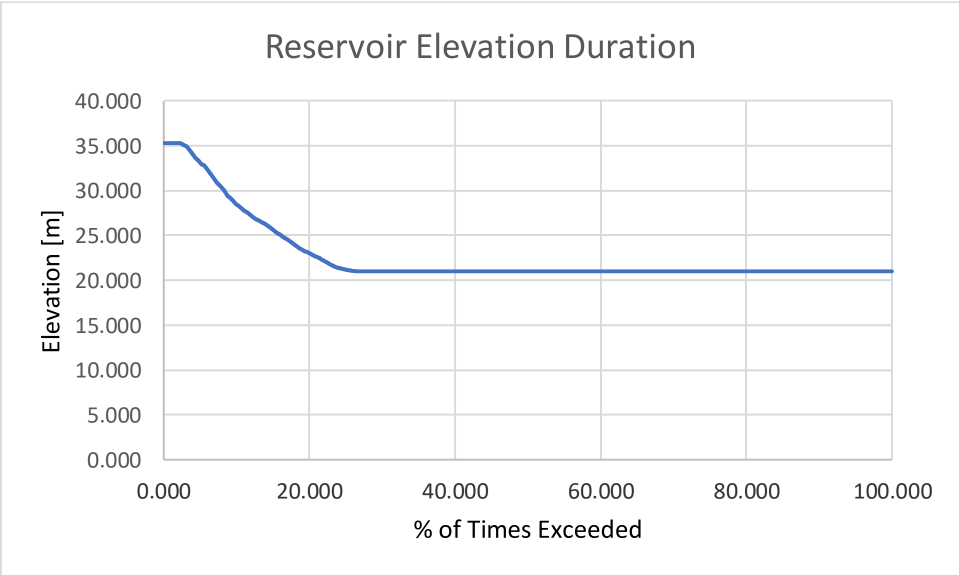

Figure 105 : Reservoir Elevation Duration 24m3/s

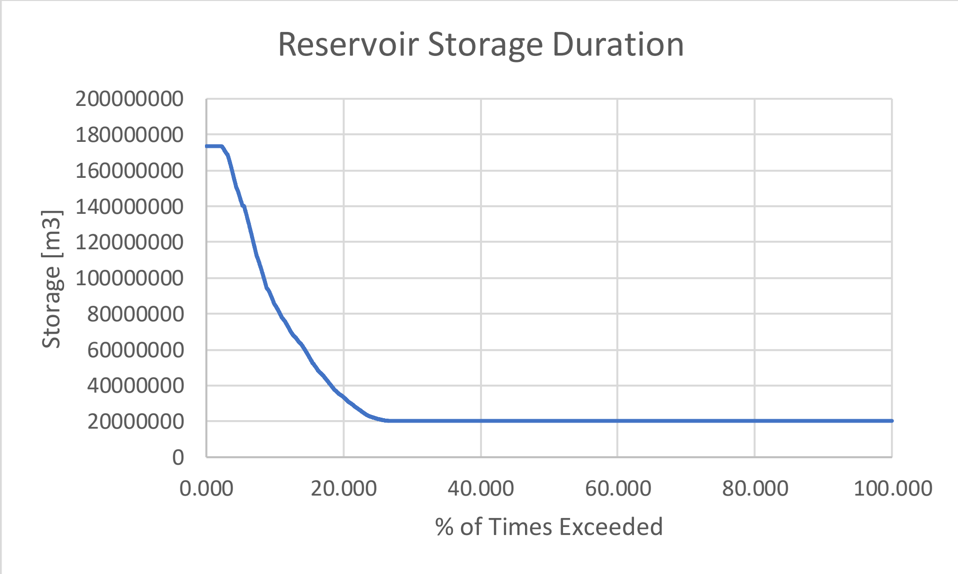

Figure 106 : Reservoir Storage Duration 24m3/s

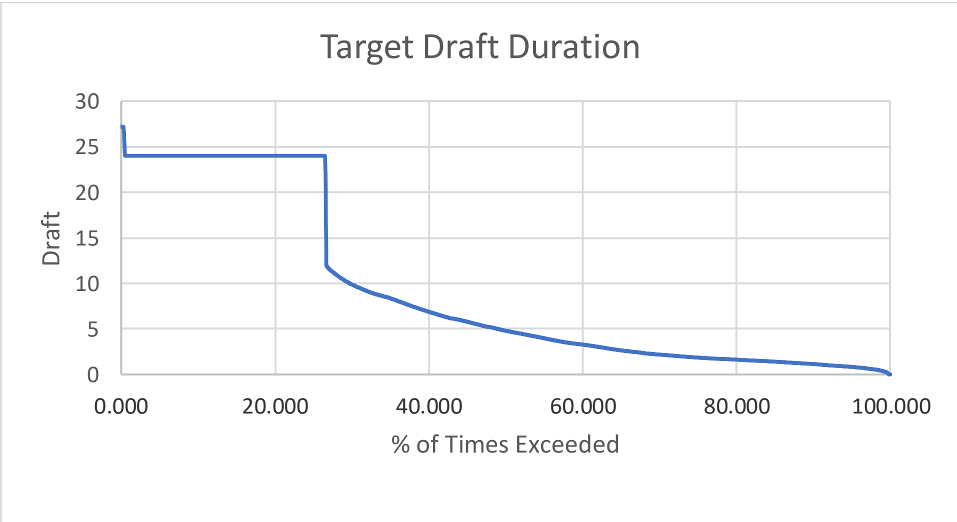

Figure 107 : Target Draft Duration 24m3/s

Appendix C: Operational Guidelines

- <u>Target Draft:</u> 9 m^3/s

