Reservoir Operation Optimization to Reduce the Pollution in Lempa River

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Reservoir Operation Optimization to Reduce the Pollution in Lempa River

Master Science Thesis
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Abstract

Establish optimal reservoir operational rules in a reservoir is a subject for water management, that not only due to the efficiency of the water use but also in the relationships with another environmental factors. That is the case when the functioning of a multipurpose reservoir is affected by external forces that commits its competences and the improving of those forces have a conflict with the main objectives of the reservoir. In this thesis, and exploration is made of the potential of a simulation-optimization model technique to improve the Güajoyo hydropower generation modifying the operation rules and decrease the level of contamination in the reservoir's water.

Nowadays, the Güajoyo hydropower plant in El Salvador is the one between four that is capable of generate the highest energy production, however it presents high level of eutrophication due to the algal bloom that are presented in the dry season. This reach its peaks of inconvenience when in 2020 the water treatment plant of Torogoz that received water that comes from the reservoir present high concentration of geosmine that is a substance produce by the cyanobacteria, cause discomfort in the users of the service.

This research focus in the development of three tools, the first is the WEAP software where the simulation of the basin was simulated and it produce the inputs of the other tools. A Delft3D model was generated to represent the concentration of contamination in the lake and to set a minimum acceptable water level. Finally, a genetic algorithm is simulated in a Python script that aims to maximize the hydropower generation.

The results of this thesis have shown that GA can improve considerably the performs of the hydropower plant increasing the hydropower generation in the period of study by 2%. However, the reservoir operations obtained weren't capable of accomplish the constraint rules in for the studied timeframe.

the optimization result evaluated in the model is capable of produce more energy than the reference scenario, however, it was capable of follow the constraints requirements.

Keywords: reservoir operation, simulation-optimization model, genetic algorithm, WEAP, Delf3D, water quality model, algal bloom.

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Chapter 1 Introduction

1.1 Background

The Lempa river basin is the second bigger basin in Central America. Is shared by three countries Guatemala, Honduras, and El Salvador which covers almost 50% of the territory. Is divided into three parts, the upper basin shared by the three countries, the medium basin has the bigger area and is shared only by El Salvador and Honduras, and the lower basin entirely in El Salvador (Plan Trifinio, 2009).

The Lempa River, the main river of the basin, is the principal water source of El Salvador and also for the country's capital, the city of San Salvador, which supplies almost the entire water for the city consumption and counts with 20% of the total population of the country. It takes water from the Lempa River through the treatment plant Torogoz, which pumps water directly to supply the capital.

El Salvador presents a tropical climate with a dry and rainy season very pronounced where the temperature varies mostly due to the elevation than for the season. The temperature can oscillate between 28 and 22 °C in the lower zone (0-800 MASL) and 19 °C to (occasionally) be lower than 0 °C in the high part (1800-2800 MASL). The dry season appears in the first four months of the year with average values that can be less than 75 mm a month in the most affected zones of the country. The rainy season appears in the next eight months, with a significant decrease in the precipitation between the months of July and August (Figure 1.1-1), it presents average values of 100 mm a month in all country, however, in the north and the west of the country the total monthly rainfall can exceed 200 mm (MARN, 2018).

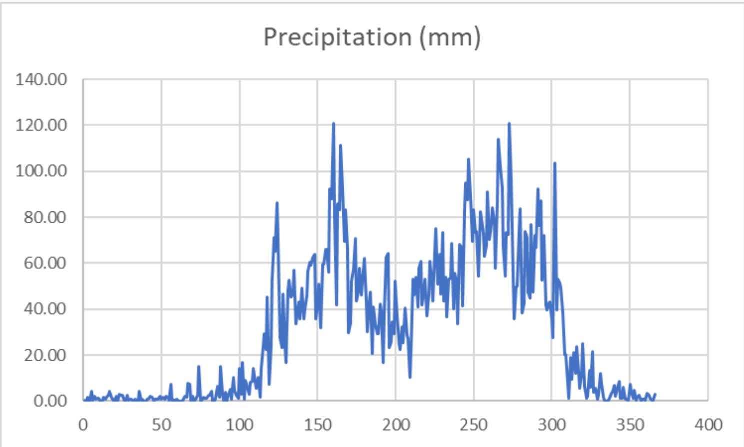


Figure 1.1-1 Daily average precipitation in the Lempa Basin.

Owing to its location is exposed to extreme climate events such as big storms and prolonged rainy and dry seasons that affect a big part of the country. El Salvador is affected by storms with origin in the Caribbean Sea and in the Pacific Ocean been the second one where the biggest storms are born. More related to the topic of this project, the strong dry seasons can be defined as seasons where the total rainfall in a rainy season is less than 1 mm in a period of more than 15 days (MARN, 2017), usually, these events are related to El Niño phenomenon that can appear for more than one year and affect almost the entire country (MARN, 2018).

In El Salvador exist four hydropower plants located in the Lempa river basin that are capable of producing 25% of the total demand of the country, Cerrón Grande, the 5 de Noviembre, 15 de Septiembre, and the Güajoyo hydropower plants. In the last couple of years, the last one is the one that generates more energy (

Table 1.1-1), and the only one that doesn't depend directly on the Lempa River, the main river of the basin, although it discharges to the Desagüe river, one of its tributaries (Diaz, et al., 2021).

Table 1.1-1 Energy produced by hydropower plant in MwH (MARN, 2022a)

Reservoir	2019	2020	2021
Güajoyo	28145.58	54581.01	48919.31
Cerrón Grande	395672.94	395672.94	395672.94
5 de Nov	427346.34	427346.34	427346.34
15 de Sep	484834.66	484834.66	484834.66

In January 2020, an algal bloom problem appears in the treatment plant Torogoz, back then called Las Pavas, that produce an odor and a taste that was perceived by the customers of the service as unacceptable and generate many complaints. For this reason, a study was made to understand the origin of this problem and that is going to be expose next.

1.2 Problem description

Algae exist in a natural state in the Lempa River, however, algal blooms are caused by an excessive load of nutrients that feed the microorganisms, in particular nitrates and phosphates, that comes from animal and human waste or from agriculture. And in the study previously mentioned it has been found that, in this case, almost 75% of the nutrient-based pollution comes from lake Güija (USAID and SWP, 2021).

The Güija Lake is a natural reservoir located in the Upper Lempa Basin and is shared by Guatemala and El Salvador. The lake has an area that can reach at its maximum capacity a total of 51.68 km^2 and is used as a reservoir to supply the Güajoyo hydropower plant that discharges close to the mouth of Desagüe River to finally join the Lempa river downstream as we can see in Figure 1.2-1.

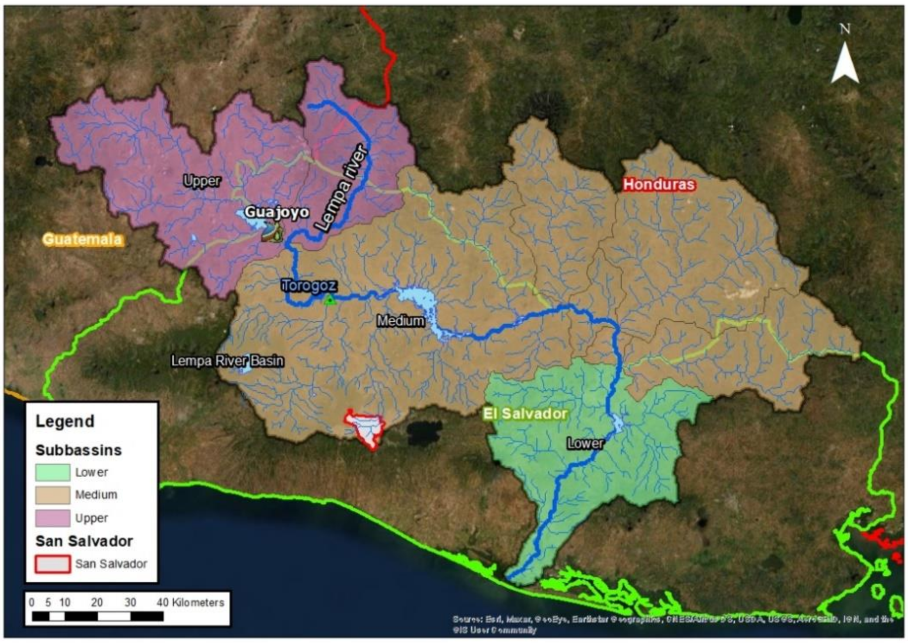


Figure 1.2-1 Lempa River Basin. Basemap obtained by ESRI Basemaps.

The lake is fed by three principal tributaries, Ostúa, Angue, and Cumapa rivers the three tributaries nutrient loads produced by agricultural hillside production and human waste from almost 350,000 people that comes from the Metapan city. There're also agricultural practices on the border of the lake and in-lake and shoreline fish farming (USAID and SWP, 2021).

The nutrient loads together with a rise in temperature and a decrease of the precipitation produce a eutrophic state in the reservoir that promote the growth of cyanobacteria that were transported through the Desagüe river to the treatment plant Torogoz generating the problem already mentioned.

1.3 Objectives

The objective of this research is to explore a methodology that allow to maintain or increase the hydropower generation in Güajoyo while decrease the contamination levels using an optimization algorithm that allows modifying the reservoir operation rules.

This general objective will be reached by the following specific objectives:

- To analyse the water system in the Desagüe basin and develop a water quality simulation model of the reservoir.
- To formulate an optimization problem that considers the different actors in the system.
- To develop an efficient reservoir operation strategy to reduce contamination and maintain hydropower generation.

1.4 Research questions

- Is it possible to optimize the water quality of a reservoir by operating the discharges while considering hydropower objectives?
- Is it possible to improve the water quality of the reservoir in extreme events such as prolonged dry seasons?
- Is there a viable trade-off policy between water quality impact and loss of hydropower generation?

1.5 Literature review

The reservoirs usually are considered multipurpose infrastructure because they have to satisfy different purposes. Depending on the kind of the reservoir, its operation has to regulate the discharge to optimize the energy production, minimize the flood hazard, the negative environmental effects, and avoid water shortage. However, most of the time these variables are mutually exclusive, e.g. high-water levels can generate more hydropower but not leave much storage capacity in case of a warning flood event.

These functionalities represent a problem for the planners and managers that have to make choices to improve the way of how these complex systems works based on alternatives that compare the operating policies with the desired objectives. These alternatives are usually obtained with the aid of optimization that are methods designed to obtain the system performance neglecting the inefficient values (Loucks and Van Beek, 2017).

Various methodologies have been suggested to optimize the operational rules of a reservoir, that consider simulation modelling, optimization modelling, or the combination of both that have the simulation modelling as starting point and implementing an optimization algorithm to simplify the simulation process (Rani and Moreira, 2010). This research will consider this combined approach starting with a simulation model that will represent the hydrological behaviour of the Güajoyo Reservoir.

1.5.1 Hydrological simulation model

Many developments and models have been realized for this purpose, between the most popular can be mentioned SWAT model (Arnold, et al., 1993), which is capable to realize sophisticated physical hydrologic processes, or the US Army Corp of Engineers, HEC-ResSim (USACE, 2021) that can describe the operation rules of the reservoir but need other programs to generate inflows.

In this project the selected program to simulate the hydrology in the reservoir is WEAP. It involves several physical hydrologic processes combined with the management and operation of installed infrastructure. It also counts with a friendly Graphic User Interface (GUI) and is easy to modify with an API with code language (Yates, et al., 2005).

Several studies have been made using WEAP, which can be highlighted a study made by Khoshnazar, et al. (2021) where a model of the Lempa River Basin was developed that where time series of runoff, infiltration, potential and actual evapotranspiration were obtained and calibrated. The two values were next used to calculate drought risk index that contributes to create a drought risk assessment methodology and to have a increase the knowledge of the drought in Central America.

1.5.2 Water quality model

Water quality models has been an effective tool to study the algal bloom that are occurring with more frequency and intensity around the world. The algal bloom is produced by the excessive loads of nutrients for the catchment in combination with relative high water temperatures (Paerl, et al., 2011).

Like the hydrological simulation model, several models have been developed to simulate the interaction between the environment, a network that connects the water bodies and the lake ecosystem (Janssen, et al., 2019). In this research Delft3D-WAQ model will be developed because of its capacity to understand through a mathematical model the interconnection between nutrients and the algal bloom (DELTARES, 2020b).

Deflt3D-WAQ has been used with its module ECO to evaluate the relationship between the hydrological and hydraulic behaviour and the ecosystem of Abras de Mantequilla wetland to produce knowledge of the system and generate management advice (Alvares M., 2019).

1.5.3 Optimization

Optimization of reservoir operation concerns the allocation of water resources, the developing of streamflow regulation strategies and in most of the cases, reservoir operating rules, and using these rules as guidance, help the operators to make decisions of the releases in the operation. The decisions involve a set of rules of regulation plans, operating procedures, or release policies that indicate how much water needs to be store and release depending of the different (Wurbs, 1993).

There have been many types of research in the use of optimization techniques subject to optimization of reservoir operation. Yeh (1985) made a first review on the projects that involves reservoir operation modelling, where he evaluates some classic optimization methods such as Linear Programming, non-linear programming, and dynamic programming.

All this methods are affected by the well-known “curse of dimensionality” that increments dramatically the time required to solve the problems with the increase of complexity of the problem to be evaluated (Feng, et al., 2017).

Consequently, explorations in novel approaches to solving complex natural optimization problems have been developed. One that is gaining more interest in the field of ORO that consider energy optimization as one of the objective functions is the Meta-Heuristic approach, which we can classify in five groups: Evolutionary algorithms (EA), Swarm Based algorithms, Population Base algorithms, and Nature Inspired algorithms, where genetic algorithms (GA) and Particle Swarm Optimization (a subset of EA and Swarm Based algorithms respectively) are the most commonly used (Azad, et al., 2020).

The optimization part of this research will be achieved with a GA. This is a probabilistic algorithm based on the Monte Carlo technique used to solve optimization problems that try to find the closes solution to the optimal value through a series of processes that are inspired by natural phenomena such as genetic inheritance and Darwinian strife for survival (Michalewicz, 1992).

The efficiency of the GA has been study in different research projects that involves optimization problems with only one objective function, such as Wardlaw (1999) that use GA in the four-reservoir problem formulated by Larson (1968) to find an optimal value and compare it with the already solved, demonstrating that GA provide with robust acceptable solutions.

