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Assessing Water Quality Modeling in Subtropical Regions Based on a Case Study of the Aguamilpa Reservoir

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ASSESSING WATER QUALITY MODELING IN SUBTROPICAL REGIONS BASED ON A CASE STUDY OF THE AGUAMILPA RESERVOIR

by

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GRADUATE COMMITTEE APPROVAL

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BRIGHAM YOUNG UNIVERSITY

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ABSTRACT

ASSESSING WATER QUALITY MODELING IN SUBTROPICAL

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THE AGUAMILPA RESERVOIR

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The shortage of water in Mexico has made public and private institutions look at reservoirs as an alternative solution for present and future water supply. However, eighty percent of the existing reservoirs in Mexico are contaminated at some level, many severely. Water quality models are water-management tools used to diagnose water quality problems and the impact of various environmental conditions. They can be effective in assessing various measures of remediation leading to improved water quality. In most of the cases such water quality models have been successfully applied in reservoirs located in temperate climates. However, the use of water quality models in subtropical reservoirs, especially those in developing countries, have relatively little application because either basic data are not available or because they are not sufficient.

In this study, a preliminary water quality model was developed for a subtropical reservoir to assess both the ability to collect adequate data and the model's underlying applicability in a subtropical region. The Aguamilpa reservoir is located in the western part of Mexico (Nayarit). It was built for power generation, irrigation and as a fishery. CE-QUAL-W2 is a two-dimensional hydrodynamic and water quality model suitable for long and narrow water bodies. Geometrically the Aguamilpa reservoir is long and deep, making it an ideal candidate to be modeled by CE-QUAL-W2. The model was developed for 1995 and 1996 because of a wider availability of historical data during this period. In addition to a preliminary model and assessment of applicability in this subtropical region, a monitoring and data acquisition plan was designed to identify the minimum required data which must be used to update, calibrate and simulate the water quality parameters. Once the model is calibrated, it may be used to simulate the water quality changes occurring with respect to environmental, climatological and anthropogenic effects. Further, the model may be used to prescribe operating procedures upstream as well as at the dam which can serve to improve the overall water quality. The development of the model at Aguamilpa can serve as a guideline for developing similar water quality models in this and other similar subtropical locations.

ACKNOWLEDGMENTS

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I owe a special debt of gratitude to my best friend, my wife Edith, who always encourages me to keep going and for her love. I also wish to thank my family for their support, teachings, and love; especially to my dad, Angel Obregon, for helping me to get field data.

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1 Introduction

Lakes and reservoirs (natural or artificial) are key elements of water resources, providing services for humans and a habitat for innumerable species of animals and plants. In Mexico, artificial reservoirs have been built primarily to store large volumes of water used for power generation, with secondary purposes being flood control, irrigation, fishing, recreation, aquaculture and transportation. The shortage of water in Mexico has made the National Power Commission (Comision Federal de Electricidad or CFE), the National Water Commission (CONAGUA), and public/private institutions look at reservoirs as an alternative solution for present and future domestic water supplies. However, CONAGUA has reported that eighty percent of the four thousand five hundred existing reservoirs in Mexico present different grades of pollution, many of which are severe (Arredondo et al., 2008). This water quality degradation in reservoirs has been caused by the intense use of fertilizers in agriculture, watershed modifications, land use changes, introduction of exotic species, overfishing and untreated wastewater discharges. The addition of nutrients such as phosphorous and nitrogen have classified most Mexican reservoirs as eutrophic. Little is known about the reservoirs' water quality conditions, due to the fact that basic data either has not been collected or are insufficient (Huszar et al., 2006). Moreover, management tools, such as water quality models, have not been applied with great demand in Mexico because of the aforementioned reasons. Water quality models have been successfully used in worldwide reservoirs located mostly in temperate climates with a few cases in subtropical reservoirs to determine the water quality management actions needed to reduce or eliminate water quality impairments. Modeling sub-tropical reservoirs is a little or unexplored area. Aguamilpa reservoir, located in the northwest region of Mexico, is an exceptional case study to show the applicability of water quality models in sub-tropical zones. Considering the precedent facts described above, the objectives and scope for this study are established.

1.1 Objectives

- Identify an adequate water quality modeling tool for a subtropical reservoir using the Aguamilpa reservoir as a case study;
- Identify limitations and adjustments of the selected model;
- Determine how the selected water quality model is applicable in a developing country like Mexico. Identify the sources of data available for developing and using a water quality model;
- Develop an initial water quality model for the Aguamilpa reservoir using existing data, supplemented with estimates in cases where gaps exist;
- Use results of the developed water quality model to refine a monitoring and data acquisition plan that covers the gaps and extends the ability to calibrate and use the model in a predictive nature.