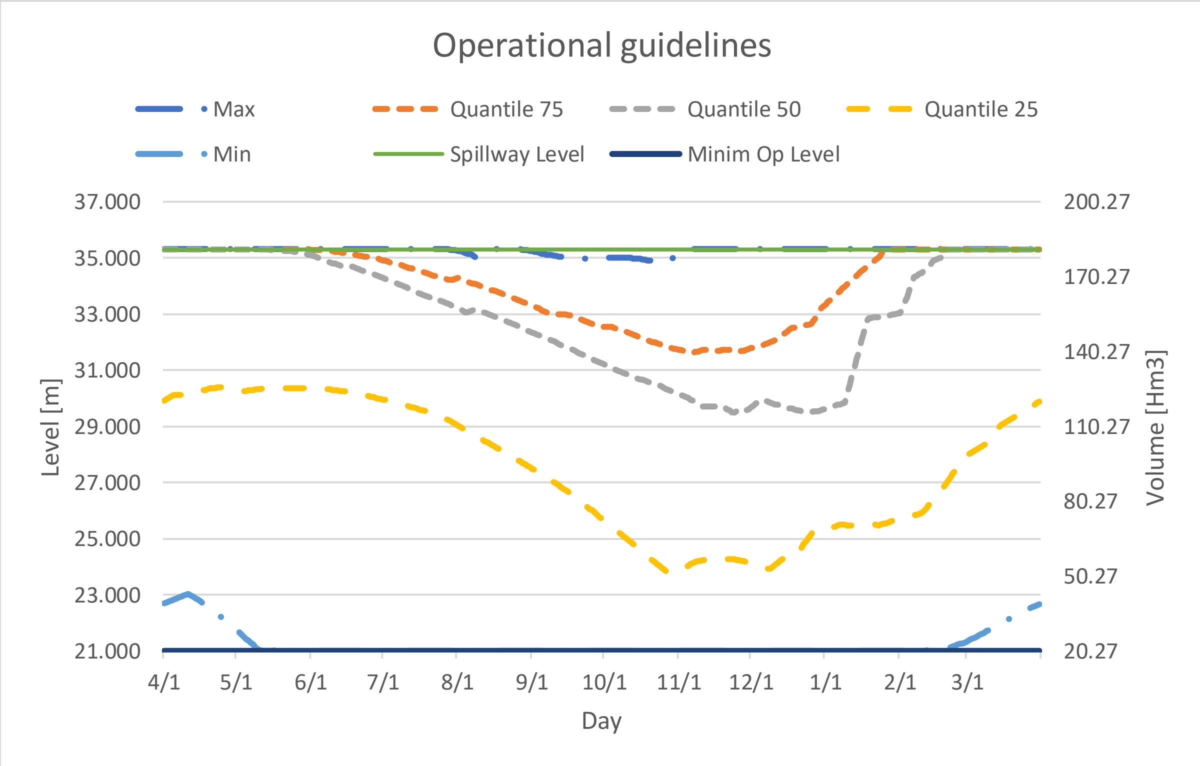

Figure 108 : Short-Term Operational Guidelines 9 m^3⁄s

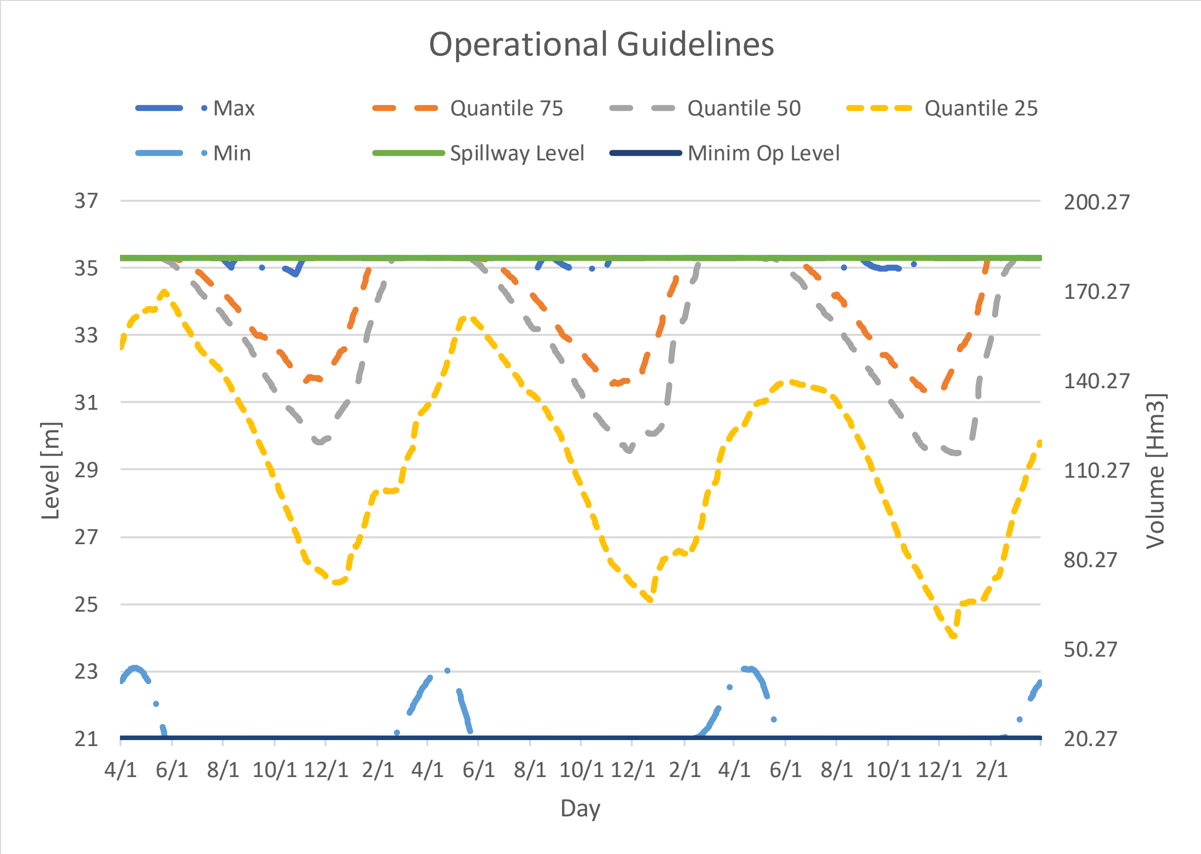

Figure 109 : Medium-Term Operational Guidelines 9 m^3⁄s

- <u>Target Draft: </u>10 m^3/s

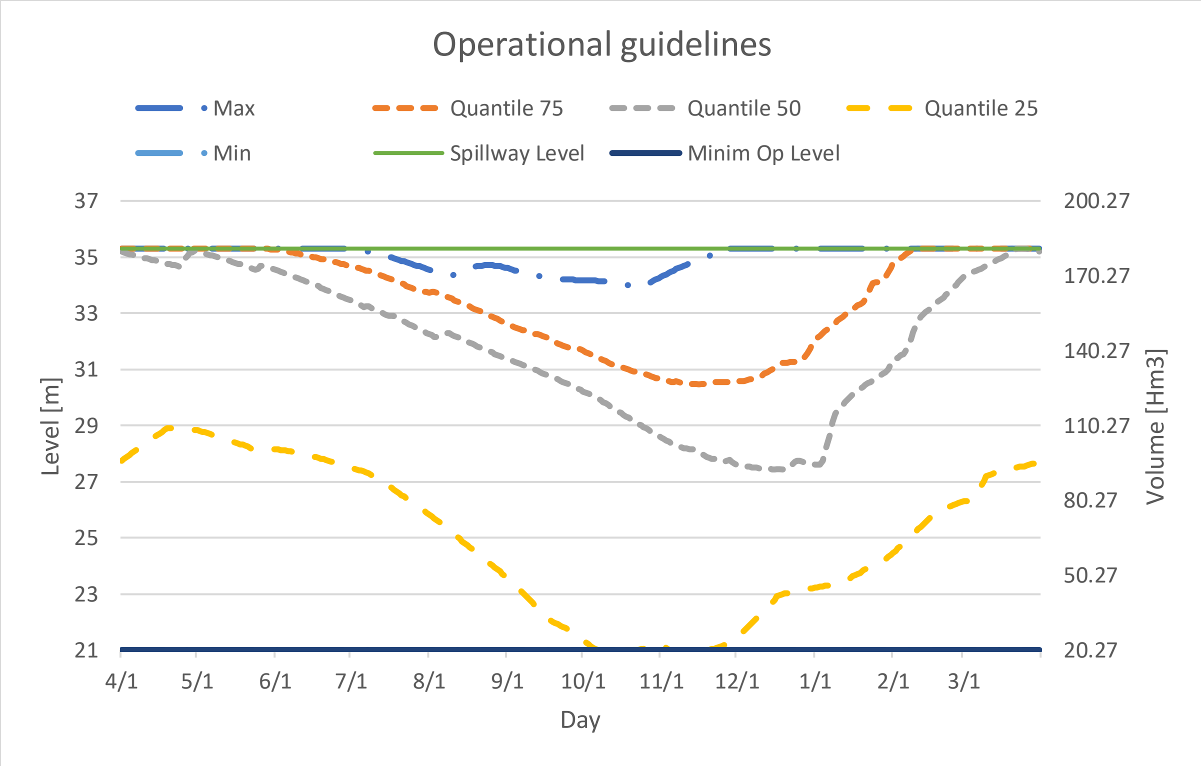

Figure 110 : Short-Term Operational Guidelines 10 m^3⁄s