1.6 Innovation

The methodology developed in this project can obtain the following innovations:

- The use of a simulation model for water allocation with a water quality model to develop a computational framework to optimize the water level on a reservoir in different scenarios.
- The application of an optimization algorithm that considers the hydropower generation and the contamination in the reservoir.

1.7 Practical value

The outcome of this research aims to benefit stakeholders in the water management area and more directly the ones related to reservoir operation. The results will provide a tool that facilitates the decisions in the particular case of multipurpose reservoir operation, which is expected to be used specifically in Güajoyo reservoir to improve the life quality of the people that depends on the Lempa River.

1.8 Thesis structure

The thesis is divided in five chapters. The present chapter provides a general overview of the research framework giving a description of the background of the zone of study, a description of the problem that is presented, defining the objectives and the research questions, also a literature review is made where different methodologies has been applicated to solve similar problems, we describe the innovation and the practical value of this project.

In chapter two we describe the methodological framework, which is divided in four parts that involves the data collection, the develop of a water allocation model, a water quality model and finally the optimization model. Third chapter is the Case Study where information of the zone, the problems and the data available are defined.

In chapter four the methodological framework is followed dividing the chapter in three parts, the water allocation model setup, the water quality model setup, and the optimization model setup. In the chapter five, the results are presented and analysed in terms of the reservoir operation politics and performance of the GA.

The sixth chapter, of the research present the conclusions and it closes the document making some recommendations regarding the applicability of the methodology and the performance of the optimization algorithm.

Chapter 2 Research methodology

In this chapter is presented the methodology that is followed in the research. The workflow presented in **Error! Reference source not found.** is divided in four major steps, the first one involves the system analysis and data collection necessary to develop the models (step 1), followed by the preparation of a water allocation model generated in WEAP that will be calibrated from an existing model of the basin (step 2), a water quality model to reproduce the behaviour of the contaminants in the reservoir with Delft3D (step 3), and concluding with an optimization algorithm (step 4).

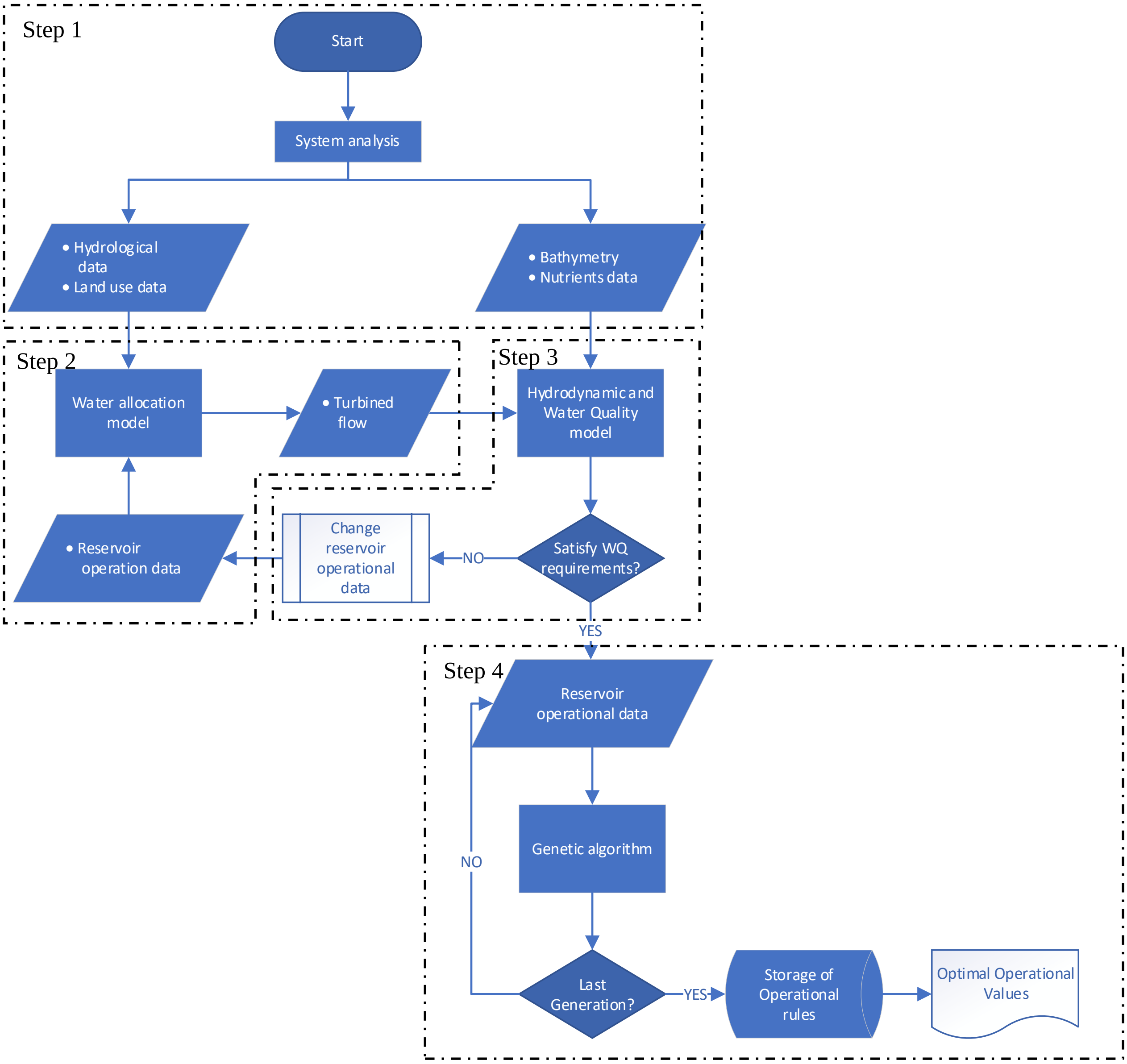


Figure 1.8-1 Research methodology workflow

2.1 Data collection

One WEAP model was provided by the Stockholm Environmental Institute (SEI) where the entire Lempa River Basin was modelled. The model was simplified to represent only the Desagüe basin and reduce the time of calculations. It had defined several parameters such as the schematic construction of the Desagüe and Lempa basin, and the Güajoyo reservoir, and the necessary information to produce an initial rainfall-runoff evaluation.

However, the necessary inputs to calibrate a model that represents the Güajoyo basin were obtained from satellite databases and information provided by the Ministry of Water and Natural Resources (MARN).

Due to the difficulty to find gauge stations in the area, it was decided to evaluate different satellite databases in the modelling process. It was used some databases recommended by Beck, et al. (2017) for the small resolution and the mean correlation, such as CHIRPS V2.0, ERA-Interim, and the one used by default in WEAP Princeton Global Meteorological dataset, were the first one which produces the more accurate results.

A single daily CHIRPS V2.0 data had to be downloaded from the database, for that reason a python script was used to obtain several days that covers a range of data from 2013 to 2019 with a resolution of 0.5°. The data was modified using xarray library in python (Hoyer and Hamman, 2017) to join the files and create one file that WEAP can read.

Also, inflow, outflow and reservoir water level data were provided by MARN, besides some general reservoir operation rules that are expressed in

Table 1.1-1.

Table 2.1-1 Summary of data collected for WEAP model.

No.	Description	Period
1	Dam inflows	2002-2020
2	Turbined flow	2002-2020
3	Reservoir water level	2002-2020
4	Total monthly hydropower generation	2015-2021
5	General energy production information	2021

For the water quality model in Delft3D the bathymetry of the reservoir was obtained, also a technical report with concentration levels in the rivers that discharge in the reservoir (MARN, 2020) and information about the concentration levels in the reservoir.

2.2 Water Resource System Model

A water resource system model can represent the behavior of the components, interactions and processes of the different elements in the system through mathematical expressions (Loucks and Van Beek, 2017). In this part of the methodology process an analysis of the basin behavior and the reservoir operation is represented through the model WEAP.

2.2.1 Water Evaluation and Planning model

A base WEAP model was developed by the SEI for the entire Lempa River Basin. The model was used to obtain a robust representation of the water allocation of the system, it has information about demand sites, operation of two of the four existing reservoirs, and the catchment processes such as evapotranspiration and runoff with a daily climate data that goes from 1948 until 2010.

Even though this model has a considerable database of the basin, it was necessary to make some adjustments to fit better into the current research objective. First, the area of study covers only the upper part of the basin, specifically the Güajoyo basin, for that reason the middle and lower basin, and the upper Lempa Basin that does not correspond to the study area, information was eliminated, this simplifies the model and improves the calculation time of the program. The second adjustment was the modification of the parameters of the Rainfall-Runoff method to calibrate them with the information on the reservoir inflow that we received. And the third change was the modification of the physical, operational and hydropower generation of the Güajoyo hydropower plant.

2.2.2 Rainfall-Runoff Method

WEAP counts with five methods to calculate processes like runoff and evapotranspiration, the one used in this research is the Soil Moisture method. This method is one-dimensional and considers that the basin can be divided in many areas and all of them has two layers or buckets, the top one named root zone bucket is considered shallow-water capacity and the deep zone or bottom bucket is considered deep-water capacity that can be defined separately and the water balance is expressed as in Equation 2.2-1.

Equation 2.2-1 Water balance equation for a basin.

$$Rd_j \frac{dz_{1,j}}{dt} = P_e(t) - PET(t) * k_{c,j}(t) * \frac{5z_{1,j} - 2z_{1,j}^2}{3} - P_e(t) z_{1,j}^{RRF_j} - f_j * k_{s,j} * z_{1,j}^2 - (1 - f_j) * k_{s,j} * z_{1,j}^2$$

The $z_{1,j}$ value represents the fraction of the root zone effective storage, P_e is the effective precipitation. Rd_j is the land cover fraction j soil holding capacity in mm, RRF_j is the Runoff Resistance Factor that decrease the runoff while this value increase. The last two terms represent values of interflow and percolation where $k_{s,j}$ is the root zone conductivity and fj is a coefficient that depends on physical parameters of the basin such as topography, land cover type, and soil.

PET is the potential evapotranspiration calculated with the Penman-Monteith equation modified (Maidment, 1993), $k_{c,j}$ is the crop coefficient for one defined area of the basin. for this model we consider that only one area for the entire basin. A representation of the model is shown in Figure 2.2-1 (Sieber and Purkey, 2015).

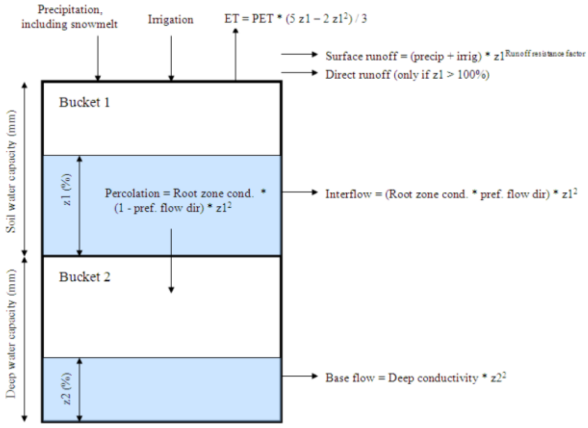


Figure 2.2-1 Conceptual diagram of the water balance calculation in WEAP (Sieber and Purkey, 2015).

2.2.3 Reservoir operation

From the reservoir operation the inputs of the optimization algorithm are obtained, the total energy generation of the turbine will be the objective function, for that reason the understanding of the process of energy generation is critical. The WEAP model for reservoir uses the water balance equation (Equation 2.2-2) to obtain the flow that passes through the turbine.

Equation 2.2-2 Reservoir Water Balance Equation.

$$Outputs\ (O) = Inputs\ (I) - Change\ in\ storage\ (\Delta S)$$

The outputs for this model are the flow that passes through the turbine, the net evaporation (difference between the actual evaporation and the precipitation), and the discharge in a spillway that only will be consider if the water level is bigger than the maximum storage capacity of the reservoir.

The storage for operation (StO) that is the total storage in the reservoir available as outflow. The StO is the total of initial storage plus the inflow and the net evaporation, that will be negative in case that the evaporation is bigger than the total precipitation, the value of the evaporation is obtained multiplying the reference evapotranspiration by the soil evaporation coefficient (Allen, et al., 1998). However, WEAP doesn't use the entire StO as outflow, instead it depends on some constraints such as the maximum flow that can pass through the turbine and the reservoir operation rules in what is called storage available for release (StAR).

The StAR depends in which zone of the reservoir is the actual volume of the water. WEAP divides the storage into four zones (Figure 2.2-2), the first one is the Flood Control Zone and is only fill when a flood event occurs, the second is the Conservation Zone where WEAP allow to release the entire volume of water available, the third or Buffer Zone that restrict the quantity of water available according to the Buffer Coefficient, and finally the Inactive zone where no water is available to be used as outflow.

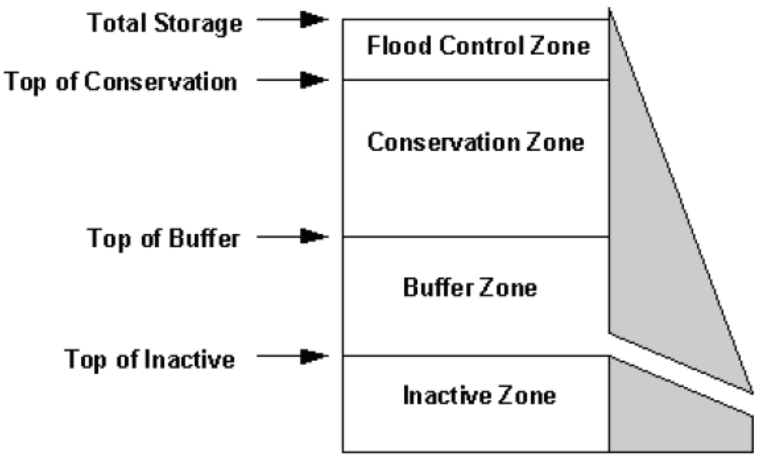


Figure 2.2-2 Illustration of Reservoir operation in WEAP.

The StAR is then given by the Equation 2.2-3 and the limits of every zone are set by the volume of Total storage, Top of Conservation, Top of buffer and Top of Inactive. It has to be highlighted that even if the volume is above the buffer zone, the volume in the buffer zone will still be limited by the Buffer Coefficient.