1.2 Scope of the Study

This study is part of an important ongoing project titled "Development of a water quality model for the Aguamilpa Dam (Nayarit)," sponsored by the National Council of Science and Technology (CONACYT) in Mexico to evaluate water quality in the Aguamilpa reservoir. This study is one part of a larger effort being coordinated by the Center of Investigation and Advise in Technology and Design of the State of Jalisco (CIATEJ). The other two research projects being done locally in Mexico are: 1) Water quality temporal and spatial analysis; and 2) Hydrologic balance for the Aguamilpa reservoir. The particular scope of this part of the ongoing project is to select and design a water quality model while identifying gaps in available data and needs for monitoring additional data.

An overview of water quality models and subtropical reservoirs is described. Development of a water quality model for a subtropical reservoir (Aguamilpa) is explained; describing the criteria used for the model selection, CE-QUAL-W2. A water quality monitoring plan is defined from the developed model. The study also presents results of the water balance calibration and water quality pre-simulations using sample water quality constituents. Conclusions obtained from this model are explained and future work is proposed to allow the improvement of a water quality model and its application for reservoir management.

2 Background

2.1 Study Site Description

The Aguamilpa reservoir, located in the northwestern area of Mexico, was built between 1989 and 1994 primarily to meet growing demands for electric energy, with flood control, irrigation and fishery usage being secondary. The reservoir is part of the Santiago and Huaynamota hydrologic system and it occupies approximately 60 km (37.3 miles) along the Santiago River, one of the most important and largest rivers in Mexico, and 25 km (15.5 miles) along the Huaynamota River. The Aguamilpa-Solidaridad dam is located in the state of Nayarit (104°46'29" longitude West and 21°50'32" latitude North), 52 km (32.3 miles) north from the capital city, Tepic (Figure 2-1). It is a rockfill dam that stands 187 meters (613.5 feet) high and 642 meters (2,106.3 feet) long. At the time of construction and until June 2005 the Aguamilpa dam was the highest concrete faced rockfill dam operated in the world. It has a controlled-crest spillway structure, set at an elevation of 210 meters (689.0 feet) above mean sea level. This structure was designed for a peak flow of 17,900 m^3/s (632,000.0 cfs) or 10000-year return period. According to the International Commission on Large Dams (ICOLD), the Aguamilpa dam is classified as a "large dam," because it is higher than 15 meters (49.2 feet), and its spillway can discharge over 2000 cubic meters per second (70,630.0 cfs) (IUCN and WB, 1997).

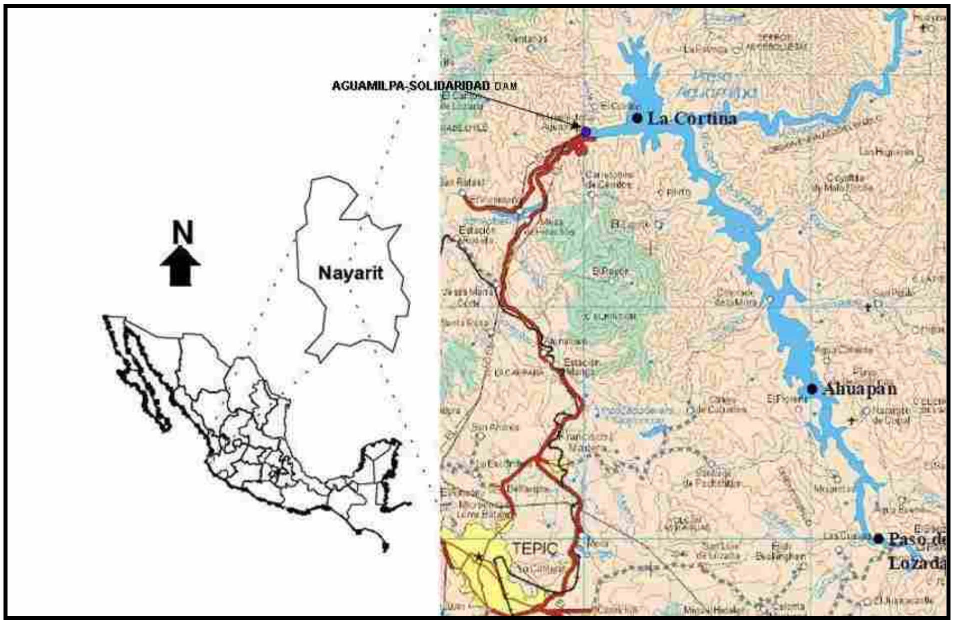


Figure 2-1: Aguamilpa Reservoir and Aguamilpa-Solidaridad Dam, Nayarit, Mexico (INP, 2006)