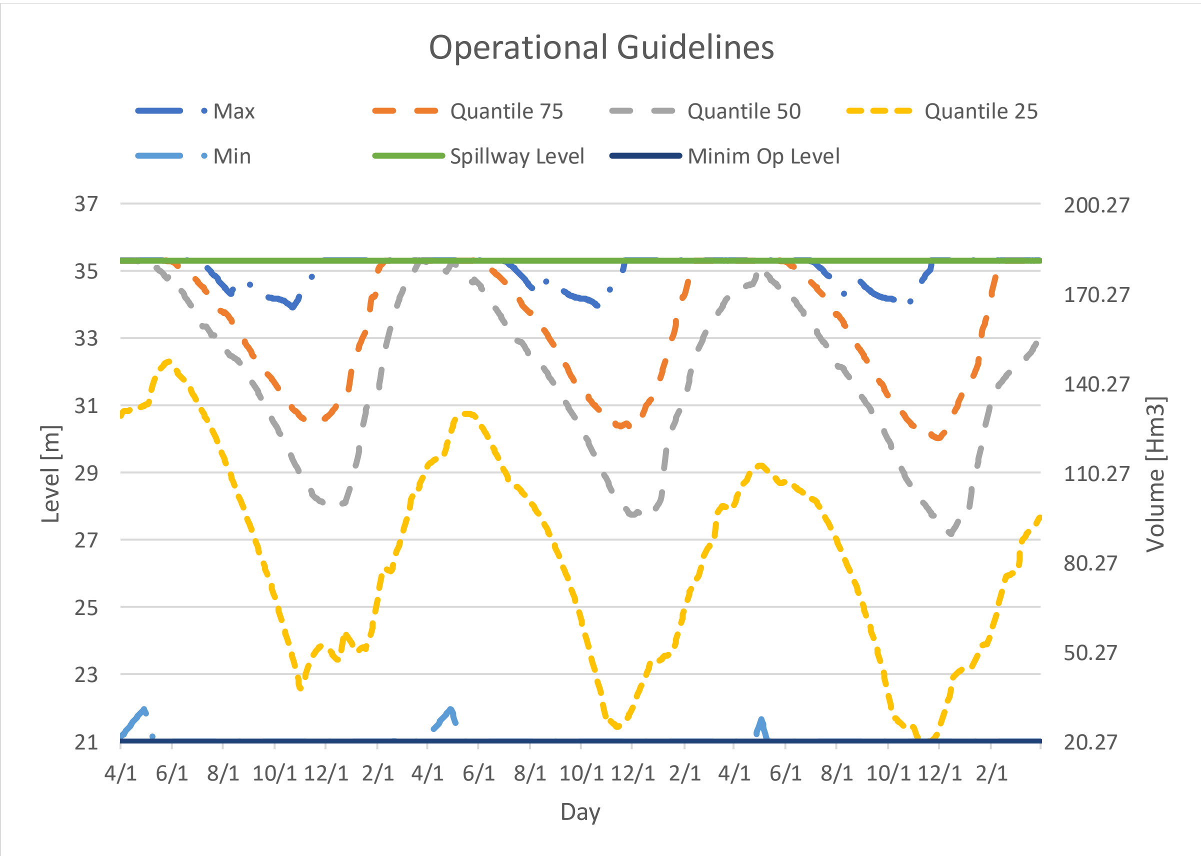

Figure 111 : Medium-Term Operational Guidelines 10 m^3⁄s

- <u>Target Draft:</u> 12 m^3/s

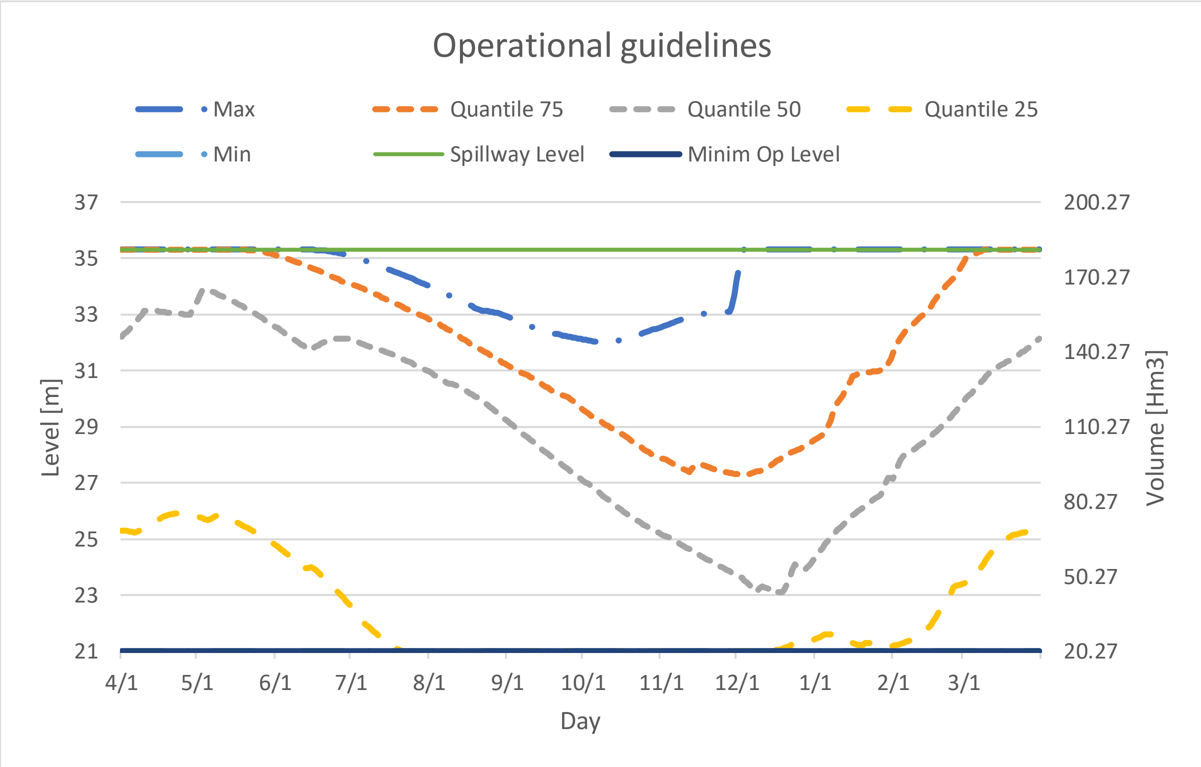

Figure 112 : Short-Term Operational Guidelines 12 m^3⁄s

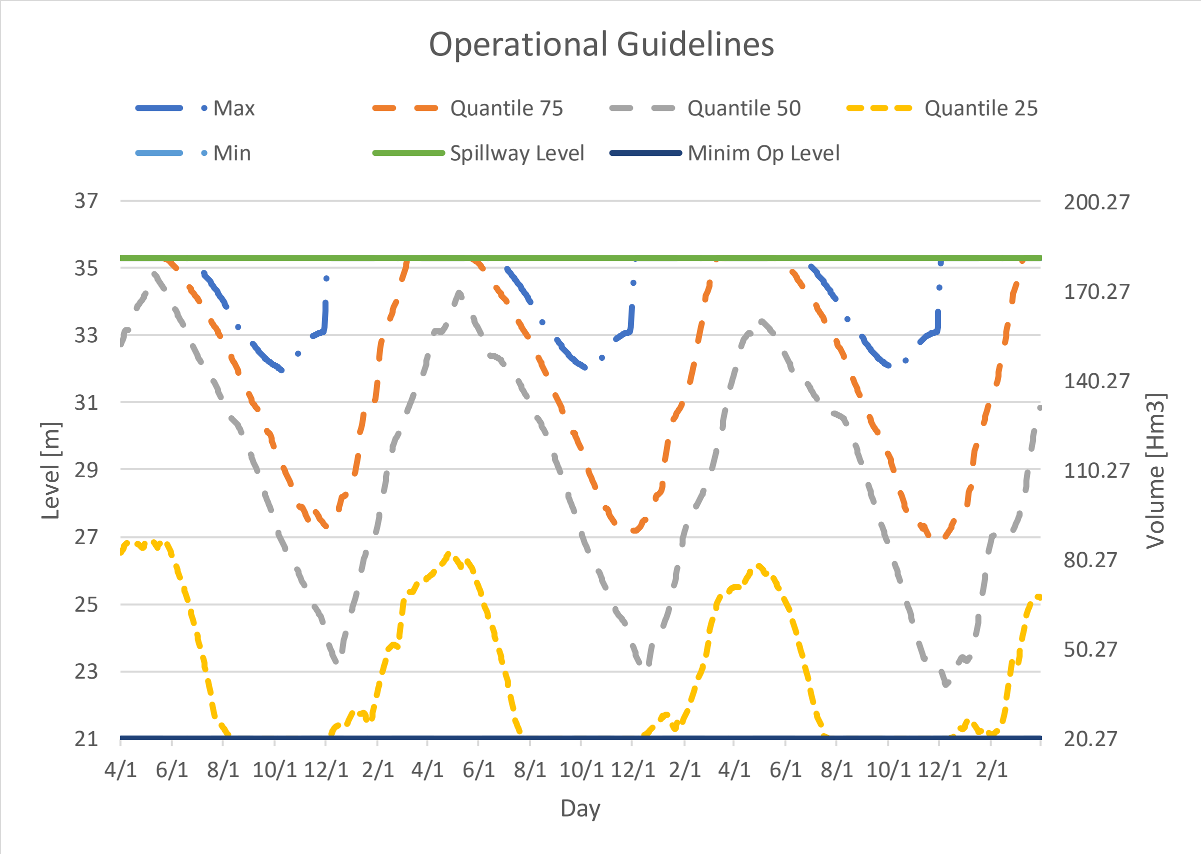

Figure 113 : Medium-Term Operational Guidelines 12 m^3⁄s