Equation 2.2-3 Storage for release.

$$\text{StAR} = FloodAndConservationVol + BufferVol * BufferCoefficient$$

Finally, the total hydropower generation is the value that we optimized and is obtained by the Equation 2.2-4 and is the product of the outflow produced by the StAR named volume of water through the turbine (VTT) by what is called hydro-generation factor (HGF) (Sieber and Purkey, 2015). Values such as drop elevation, Plant Factor and Plant Efficiency were obtained from the MARN.

Equation 2.2-4 Hydropower Generation Factor.

$$\text{HGF (GJ)} = 1000 * DropElevation * PlantFactor * PlantEfficiency * 9.806/10^8$$

Equation 2.2-5 Hydropower generated for one timestep.

$$HP = VTT * \text{HGF}$$

2.3 Delft3D Water Quality Model

Delft3d Water Quality Model (Delft3D WAQ) is used to obtain the minimum water level necessary to be consider to have acceptable conditions. To achieve this is necessary to develop a hydrodynamic model with Delft3D Flow that is going to be an input for the Water Quality model and finally obtain the Water Quality index from it.

2.3.1 Hydrodynamic model

The hydrodynamic model takes two inputs from the WEAP model, the inflow to the reservoir, the environment temperature and the flow that pass through the turbine as a discharge in the model.

2.3.2 Delft3D hydrodynamic governing equations

The governing equations in Delft3D are the Navier Stokes equation for incompressible fluid. For this it in a finite difference grid solve the momentum and continuity equations and a set of initial and boundary conditions.

In vertical direction Delft3D can be defined with two different vertical grid system: the σ coordinate system (σ-model) and the Cartesian Z co-ordinate system (Z-model). The σ-grid create a set of layers of different high parallel to the bottom of the water body and the water surface, the Z-grid create parallel grids with the same high and the number of active layers depends on the depth (Figure 2.3-1). The Z-model will be used in this research because it has the advantage that offers a better representation of a stratified water system affect the vertical exchange processes.

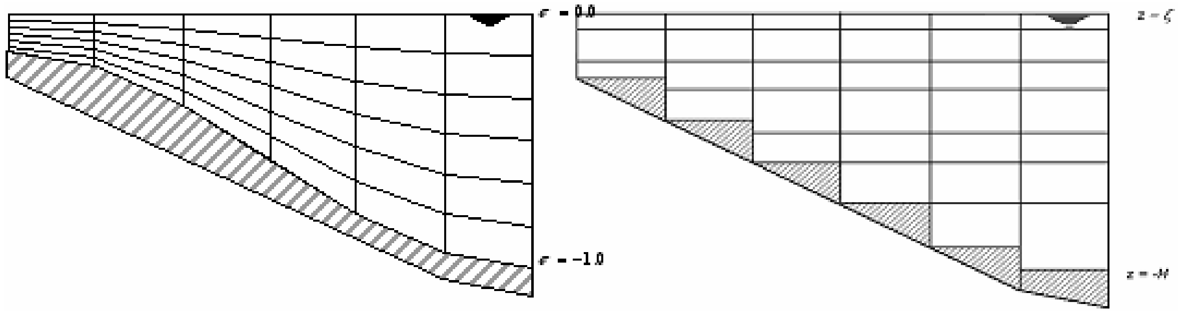


Figure 2.3-1 σ and Z grid comparation.

The numerical schemes used in the hydrodynamic model are defined for horizontal and vertical advection for momentum equation and horizontal advection and diffusion for transport are showed in Table 2.3-1 (DELTARES, 2020a). The model produces a communication file that is used as input for the Delft3D-WAQ model with information about grid, time, waste loads, and water velocity and other hydrodynamic process.

Table 2.3-1 Advection and diffusion schemes for Z-layer model (DELTARES, 2020a).

Process	Options selected
Horizontal advection	Flood solver
Vertical advection term	Fully implicit time integration
Horizontal advection for transport	Van Leer-2
Horizontal diffusion for transport	Fully explicit time integration

The inputs of the model are the reservoir inflow and the temperature from WEAP, we also consider the reservoir outflow as a discharge in Delf3D as the user manual recommends.

2.3.3 Delft3D WAQ model

Delft3D-WAQ solves the advection-diffusion-reaction equation on the predefined grid for one or many substances Equation 2.3-1.

Equation 2.3-1 Advection-diffusion-reaction equation.

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} - D_x\frac{\partial^2 C}{\partial x^2} + v\frac{\partial C}{\partial y} - D_y\frac{\partial^2 C}{\partial y^2} + w\frac{\partial C}{\partial z} - D_z\frac{\partial^2 C}{\partial z^2} = S + f_R$$

The substances have to be defined by the user, nevertheless, the model counts with the processes library a wide range of predefined processes and substances divided into functional groups that can be selected to study the required water quality parameters. An example of these groups can be the primary production group that represents the phytoplankton growth and requires the definition of functional groups like nutrients nitrate, ammonium, phosphate, and silicon. Figure 2.3-2 shows the interaction that delft3D-Processes Library considers (DELTARES, 2020b).

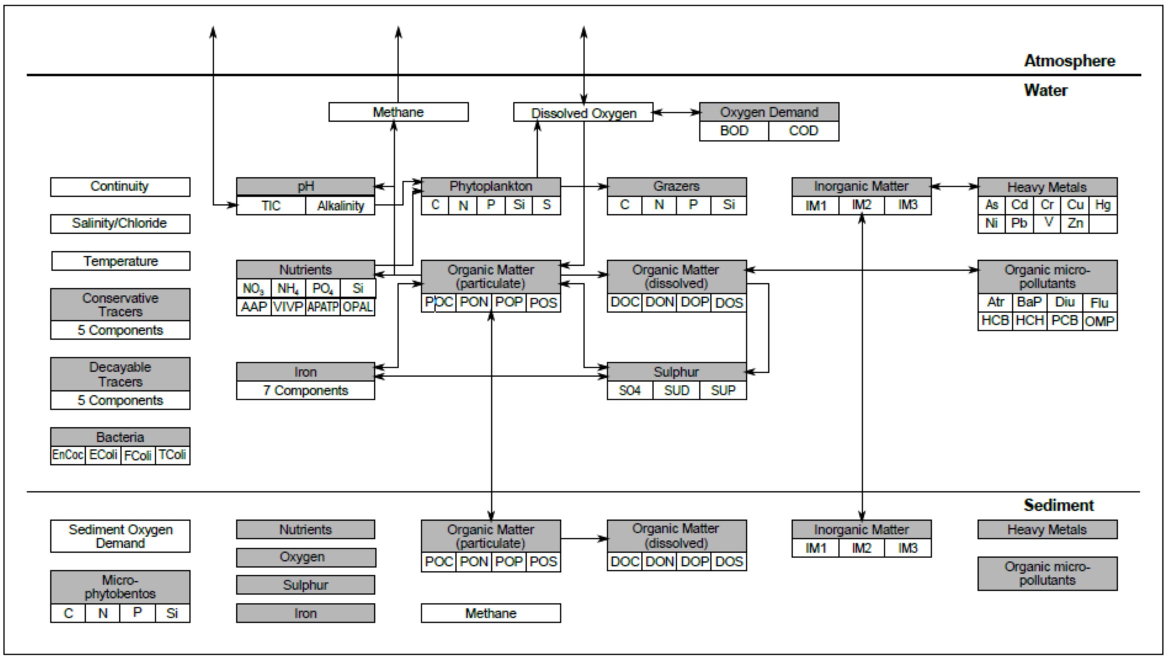


Figure 2.3-2 General overview of substances included in D-Water Quality (DELTARES, 2020b).

This part of the methodology is about understand the behaviour of de algae growth process in the reservoir. To represent the algal growth, the process library offers two approaches: BLOOM and DYNAMO (DELTARES, 2020b). BLOOM can be selected by the choosing the ECO option, this permits the user to model several algae species with different characteristics between them with a more sophisticated growth model that considers production, respiration, excretion, mortality, grazing, resuspension, and settling, however, to implement the BLOOM approach a differentiation of the phytoplankton species needs to be measured.

DYNAMO is limited to two groups of algae, “algae” and “diatoms”. With this approach general coefficients are selected that imply an advantage in its use, however, this simplicity has the disadvantage that the results are less accurate. This model applies the Monod model to determine the growth rate (Equation 2.3-2).

Equation 2.3-2 Primary production rate.

$$knp_i = fdl_i * frad_i * fnut_i * ftp_i * kpp_{i,20} - krsp_i$$

Where knp is the net primary production rate constant for the algae, fdl, frad, fnut, and ftp are the daylength, light, nutrient, production limitation functions respectively, kpp_{20} potential maximum production rate constant at 20 °C, and krsp total respiration rate constant.

The nutrients related to the algal growth are Phosphorus (P), Nitrogen (N), and Silicate (SiO^{4-}), however, the first two have been the principal focus to control eutrophication.

Phosphorus is usually scarce in nature for three reasons, only a part of the total phosphorus is available to be consumed by the phytoplankton, the reactive soluble phosphorus or orthophosphate (PO_4^{3-}), it doesn’t exist in gaseous form like nitrogen, and it tends to settle into the water bed making it not available for consumption.

The nitrogen process is very complex, however, is very important to understand it for the substance that has to be chosen in the process library, the natural N cannot be consumed by all the phytoplankton species (cyanobacteria can consume N in its natural state), phytoplankton can consume the organic N that is the product of animal and bacteria consumption, this organic N is later transformed into ammonium Ion (NH_4^+) and Ammonia gas (NH_3) through a process called ammonization, only NH_4^+ can later be consumed by phytoplankton to start the nitrification process, it consists in the transformation of NH_4^+ into Nitrites (NO_2^+) to be later consumed by bacteria and generate Nitrates (NO_3^-) this last one can also be a source of supply for phytoplankton resulting in organic N.

The nitrification process consumes oxygen so, in a eutrophicated water body where the level of oxygen is low, the process stops and start the consumption of NO_3^- by some bacteria generating NO_2^+, this is called denitrification, known that NO_2^+ cannot be consumed by phytoplankton but it can by some bacteria transforms it into natural nitrogen to starts the cycle. This process is resumed in Figure 2.3-3 (Chapra, 2008).

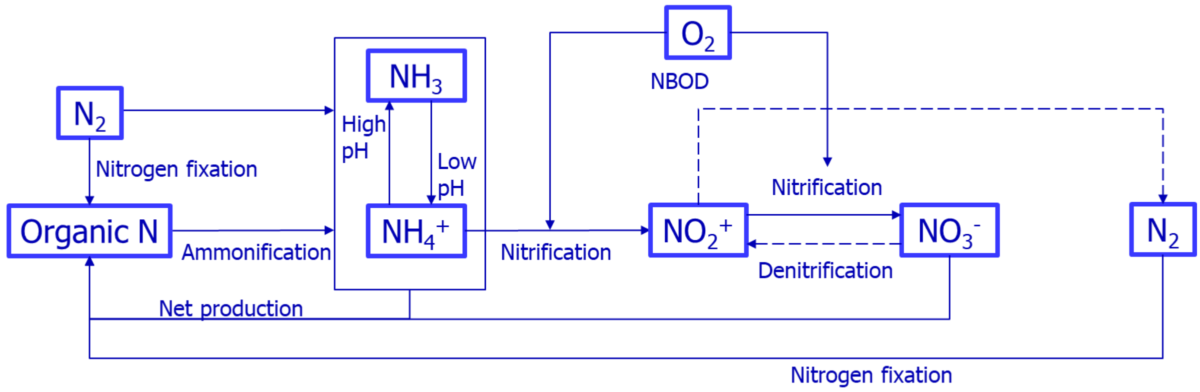


Figure 2.3-3 Nitrogen process scheme.

The substances choose from the library then are Algae (non-Diatoms) from the algae Group and the Ammonium (NH4), Nitrate (NO3) and Ortho-Phosphate (PO4) from the Dissolved inorganic matter group. The initial condition of the nutrients and algae in the reservoir where obtained by MARN (2022b) and the waste loads that comes from the inflow of the reservoir defined in the hydrodynamic model where provided by MARN (2020). The information of the inflow loads are yearly measures, for that reason in the model has been set by a constant load in all the time frame.

2.3.4 Water Quality Constraint

The reason to build a water quality model in this research is to generate a constraint to the optimization algorithm. The concentration of the algae is expected to be inversely proportional to the volume of water in the reservoir, in that order of ideas, when the concentration of algae is bellow certain limit that we are going to define, the elevation and consequently, the volume of water will be the minimum water volume constraint of the optimization algorithm.

The limit of algae concentration is obtained from Ibelings, et al. (2021) where an average correlation of 1:1 is made between the chlorophyll-a and the total Phosphorus concentration for medium depth lakes with a maximal depth that goes from 8.5 m to 29 m, and a total concentration of total phosphorus of 50 gP/L which means that the elevation value that produce a concentration of chlorophyll-a bellow 50 gChll/L is going to be used in the optimization model as a constraint.

2.4 Optimization

The main objective of this research is to maximize the energy production of a reservoir while reducing the water pollutants concentration. In principle find the maximum or minimum values relates an optimization problem.

The two objectives are directly or indirectly related with the water elevation, the water necessary to pass through a turbine depends on how much water in the reservoir is available, and the water contamination concentration depends on the mass of the contaminant that is present in the volume of water in the reservoir that is related to water elevation.

The more water is discharged through the turbine more energy will be generated, however is the discharges increase the water elevation will be reduce which will increase the pollutants concentration in the reservoir.

Having this in mind, the problem can be see it as a multi-objective optimization problem with two objective functions, produce energy and decrease pollutant concentrations. However, the purpose of the water quality model is to transform the objective function of reduce the water contaminations in a constraint identifying an acceptable minimum water level transforming the problem only in single-objective optimization, maximise energy generation.

$$f_{(\max)} = hydropowerGeneration$$

The hydropower generation is going to be calculated with the mathematical model proposed in WEAP, that divide the volume of water in different zones (see chapter 2.2.3). The top of inactive is going to be the minimum capacity of the reservoir, the top of conservation in this case is going to be considered as the maximum capacity of the reservoir, in both cases are constant values and neither of them can be modified.

The top of buffer and the buffer coefficient are the two only variables that can be manipulated to achieve an optimal solution and that's why they will be considered as the variables of the optimization problem.

Nevertheless, to achieve an optimal certain constraint needs to be considered. First the minimum water elevation to prevent a high concentration of pollutants; and second, the total energy generated in a month is preferable than the total energy generated in the entire timeframe.

To solve the optimization problem this research will apply the Pymoo library in python to address a single-objective optimization with a Genetic algorithm (Blank and Deb, 2020). This optimization algorithm can only realize minimization algorithm, but a maximization problem can be defined multiplying the objective function by -1. The inequality constraints in the library needs to be defined as function higher-than-equal-to zero as is showed in Equation 2.4-1.

Equation 2.4-1 Inequality constraint definition example.

$$x \geq 5 \rightarrow 0 \geq 5 - x$$

2.4.1 Optimization algorithm operators

The next step is defining the operators of the GA (Figure 2.4-1). The algorithm uses a binary implementation which means that the vector values are going to be coded using the same numbers of bits. The first generation set random values of TOP and BC to initialize the GA and a fitness value is evaluated for each decision variable set and ranked. The selection process is set as random values. The crossover is a two-point crossover that is applied to all parents selected. A mutation with a probability of 0.001 is evaluated in all genes. Finally, the termination criteria will be set for the 500 generation.

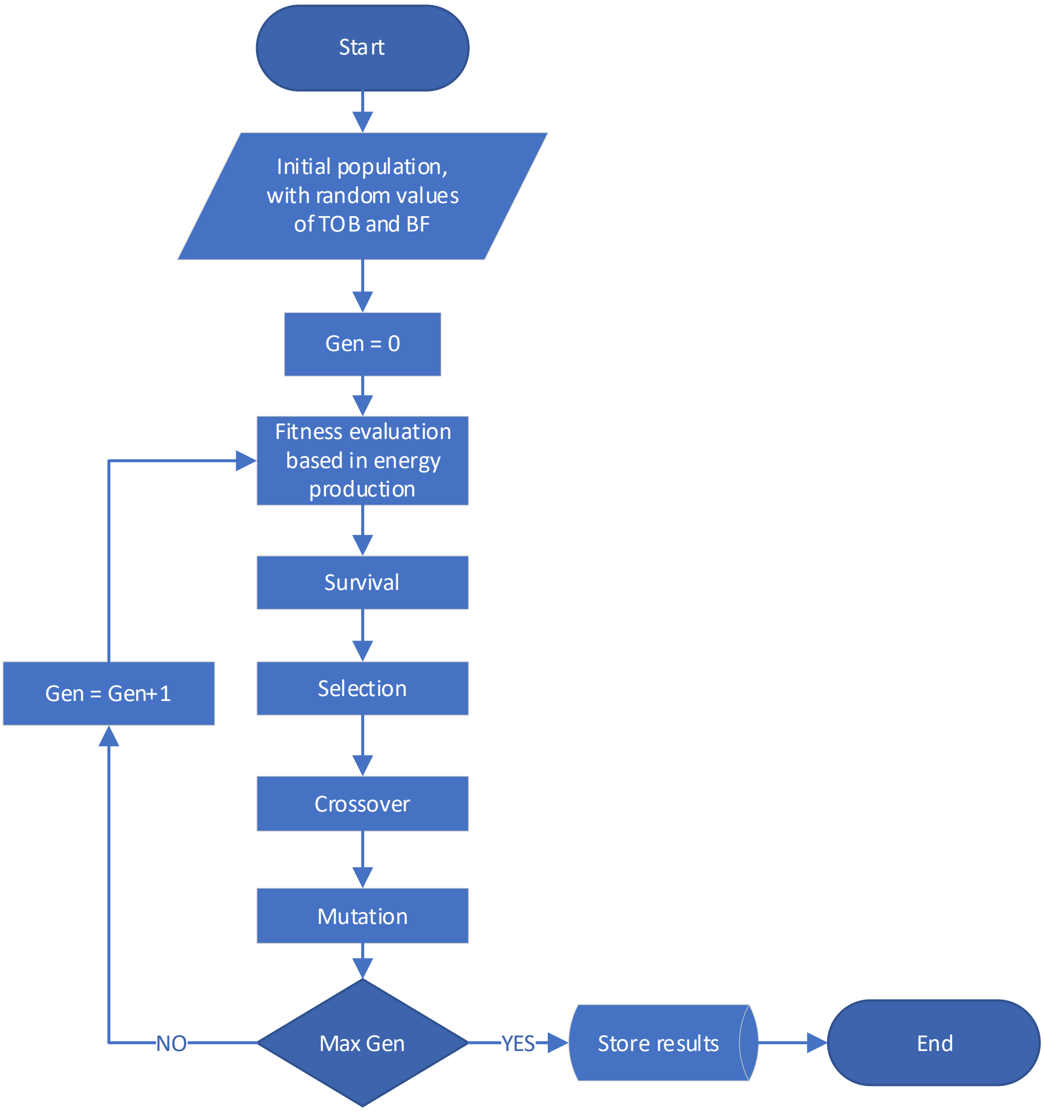


Figure 2.4-1 Conceptual optimization framework.

Chapter 3 Case Study

3.1 Case study description

Güajoyo reservoir or Güija lake is a natural lake and one of the principal sources of water of El Salvador. It has almost 45 km^2 of surface area, is located in Central America and is divided by the border of El Salvador and Guatemala where the major part of his basin is. It receives water fromthree sources, Ostua, Angue and Sanjo rivers, having the two first the origin in Guatemala, been Sanjo the only one that is born in El Salvador (Figure 3.1 1). The Ostua river is the one that produce more water and, as we are going to see later, the one that has more pollutant loads. We are not going to consider the demand of some agricultural areas, San Salvador and the reservoirs downstream for this model.

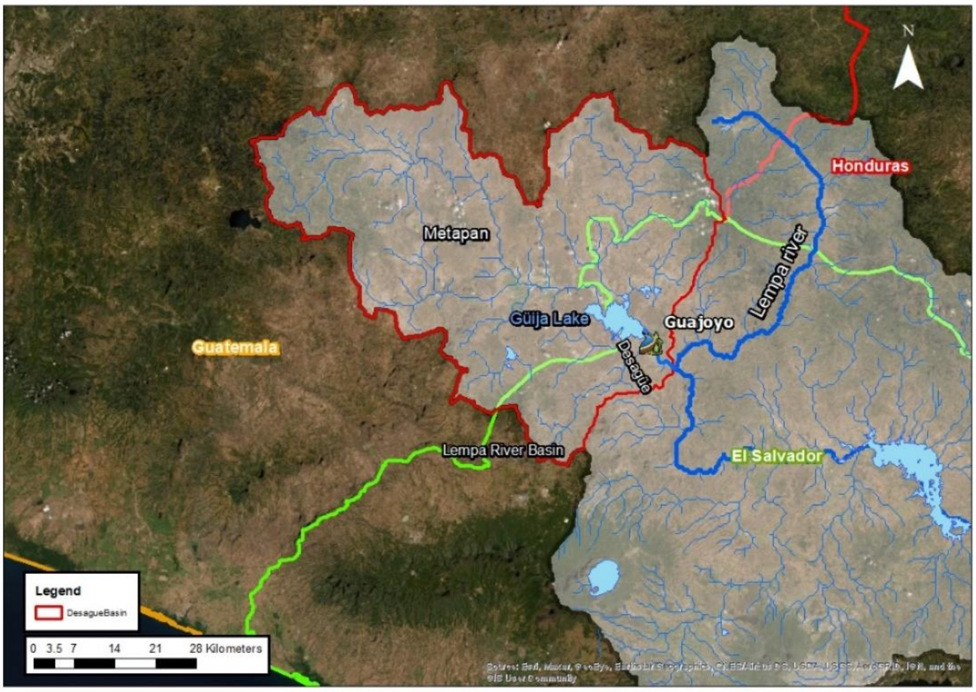


Figure 3.1-1 Güajoyo basin by ESRI Basemaps.

The agricultural activities are predominant in the basin not only in the upper part but next to the reservoir, where also fish farming is practiced that is thought that are the principal source of pollution in the lake. The lake has a touristic and historical importance because pre-columbian objects has been found in its waters.

The lake presents important levels of algal concentration specifically cyanobacteria that have reach alert levels for the lake and the Torogoz treatment plant, in consequence high levels of eutrophication, rising temperatures, and increasing of the atmospheric carbon dioxide has been detected (USAID and SWP, 2021).

The Güajoyo hydropower plant is supplied by the Güija lake but they are not connected directly. the plant is connected to the lake by what is called the Güajoyo canal Figure 3.1-2, the canal has an average depth of 12 m and a longitude of around 2.00 Km, it provides water to the turbine with a pipe that is 51m under the maximum capacity of the reservoir to finally discharge to the Desagüe river.

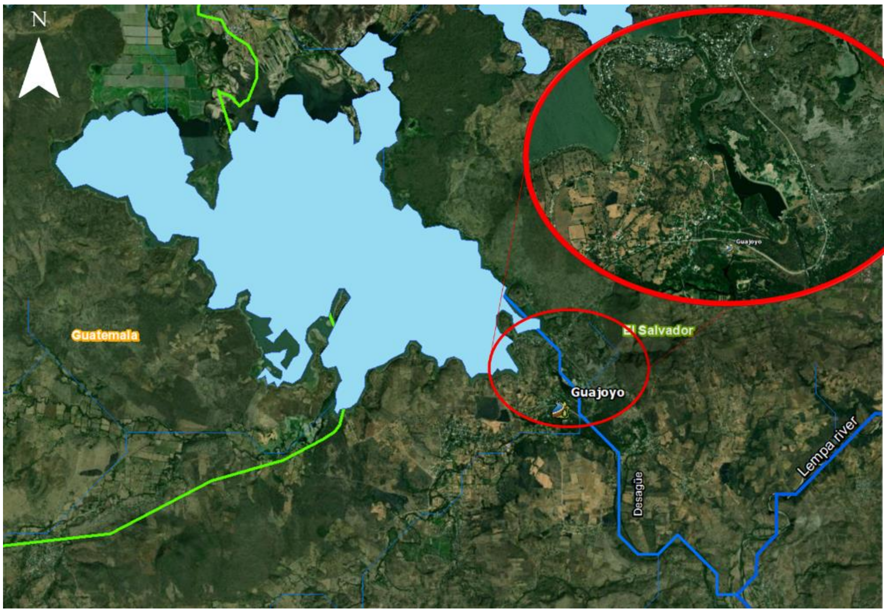


Figure 3.1-2 Güajoyo canal.

3.2 Data availability

3.2.1 Bathymetry

To create a grid needed for the hydrodynamic model first the bathymetry of the reservoir was used to generate a DEM with a GIS program, that is used to set the water quality model samples (Figure 3.2-1).

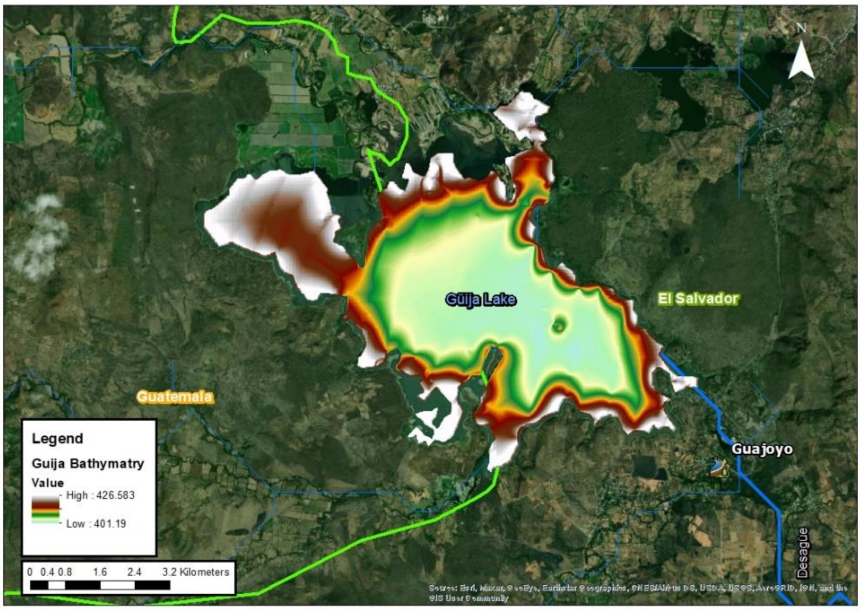


Figure 3.2-1 Güija Lake bathymetry.

3.2.2 Hydrological data

To represent the system in WEAP a dataset of inflows of the reservoir was provided with daily values of discharge in CMS for the period 2002 until 2020 (Figure 3.2-2). This dataset is congruent with the hydrologic behaviour of the basin, having a dry period at the beginning of the year and a wet season in the rest of the months with two peaks at the beginning and at the end of the season. Not all the period of time is going to be used in the model because not all datasets have the information.

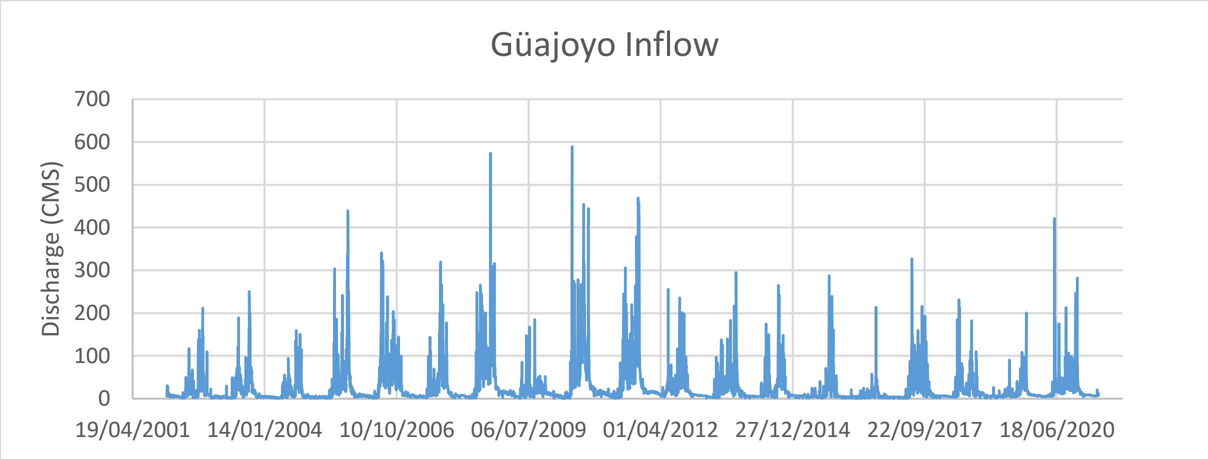


Figure 3.2-2 Daily inflow from January 2001 to December 2020.