- <u>Target Draft:</u> 18 m^3/s

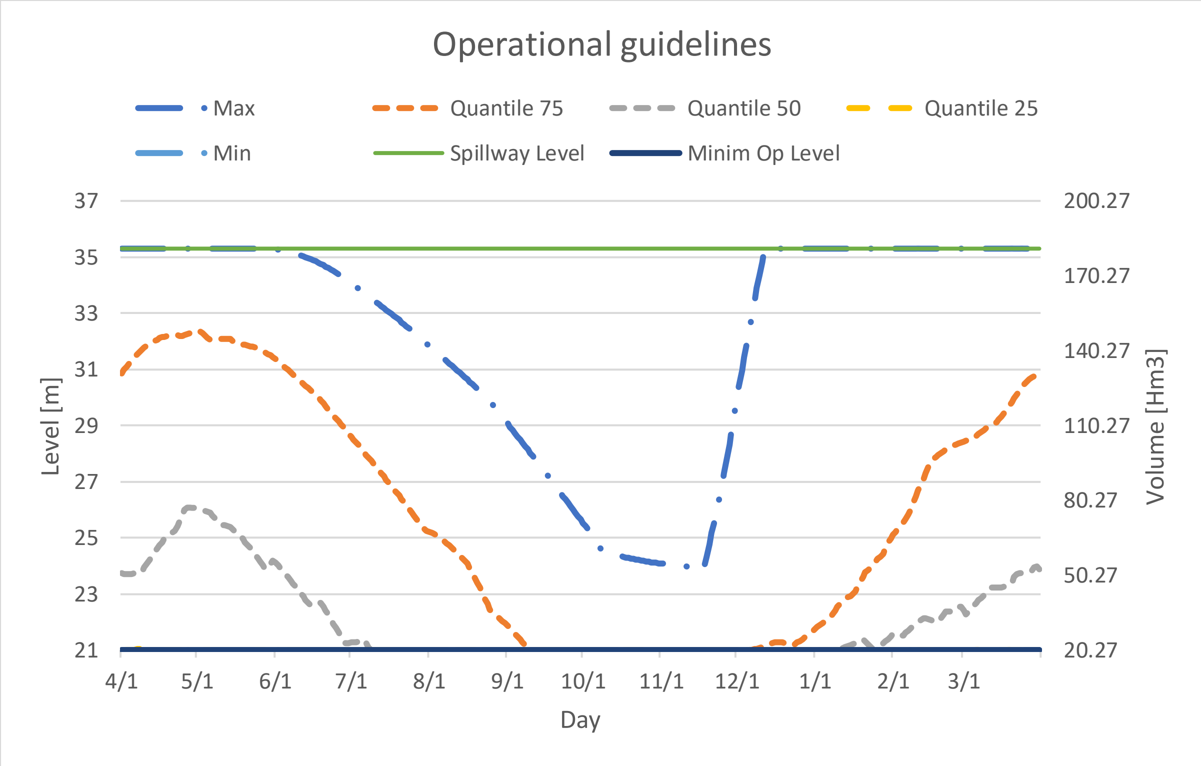

Figure 114 : Short-Term Operational Guidelines 18 m^3⁄s

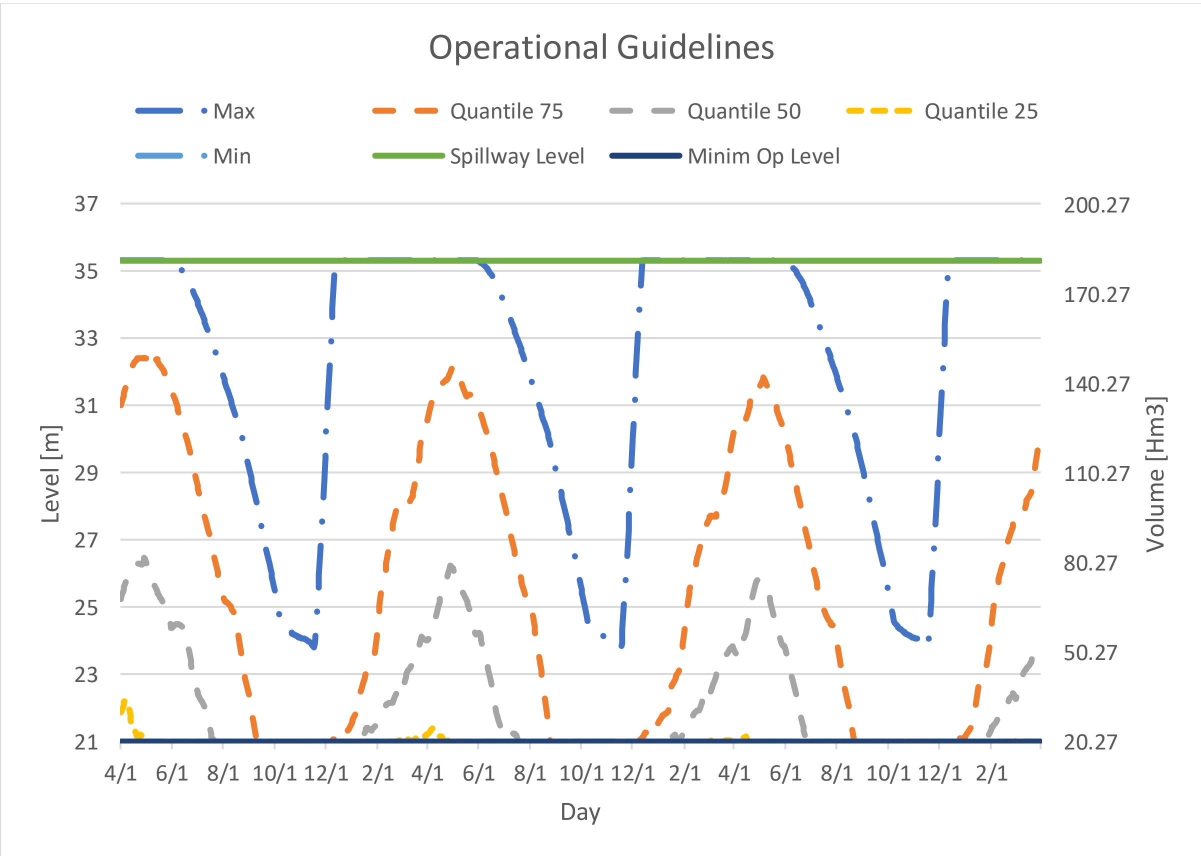

Figure 115 : Medium-Term Operational Guidelines 18 m^3⁄s

- Target Draft: 24 m^3/s

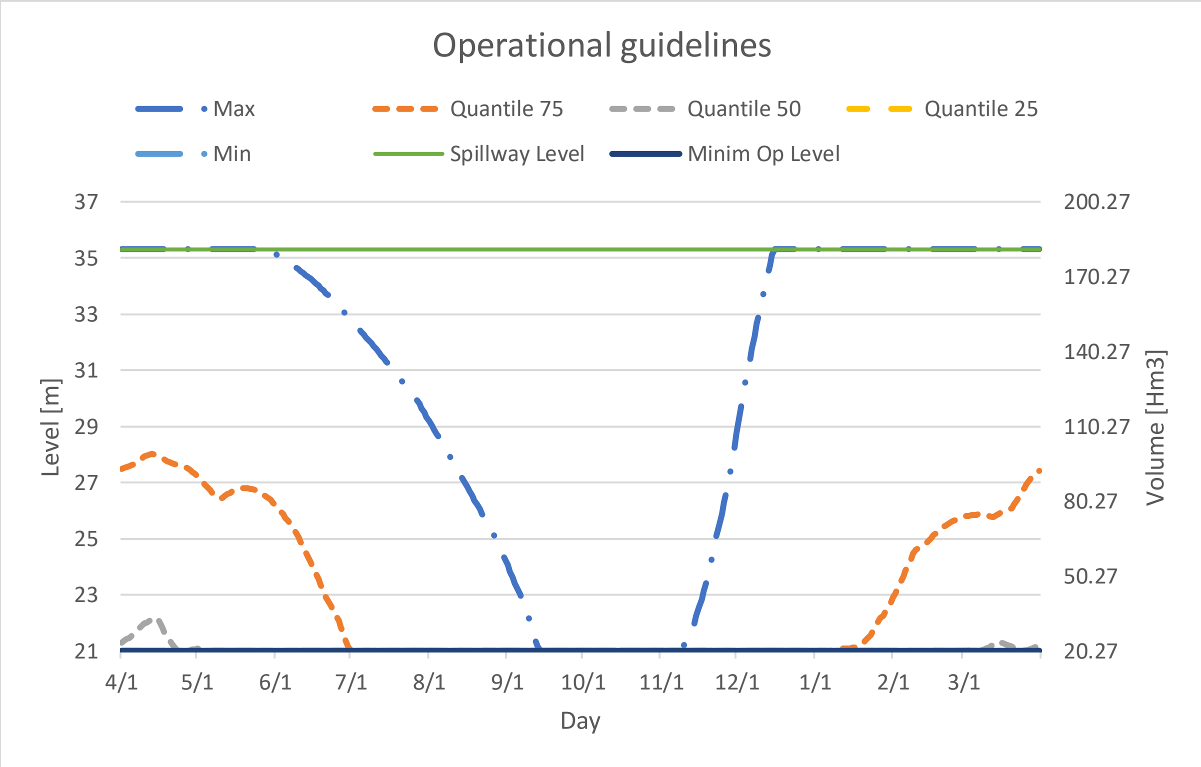