In the same way a register of the turbined flow Figure 3.2-3 and a reservoir water Figure 3.2-4 levels was provided, this information is useful to calibrate the reservoir operation

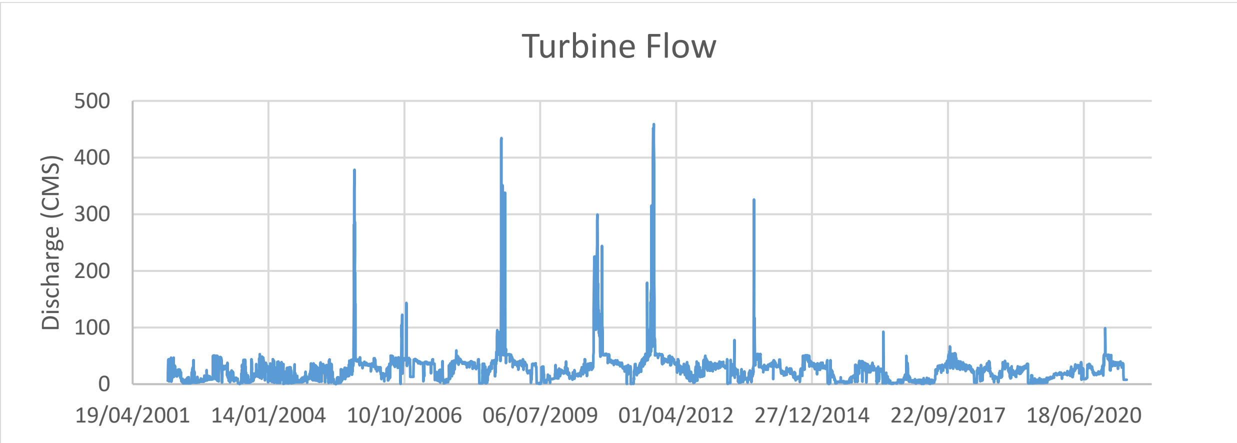


Figure 3.2-3 Daily Turbine flow from January 2001 to December 2020.

The reservoir elevation dataset was also provided for the period of 2013 until 2019 (Figure 3.2-4). In this we can see that the reservoir fills in the second part of the year the reservoir tents to fill, what is logical taking to account the hydrological characteristics of the basin. The water reservoir oscillates between the minimum and the maximum capacity depending on the season, however, a tendency of been unable to reach its full capacity can be seen in the las couple of years.

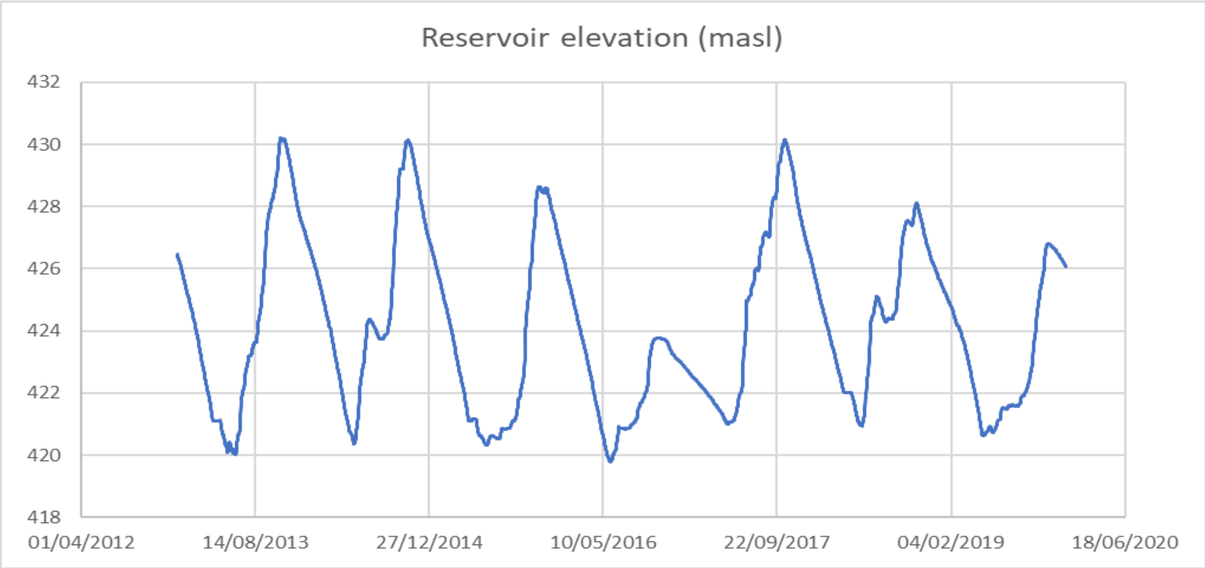


Figure 3.2-4 Güajoyo reservoir's elevation.

3.2.3 Water quality data

Existing annual water quality data of the reservoir inflows from the three main rivers necessary to develop a water quality model was provided. In the same way, some data about the reservoir conditions such as chlorophyll-a concentrations were provided.

Table 3.2-1 Table of contaminant loads.

River	Phosphates	Nitrates	Ion Nitrogen	DO
Units	mg/L PO4 -3	mg/L NO3-	mg/L NH4	mg/L O2
Ostua	4.03	6.37	0.41	7.15
Angue	1.89	ND	0.14	6.48
Sanjo	1.48	ND	0.1	6.36
Sum	7.4	6.37	0.65	0.02

Chapter 4 Simulation and optimization model setup

The purpose of this chapter is to evaluate the results of the models used and how they help to achieve the objectives of this research. Three models where developed for this project, the first one in WEAP that have the main objective of represent and evaluate the hydrology and the existing reservoir operation strategy of the Güajoyo reservoir. Followed by a Delft3D model that allows to obtain the way of how algae act in the reservoir and obtain a minimal water necessary to avoid an excessive concentration of algae. The last model involves an optimization algorithm that will use the minimum water level to obtain a reservoir operation that allows to obtain the maximum energy production.

4.1 WEAP model setup

The WEAP model has the objective of been the starting point of the research. Starting from it, the initial values that are going to be use for the water quality model and followed by the optimization model will be set.

4.1.1 Reservoir operation

In WEAP, the lake is represented as a river reservoir, this type of element can store flow to supply a demand site or generate hydropower as it appears in Figure 4.1-1. The Turbine has a maximum head of 51m and in the present counts with a maximum capacity of 889.7Mm^3 when is at its maximum elevation of 430.27m and a capacity until the inactive zone where the intake of the turbine is, is 423.6Mm^3 at 419m as is presented in Figure 4.1-2 that is the actual Volume-Elevation Curve of the reservoir. The turbine has a maximum capacity of 45CMS and counts with a spillway that can support until 400CMS.

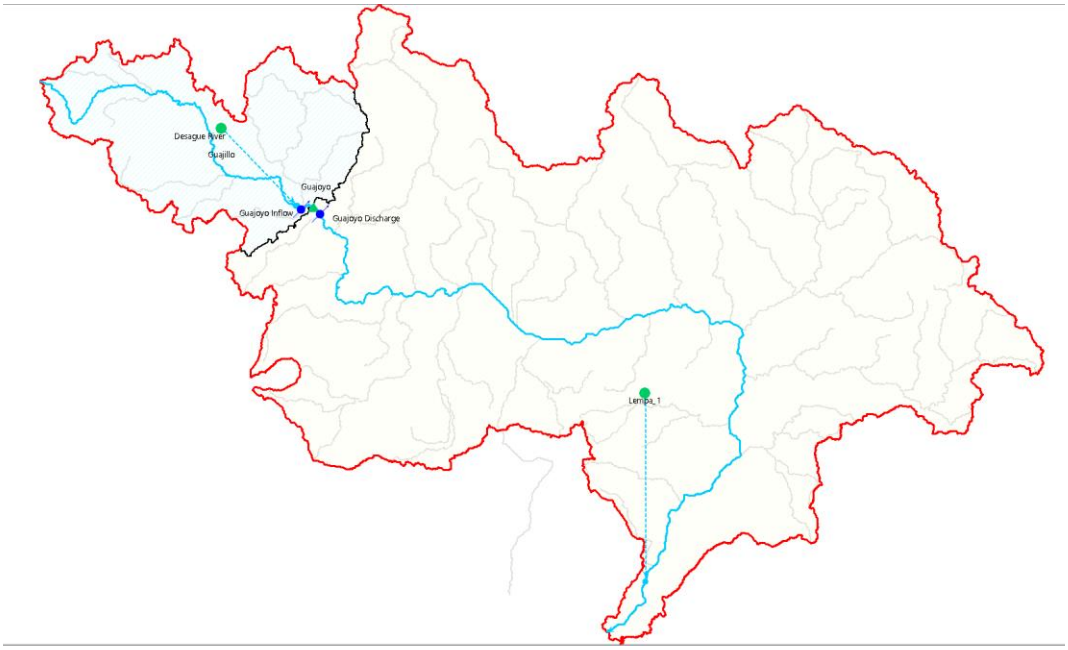


Figure 4.1-1 Schematic Diagram in WEAP.

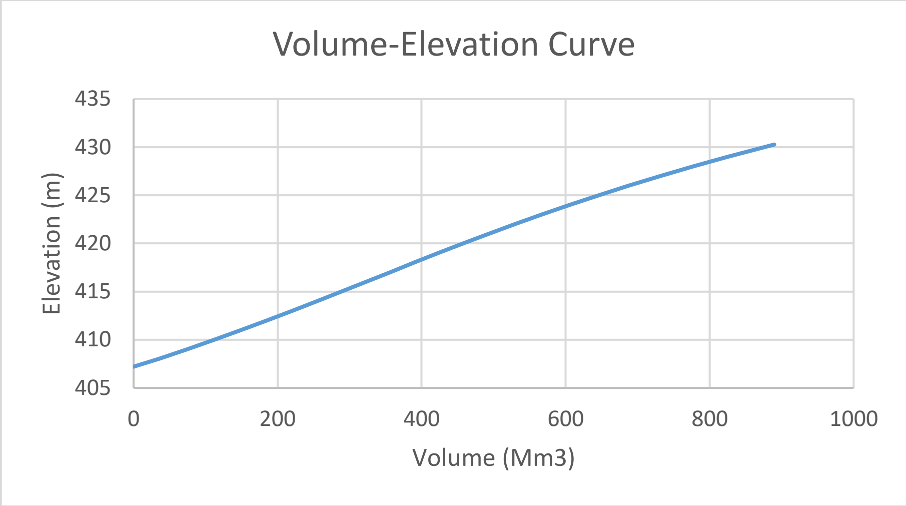


Figure 4.1-2 Volume-Elevation Curve of Güajoyo reservoir.

4.1.2 Model calibration

The first calibration made was the inflow of the reservoir using daily series from 2017 until 2019 with a CHIRPS V2.0 database. Inputs required to run the Soil-Moisture method were changed for the entire area of the basin. For the three years, an NSE and an R2 of 0.17 and 0.26 were obtained respectively.

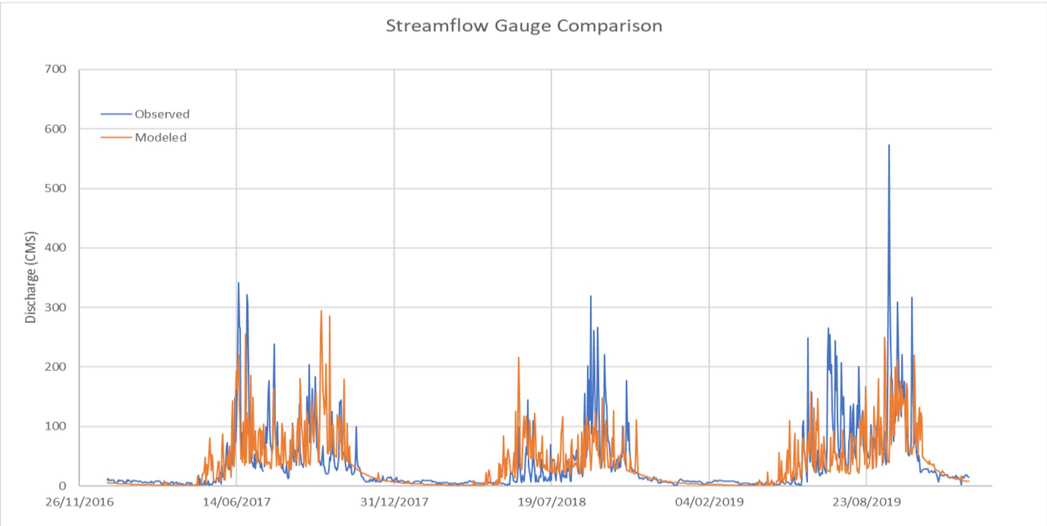


Figure 4.1-3 Reservoir inflow and gauge comparison.

In Figure 4.1-3 it can be observed that in the dry season the model has a conduct similar than the observed information but in the rainy season is not possible to emulate precisely the peaks. However, we can say that it has a relatively good performance depending of the season, even though the values of NSE and R^2 are a bit low, the trend represents quite good the period of study which for the optimization process will perform quite well.

The reservoir elevation was forced to be the same in the WEAP model as in the observed data, this was achieved by setting the top of conservation and top of inactive to the same values as the observed ones. However, it wasn't possible to achieve an acceptable calibration for the outflow (Figure 4.1-4) and hydropower generation (Figure 4.1-5) and for that reason the variables that are going to be optimized not with the real values but with the values generated by the model.

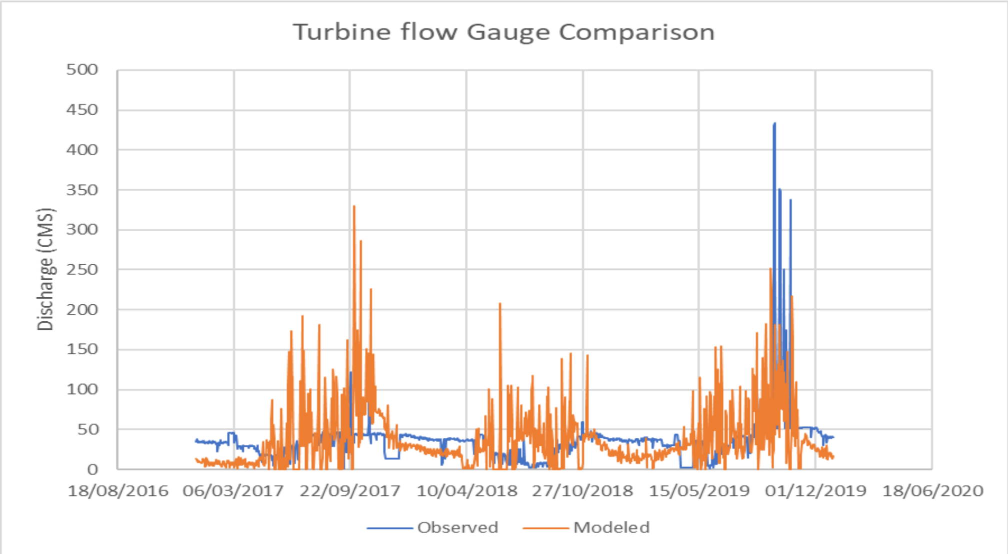


Figure 4.1-4 Turbine outflow and gauge comparison.

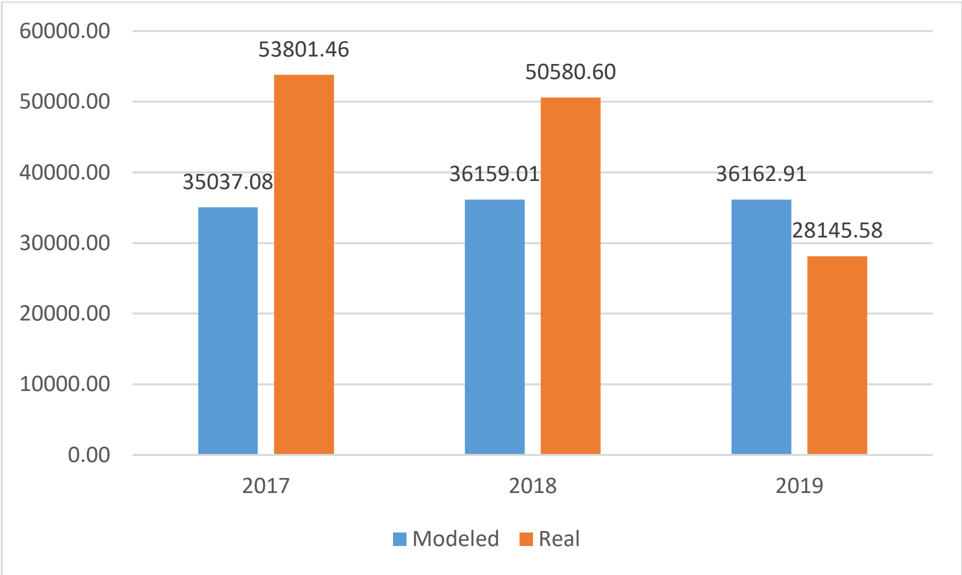


Figure 4.1-5 Generate hydropower modelled and real comparison.

Several, reasons can be the producers for this difference. Lack of data can be considered, the values of the parameters to operate the reservoir, such as efficiency, evaporation or losses in the groundwater where very scarce or presents history average values for months or years. Also, the model uses general coefficients for the entire Güajoyo basin, it didn’t differentiate between Landuse.

4.2 Delft3D model setup

4.2.1 Grid definition

Using QUICKIN tool from the Delft3D suit (DELTARES, 2020d), with the bathymetry data and a grid with a 50x50 size cell the map of Figure 4.2-1 was obtained. The reference level was set as 430m that is the maximum level of the reservoir.

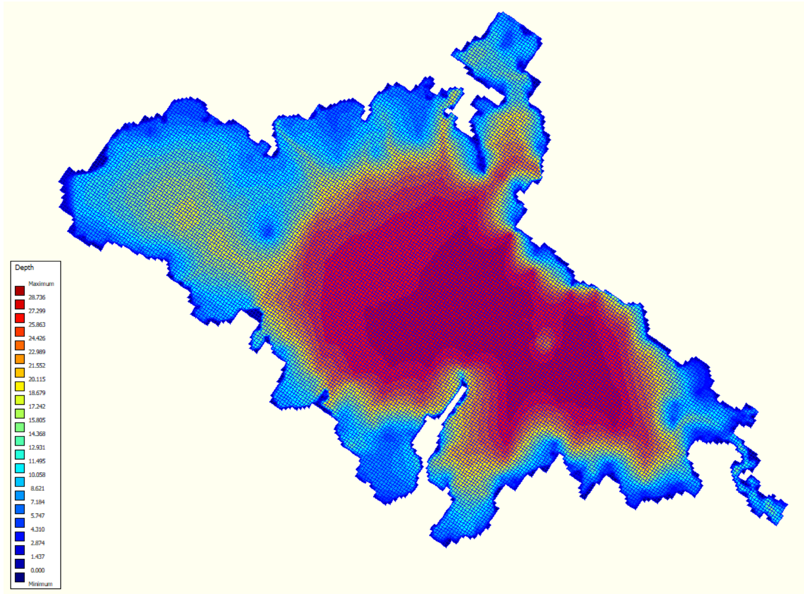


Figure 4.2-1 Bathymetry map of Güajoyo Reservoir.

4.2.2 Delft3D-FLOW

Even if the reservoir has three inflows, in the model we are considering only one. In the hydrodynamic model this inflow was put only in the Ostua river that has the biggest discharge rate of the three. The turbine is located in the canal after the reservoir, this canal is called Güajoyo canal and the discharge is represented as a Time series discharge in a cell of the grid as is shown in Figure 4.2-2.

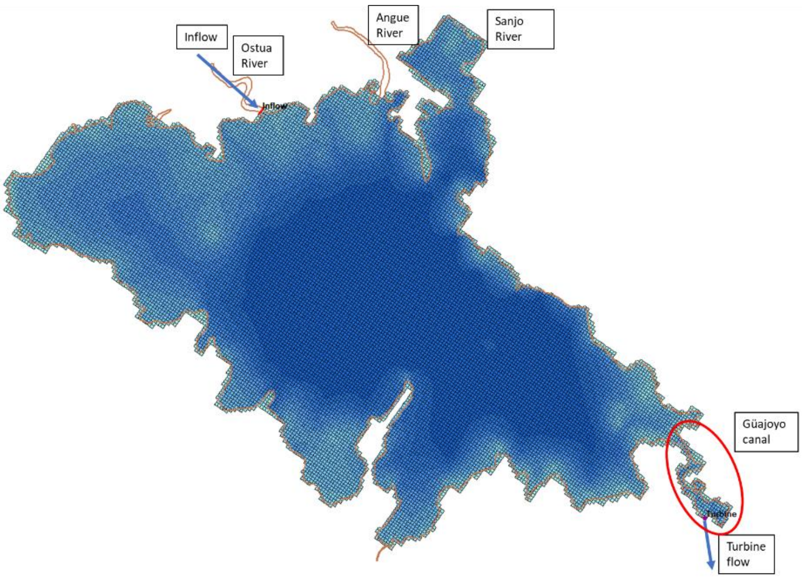


Figure 4.2-2 Hydrodynamic inflow and outflow representation.

The inflows and outflows used here where obtained by the WEAP model. A temperature information was defined in order to obtain an evaporation value and to be used in the water quality model. Other inputs are shown in Table 4.2-1.

Table 4.2-1 Hydrodynamic model parameters.

Parameter	Value	Unit
Bottom roughness (manning coef.)	0.015	
Water Density	1024	Kg/m^3
Horizontal Eddy viscosity	1	m^2/s
Smoothing time	1	Min
Simulation time	01/01/2018-31/12/2018	
Time step	1	Min
Reference level	430	m
Initial water level	-3.81	m

The model is evaluated only for one year, in this case, 2018 owing that we were capable of obtain information about the contamination levels in the reservoir for that year. And at the end of the running, elevations in Figure 4.2-3 are get.

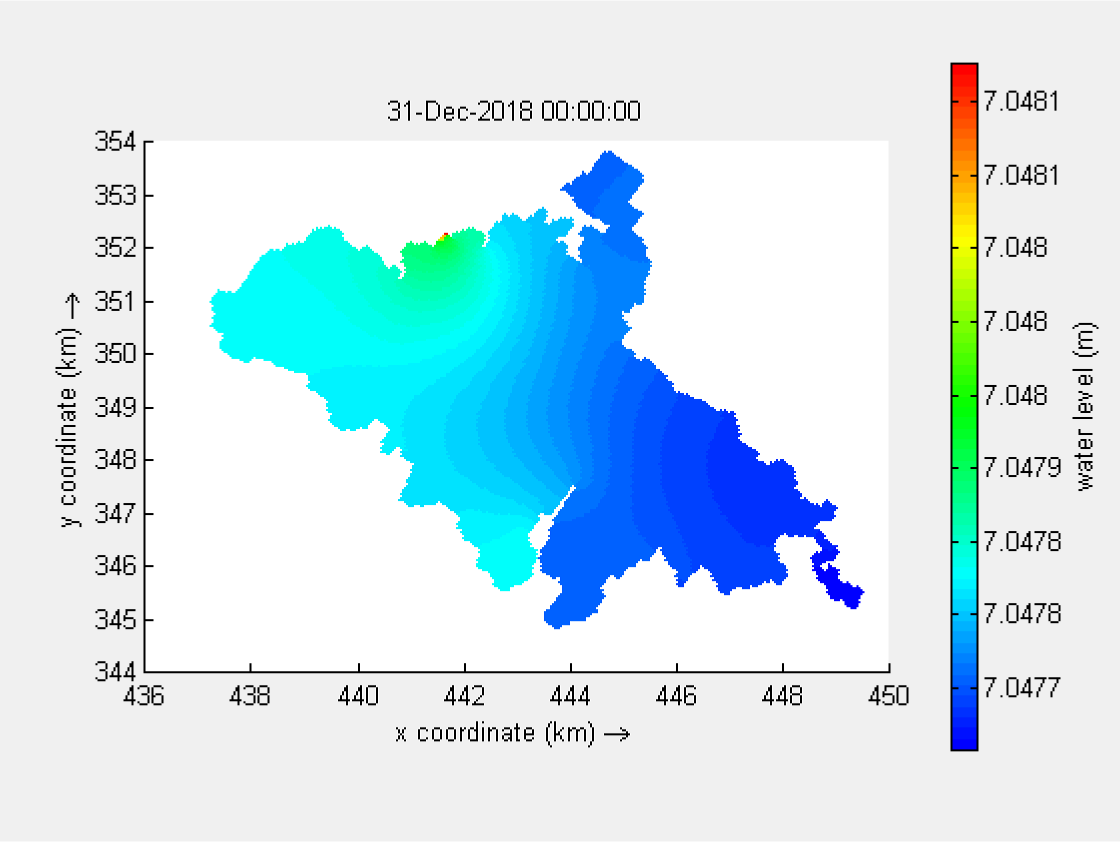


Figure 4.2-3 Water level at the end of the period evaluated.

The levels in the centre of the reservoir are showed in the Figure 4.2-4. As we can see the levels obtained in the hydrodynamic model are considerably higher than the produced by WEAP. A difference is expected because Delft3D is a physical model, and consider different procedures than WEAP, nevertheless, this difference can be a product of the evaporation or the definition of the grid in the canal where the outflow is generated.

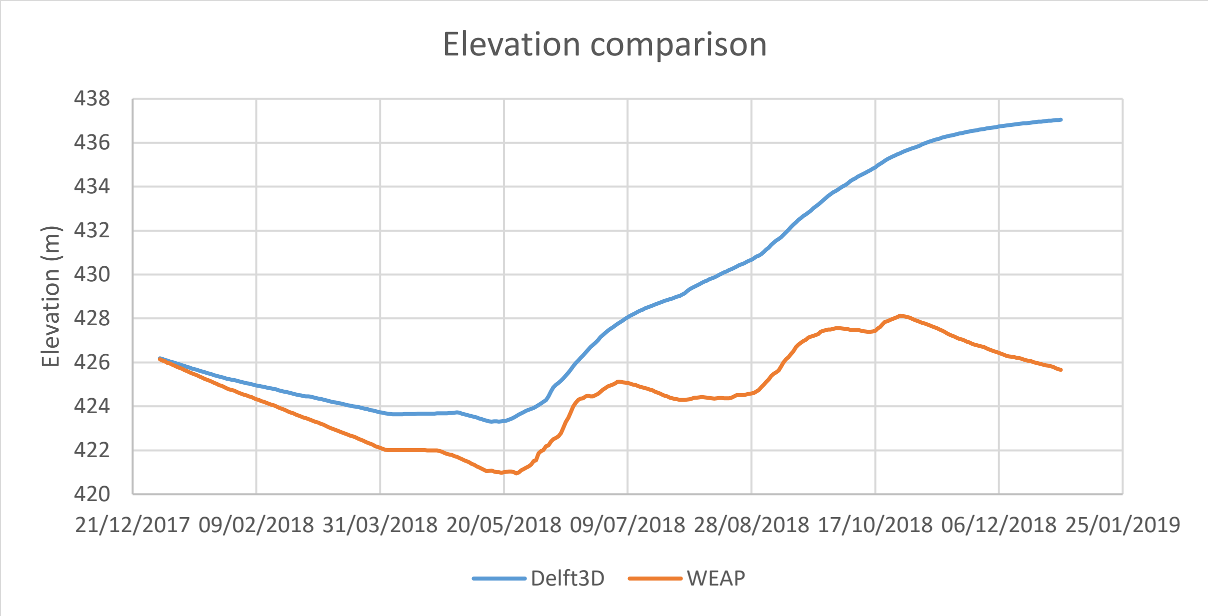


Figure 4.2-4 Elevation difference between Delft3D and WEAP.

Even if the model is not as accurate as desired, it shows a similar trend than the elevation obtained in WEAP. So, in this case the resulting coupling file will be used as the input of the water quality model.

4.2.3 Delft3D-WAQ process library

Once obtained the coupling file is obtained from the result of the hydrodynamic model, the next step is to define the processes required for Güajoyo reservoir water quality model. The process library includes the substances more common and interaction between them. As we mention in chapter 2.3.3, we are going to use the DYNAMO approach for the water quality model.

The principal reason of this es because we only count with limited data that includes a general measure of a chlorophyll in Güajoyo reservoir that doesn't make any distinction between species. Even if the model becomes simpler, the biggest disadvantage of this approach is that we cannot identify the cyanobacteria growth.