Figure 116 : Short-Term Operational Guidelines 24 m^3⁄s

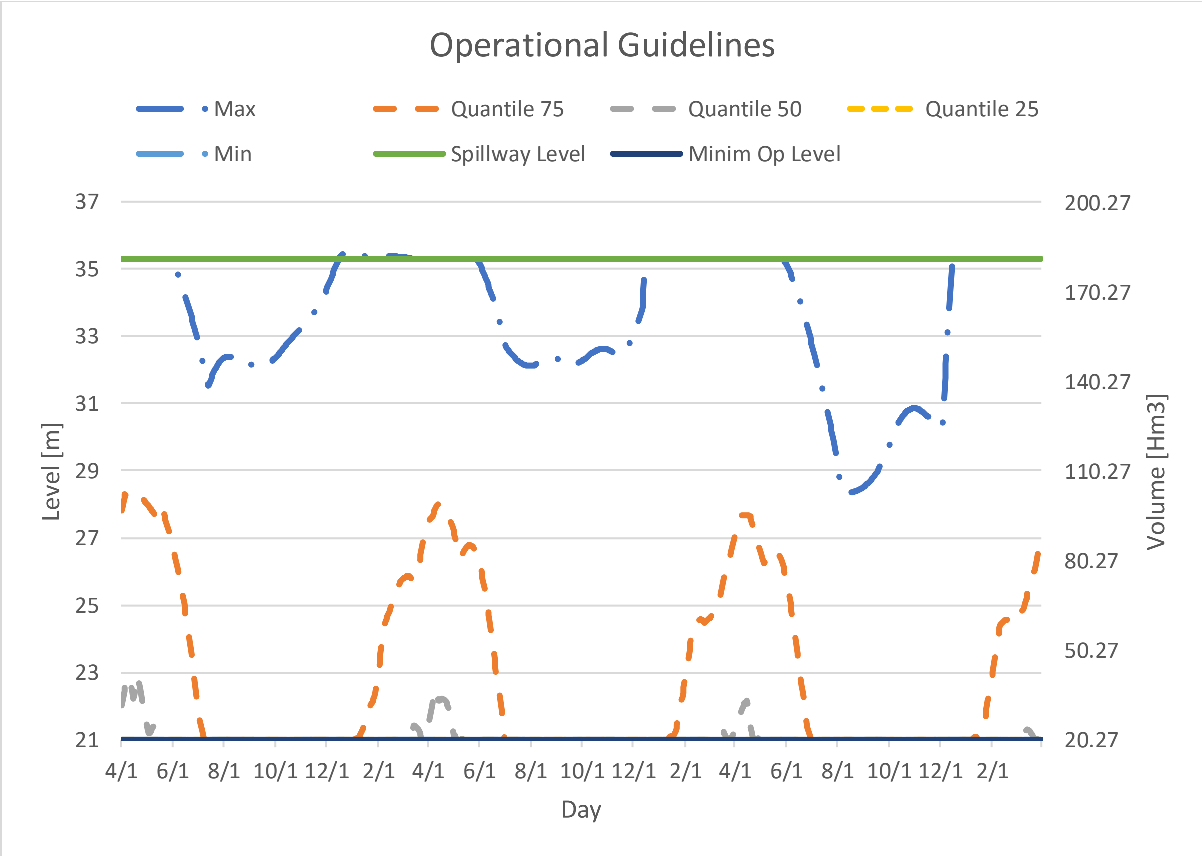

Figure 117 : Medium-Term Operational Guidelines 24 m^3⁄s

Appendix D: Gauge Stations

Estación n°	Nombre	Latitud	Longitud
4732	Bialet Masse	312330	642900
4823	Buen Retiro	312130	644700
4929	Cabalango	312320	643330
4831	Carlos Paz (munic)	312630	643030
4331	CasaGrande	310930	642830
5130	Cerro Blanco	313120	643930
5324	Copina	313400	644200
4531	Cosquin	311500	642820
4931	Costa Azul	312300	642930
5028	Cuesta Blanca	312900	643600
4833	Dique San Roque	312200	642620
4129	Ea. Los Troncos	?	?
5321	El Condor	?	?
5023	El Talar	?	?
4124	El Vallecito	?	?
	Huerta Grande		
5024	La Caballada	312730	644330
4030	La Cumbre	?	?
4230	La Falda		
4825	La Hoyada	?	?
	La Huerta		
	Las Huertas		
	Los Arroyos		
4922	Los Gigantes	312450	644800
	Los Sauces		
4430	Matacaballos	?	?
4431	Molinari	?	?
	Ojo de Agua		

4328	Olaen (El Arroyo)	311030	643730
4532	Pan de Azucar	311400	642550
	Piedras Grandes		
	San Antonio		
4529	San Buenaventura	311350	643300
4632	Santa María	311800	642800
	Santa Rosa de Yuspe		
4828	Tanti	312030	643600
4130	Thea	310400	643000
4328	Tres Arroyos (Ea. El Potrero)	?	?
4231	Valle Hermoso	310930	642830
5029	Villa Independencia	312910	643200
4020	Yerba Buena	313330	643300

Table 15 : Gauge Stations