Cyanobacteria is very important because is the producer of the principal inconvenient of the study case. The cyanobacteria can produce cyanotoxins which when they growth until been considered as a harmful algal bloom (HAB), they become a concern to health. Also, cyanobacteria produce geosmin that is the reason why the taste of the water generates the complains of the users in San Salvador.

Another limitation is related to the measures of the nutrients. We only have one value of the nutrient loads, and for that reason we are going to consider that is constant in all the period of study.

The selected substance to be evaluated is the Algae(non-Diatoms) this kind of algae can contain cyanobacteria and differs from the diatoms it doesn't depend on that much in the dissolved silicon to grow(DELTARES, 2020c). For the modelling, the nutrients were assigned as a constant load because of the limitations of the measures, which means that Delft3D will only model the algae behaviour in the reservoir, not the nutrients. A total of ten processes were selected and they are shown in the Figure 4.2-5.

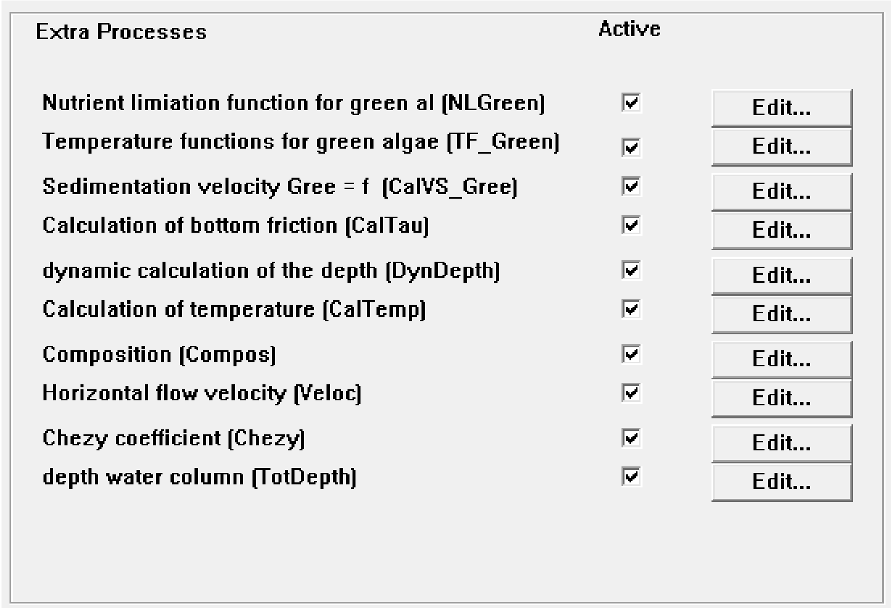


Figure 4.2-5 Selected process library.

4.2.4 Delft3D Water Quality

For the water quality model, the initial condition for the algae is the reservoir concentration of chlorophyll-a. The input numbers of the parameters are the sum of the loads that comes from the tributary rivers of the reservoir that are defined as constant values, the temperature of the water varies from 29.4 °C in January to 30.15°C in august.

The numerical scheme selected is the 21-local flux-corrected transport that has the advantage of been a fast scheme but the precision depends on the time step and the output files are for the entire year but in order to compare values with the hydrological data, the time step is daily.

The resulting concentration time series in Figure 4.2-6 shows that when the reservoir levels are considerably low, the concentration of Chlorophyll-a tents to be higher and the same in the other way.

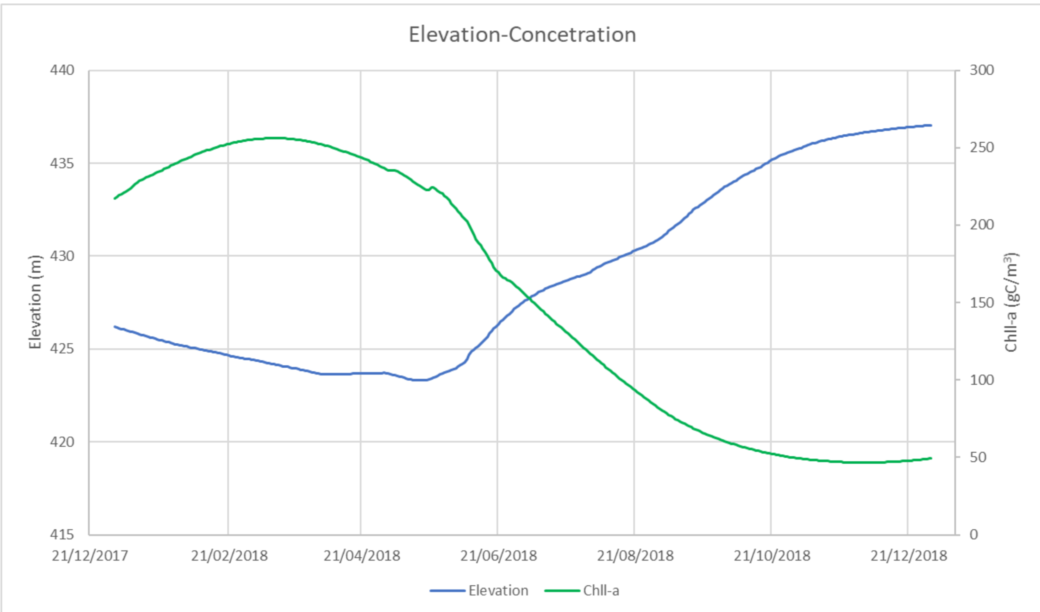


Figure 4.2-6 Reservoir elevation and Chlorophyll-a comparison.

The algae concentration has values below 50 gC/m^3 at the end of the year where the volumes of the reservoir are in their highest values. However, the values of elevation that we are going to consider as a constraint in the optimization algorithm need to be bonded with the results in WEAP elevations, this is because the procedure that we are following in the GA to obtain an energy production is the same as WEAP.

Taking this into account, the value of concentration will be compared then with the reference values of WEAP for the studied year as it appears in Figure 4.2-7. As we can see, when the concentration gets a value of less than the allowed the elevation of the reservoir is 428.03 m, however the min concentration appears when the water level reach 426.64 m, this value is the one that is going to be used because it gives a bigger range of options to the optimization algorithm.

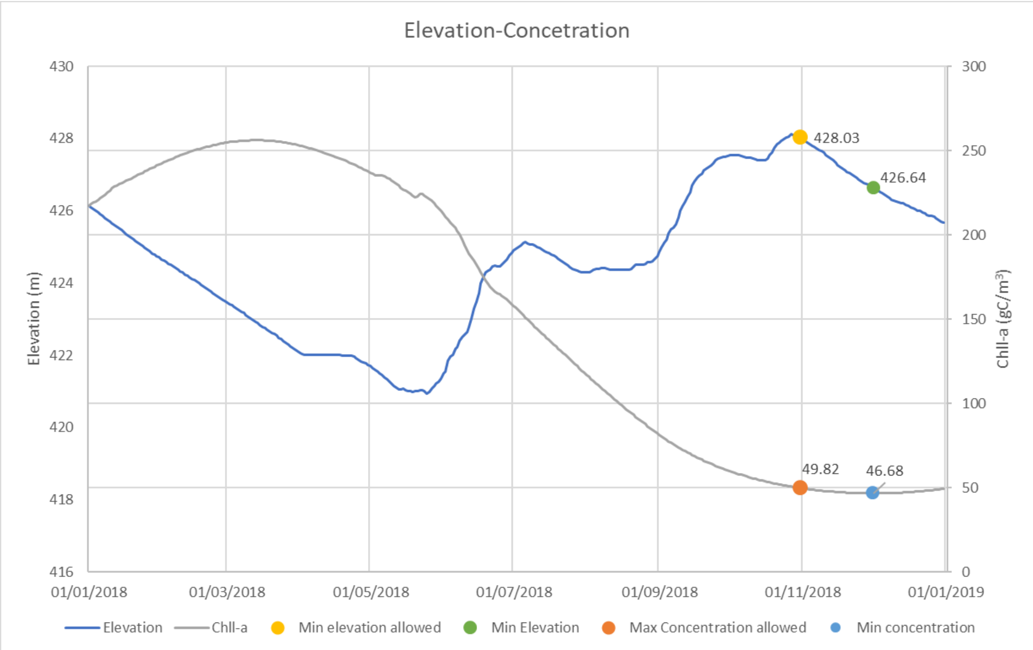


Figure 4.2-7 WEAP reservoir elevation and Chlorophyll-a comparison.

4.3 Optimization model setup

In this study, Güajoyo hydropower plant needs to be optimized to increase or maintain the energy production while the water level doesn't descent to levels that can provoke a algae bloom. To achieve this, the hydropower generation needs to be mathematically formulated and calculated based on some initial conditions.

To create an optimization problem to be solved in a genetic algorithm first an objective function, the variables and the constraints needs to be defined. The problem will use the ElementwiseProblem method that allows to define several variables.

4.3.1 Objective function

The objective function in this research aims to maximise the energy production in the reservoir. In order to achieve this, an algorithm was created to reproduce the energy generated by the reservoir defined in WEAP with the same inflow values. The function to maximize then is the Total energy generated for every timestep defined in Equation 4.3-1.

Equation 4.3-1 Objective function.

$$fmin(x_1, x_2) = -\sum HP$$

Where HP is energy generated in a timestep defined in chapter 2.2.3.

4.3.2 Variables

Two variables were defined in this project that define the reservoir operation:

- TOB: Top of Buffer.
- BC: Buffer Coefficient.

4.3.3 Constraints

Four constraints are necessary to start the algorithm those are the minimum and maximum value of the TOB and BC.

Equation 4.3-2 Maximum and minimum constraints.

$$TOB \geq TOI$$

$$TOC \geq TOB$$

$$BC \geq 0$$

$$BC \leq 1$$

Where TOI is the top of inactive, and TOC represents the top of conservation defined in 2.2.3, the buffer coefficient will have values between 0 and 1.

The energy generated needs to be considered as a constraint, however, the total energy generated can have the inconvenience that even if the total energy calculated is bigger than the real energy produced, a case where in a month the energy production is lower than the real energy produce in a month can appear.

For this reason, a constraint where each monthly energy production value needs to be higher than the real monthly energy production is created.

Equation 4.3-3 Energy generated monthly constraint.

$$HP_{month} \geq RHP_{month} \rightarrow 0 \geq RHP_{month} - HP_{month}$$

The last constraint is the water elevation. The reservoir elevation will only consider the values where the water elevation is higher than the obtained in the water quality model.

Equation 4.3-4 Water elevation constraint.

$$WE_{daily} \geq 426.64 \rightarrow 0 \geq 426.64 - WE_{daily}$$

Chapter 5 Result and Discussions

Based on the previous chapter the optimization model was run. In this chapter we are going to present the most relevant findings in the results comparing the reference scenario in WEAP and optimized scenario produced by the GA. The first step is to apply a GA is to define the parameters values.

No.	Parameter	Value
1	Sampling	Real_random
2	Selection	Random
3	Crossover	Real_two_point
4	Mutation	Real with a probability of 0.005
5	Termination	500 generation

After a long computation process that takes about 5 hours to complete, the optimal function values were obtained. The process seems to find an optimal value of 67135.65 MwH with different Top of conservation values that goes from 683.69 Mm^3 to 836.71 Mm^3 and a buffer coefficient of 0.0116 Figure 4.3-1.

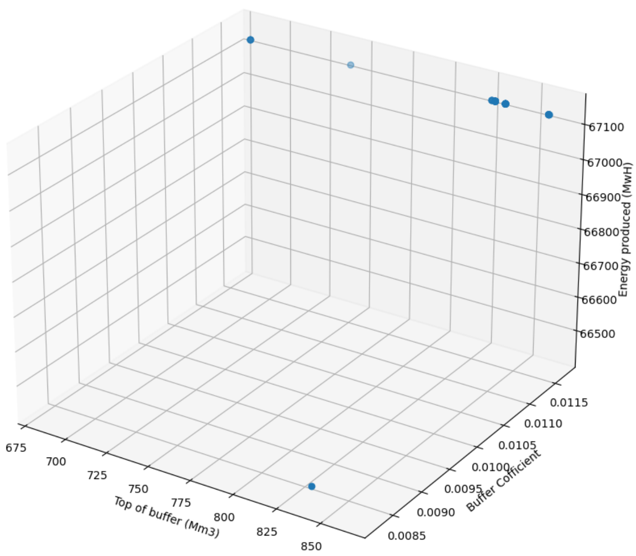


Figure 4.3-1 Variable and function optimal values.

In order to understand the similarity of the results an initial approximation was followed where three values of the TOB were selected, 683.70, 830.86 and 745.36, and introduce in WEAP into different scenarios with the goal to compared them between each other and with the reference scenario. However, it has been saw that all the results where the same for the three, so only one value will be considered 683.70 from on.

5.1 Hydropower generation

The first result to be evaluated is the hydropower generated. As it can be seen in Figure 5.1-1, the hydropower generated seems to be more adequate to the season that in the reference scenario where more water is release in the wet season a less in the dry season.

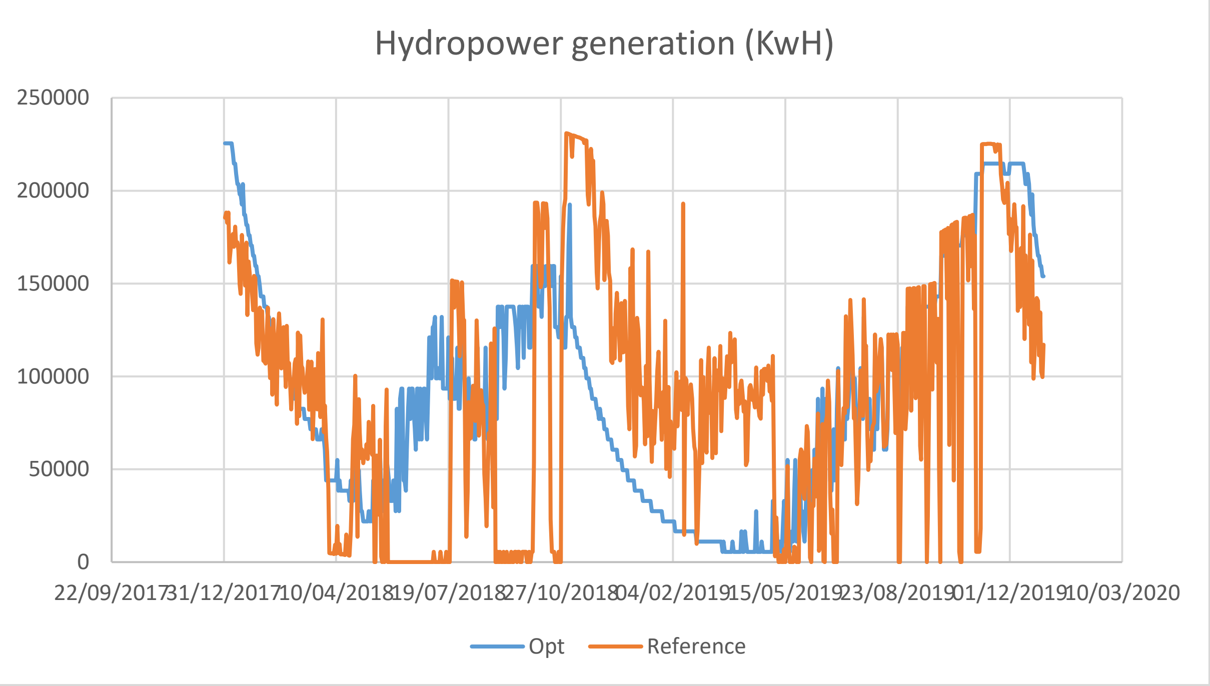


Figure 5.1-1 Energy production.

The total energy produced is 67144 MwH vs 66315 MwH for the reference scenario so it seems that the objective function of generate the major quantity of energy is working correctly. However, the optimized values don't follow the constraint of produce a monthly quantity of energy higher than the reference scenario (Figure 5.1-2). This can mean that in the optimization algorithm the values of the constraint are not good defined.

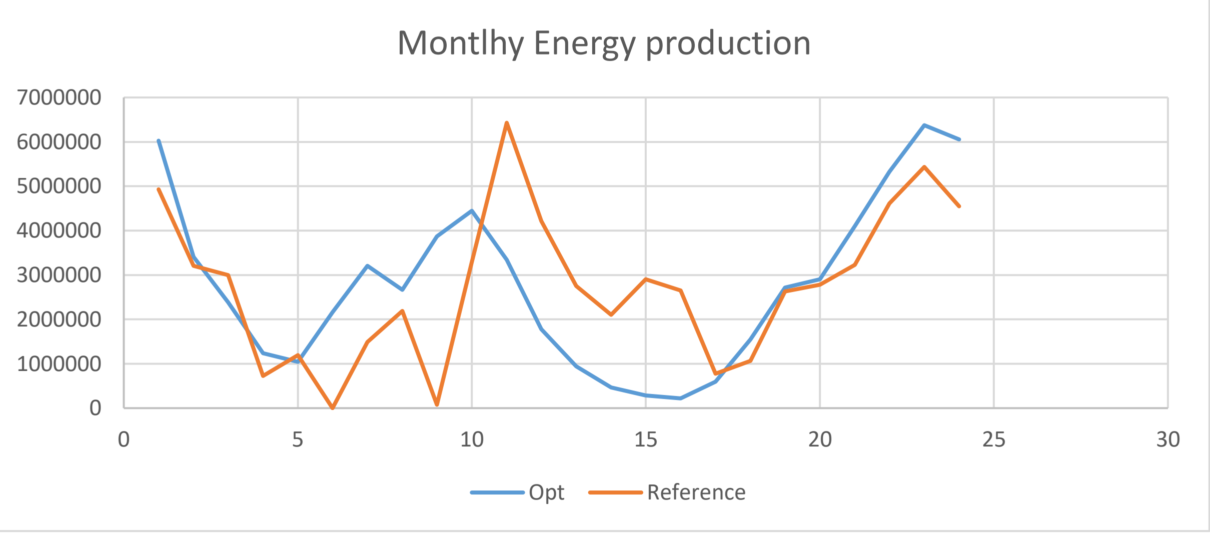
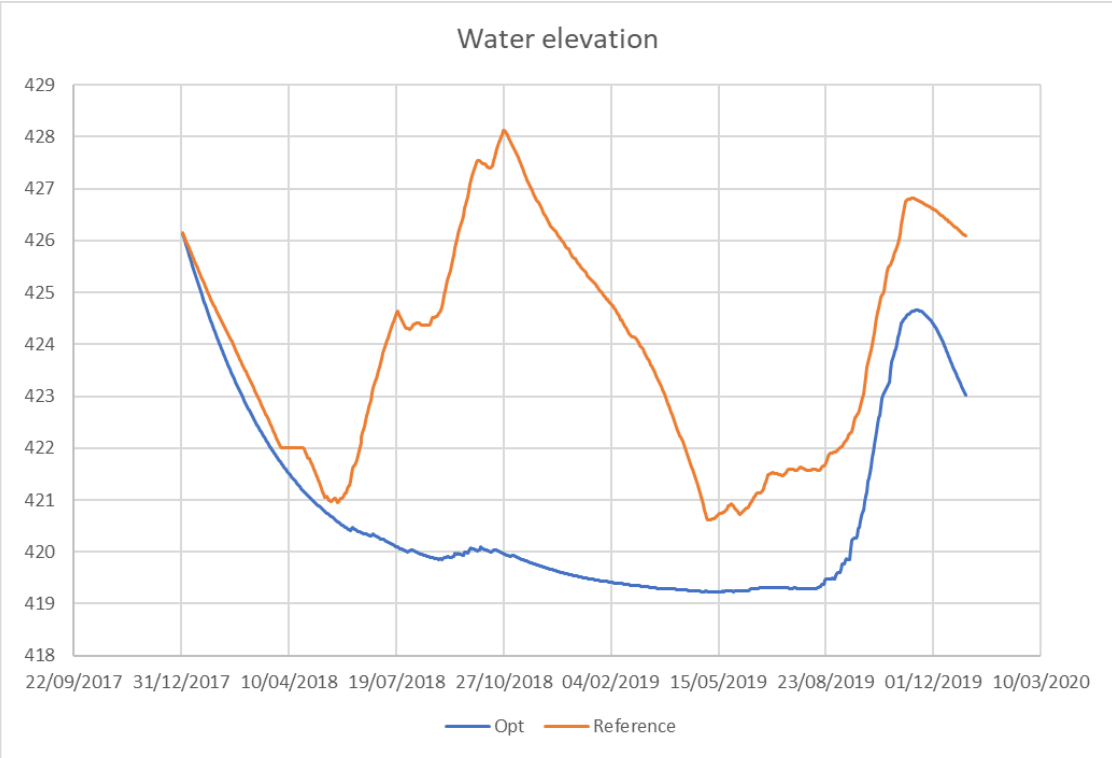


Figure 5.1-2 Monthly energy produced.

Chapter 6 Water elevation

The water elevation neither follows the constraint of the water level



Chapter 7 Conclusions and Recommendations

7.1 Conclusions

The conclusion will be presented based on the objectives introduce in chapter 1.3.

- *To analyse the water system in the Desagüe basin and develop a water quality simulation model of the reservoir.*

The water system of the Desagüe basin was evaluated with an already existing WEAP model that was modified to represent the Desagüe basin better. In general, this model offers great flexibility to represent the hydrological process of the basin, but also in a relatively simple way.

The WEAP model has the capacity to represent the hydrological behaviour of the basin obtaining acceptable values in the calibration process. However, it decays in its capability to model the reservoir operation system, specifically in the outflow and the energy generated in the system. This has the implication that the inputs of the other models are the ones provided by the WEAP, not the real ones, at least in the outflow values increasing the level of uncertainty in the other models.

The water quality model of the reservoir was realized with Delft3D which is a sophisticated model with a wide variety of processes in its library. This model was divided into two parts, the hydrodynamic model using Delft3D-FLOW and the water quality model using Delft3D-WAQ.

In the first model, the inflow and outflow data were provided by the WEAP model, however, the model shows elevations of 437m that goes beyond the maximum capacity of the reservoir of 430m. nevertheless, the water elevation has a similar trend to the one in the WEAP model, where the water descends at the beginning of the year and rise at the end of it.

A WAQ model is elaborated using the resulting coupling file of the FLOW model. The WAQ model results show an expected representation of the algae concentration behaviour. Increasing in the dry season and decreasing in the rainy season, when it reaches the minimum concentration levels of 46.68 gC/m3. Leaving aside the fact that the FLOW model is not quite precise, the conduct of the algae can be considered as good modelled.

- *To formulate an optimization problem that considers the different actors in the system.*

To achieve the maximum energy generated by the reservoir the sum of the total produced energy will be the objective function and the buffer zone and the buffer coefficient our decision variables. The optimization algorithm is capable of produce a major quantity of energy than the reference scenario, however, not always it falls in constraints violation in some days.\

The model is capable to produce 829 MwH more than the reference scenario however, the optimization model seems to have several problems satisfying the constraints values, this is evident in the beginning of the time period evaluated when it discharges a considerable volume of water in order to increase the energy production.

- *To develop an efficient reservoir operation strategy to reduce contamination and maintain hydropower generation.*

Even if the hydropower generation is higher than the reference scenario the operation strategy didn't generate a solution to the water quality issue. Is necessary to consider that for the reference scenario we didn't have reservoir operational data

7.2 Recommendations

The recommendations are further improvements to that considers the three major steps of the methodology chapter. For that reason, this sub-chapter of the research will be divided in three parts that considers every model used.

Regarding the WEAP model:

- Although the WEAP model is a good representation of the basin, a major accuracy on the calibration can be achieved is the Land use is better study and defined. the lack of rainfall gauge data to compare the generated hydrograph of the satellite datasets with the measured ones in the upper part of the basin can be a source of uncertainty for the model.
- The reservoir operation can be improved to represent better the real outflow and energy generation. In order to improve it, is necessary to obtain more data for very sensitive parameters such as loss due to ground flow or evaporation, also the necessary values for the hydropower generation such as the generating efficiency are not provided and a general value was considered to calibrate the model.

Regarding the Delft3D model:

- The grid definition in the model need to be improved, in general the model has issues trying to pass the water into the canal that supply the turbine causing that the value of the water level to decrease constantly
- In order to have a better representation of the phytoplankton species that exist in the reservoir, is necessary to realize more measurements and develop a water quality model using the ECO approach that allows to differentiate them.
- In the same way is necessary to implement more measurements of the quantity of the nutrients in dry and rainy season, in order to be able to calibrate the model.

Regarding the optimization model:

- The parameters of the optimization model give a better result in the objective function, however the model realized appears to not be able of produce better water levels than the real behaviour of the reservoir.
- Is probable than the optimal value of the provided by the optimization algorithm falls into a local minimum. So, a suggestion is to implement different values of the processes of selection, crossover and mutation in order to be tested.

7.3 Limitations

The WEAP model needs to improve the operation policies in order to obtain a better reference scenario. It has to be saying that the values of the parameters of this model are not representative for all the basin.

The optimization algorithm can work for every predefined WEAP model because it uses the same mathematical expressions. However, the constraints definitions need to be improved or change to achieve desired values.

The GA using Pymoo library requires a considered amount of time to generate results, with a population of 50 values for each variable and 500 generations, the model need approximately 5 hours to get the results. For this reason, is not recommended to use it for extended period of times

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Appendix A. Research Ethics Declaration Form

In order to design this thesis methodology several meetings with my mentors were produced, especially with dr. Gerald Corzo and dr. David Purkey, also considered the advice and processes suggested by the experts whom I had contact with. However, it takes inspiration and is based on already presented methodologies that were cited when it was necessary.

The method description to develop this research is intended to be as clear as possible, in the same way, all the data provided and the sources of this data were cited in the thesis in case someone wants to validate or better yet, improve the results that I obtained.

The results obtained in this document try to evaluate an alternative to reduce the water contamination issue in Güajoyo and improve the people's standard of living. The collaboration between all the institutes were provided without any particular interest for them or me.

The values of uncertainty in the project were highlighted in the process and in the recommendations and are based on solid bases such as optimization algorithms already been tested or the fact that the water level is directly related to the concentration of a pollutant, however, these values of uncertainty are obtained following the chosen methodology and the data. Nevertheless, several lessons were learned not only in the parts where I already have some level of knowledge but in the new areas of knowledge that I had to understand to realize this thesis such as water quality and optimization algorithms.

The results, even if they are not 100% what I expected were shown in the document without any manipulation of the data, in all cases was mentioned where did I get them from. I tried that the result of the project needs to be the most accurate or representative as possible because it involves several people that depend on the water provided by the reservoir.

The data used in this project were discussed several times with my peers, for example, rainfall dataset sources were evaluated in the company of my peers and we did make conclusions about whether it is better to use a certain source, this assistance was recognized in the construction of the document. In the same way, I always tried to use data sources or information with acceptable quality and ethical standards.

All the processes and conclusions were obtained using the results and having into account the data acquired. Even if English is not my natural language, I try to do my best to explain myself in the document, and for that, I have to be thankful to the mentors that highlight some errors in the management of the language and correct me in an educated way. I emphasize this last part because the objective of the thesis is to create knowledge that someone else may use, and for that reason good communication is necessary.

I tried always to teach what I know and to assume when I was on a bad path or have a lack of knowledge in one specific area. In the procedure of the project, both I and all the persons involved in the development of this research project try to follow always the scientific methods, every part of the methodology that elaborated following a piece of advice or a solution was sustained in the scientific method and also with my mates in the IHE discuss how to proceed in some cases using this method.

Research Ethics Committee
IHE Delft Institute for
Water Education
E ResearchEthicsCommitee@un-ihe.org

Date: 2022-03-02
To: Fernando Enrique Montejo Diaz
MSc Programme: HI
Approval Number: IHE-RECO 2021-232

Subject: Research Ethics approval

Dear Fernando Enrique Montejo Diaz

Based on your application for Ethical Approval, the Research Ethics Committee (RECO), IHE Delft RECO gives ethical clearance for your research topic Optimization of reservoir operation for the reduction of contamination in the Lempa river basin, El Salvador

This approval valid until April 19, 2022. Please notify the RECO if your research protocol is modified in any way. If you do not complete your research by the specified date, contact RECO to request an extension for the ethical clearance.

Please keep this letter for your records and include a copy in the final version of your MSc. thesis, together with your personal ethics reflection.

On behalf of the Research Ethics Committee, I wish you success in the completion of your research.

Yours sincerely,

Dr. Angeles Mendoza Sammet
Coordinator, Research Ethics Committee IHE Delft

Copy to: Archive.

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