2.1.1 Hydrology

The Aguamilpa reservoir covers an area 109 km^2 (26,935.0 acres) and the conservation storage capacity of the reservoir is 5,540 Hm^3 (4,491,350.0 acre-feet) of water at the Maximum Ordinary Water Level (NAMO) elevation of 220 meters (720.8 feet). The maximum storage capacity of the reservoir is 6,950 Hm^3 or 5,634,457.0 acre-feet (approximately 4.5 times smaller than Lake Powell reservoir located in southeastern Utah, US) at a Maximum Extraordinary Water Level (NAME) elevation of 232 meters (760.0 feet). The Minimum Ordinary Water Level (NAMINO) elevation is found at 190 meters (623.0 feet), and the reservoir storages 2,965 Hm^3 (2,403,765.0 acre-feet)

(Comision Federal de Electricidad [CFE], 1991). The drainage area to the Aguamilpa reservoir is 73,834 km^2 (18,244,780.0 acres), which represents 3.7% of the Mexican territory and it has an annual average runoff (1949-2002) of 5,437 Hm^3 (4,407,850.0 acre-feet) (CFE, 2002). There are 26 sub-basins of the Lerma-Chapala-Santiago watershed that surround and drain directly into the Aguamilpa reservoir. The two largest contributing basins are: the Lerma-Santiago River Basin with an area of 97,570 km^2 (24,110,070.0 acres) and the Brasiles River Basin with an area of 17,103 km^2 or 4,226,240.0 acres (Figure 2-2). There are 24 smaller local sub-basins draining areas immediately adjacent to the reservoir in addition to the 2 primary sub-basins mentioned above. The largest of these 24 small sub-basins occupies 264 km^2 (65,236.0 acres) of surface area, the smallest measures 18 km^2 (4,450.0 acres), and the average area of these 24 sub-basins is 78 km^2 or 19,275.0 acres (Potential Impacts, 2003).

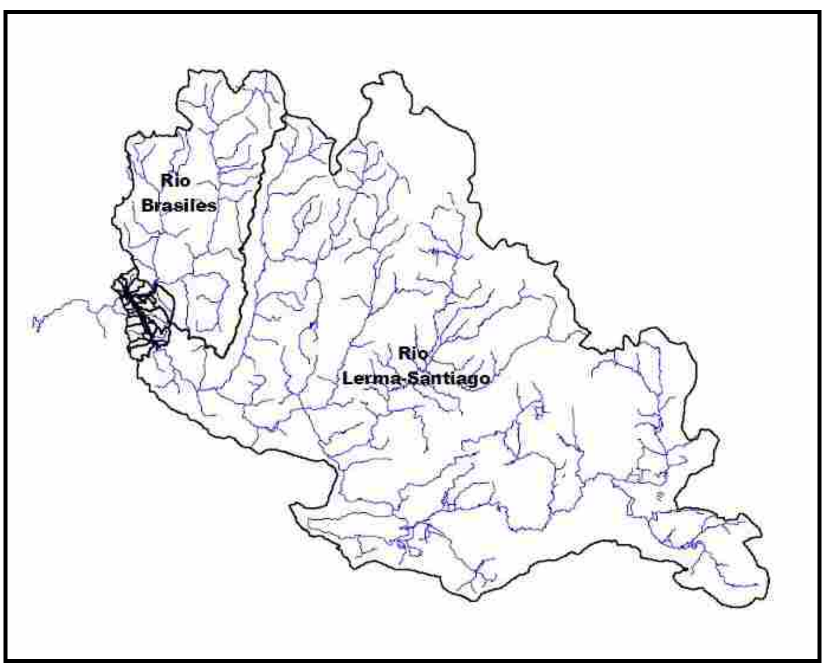


Figure 2-2: Main Watersheds Surrounding the Aguamilpa Reservoir (Potential Impacts, 2003)

As can be seen in Figure 2-3, the Lerma-Chapala-Santiago watershed includes three rainfall zones: 300-600 mm/year, 600-1000 mm/year, and 1000-2000 mm/year. The majority of the small 24 small sub-basins are located in the highest rainfall zone (1000-2000 mm/year).

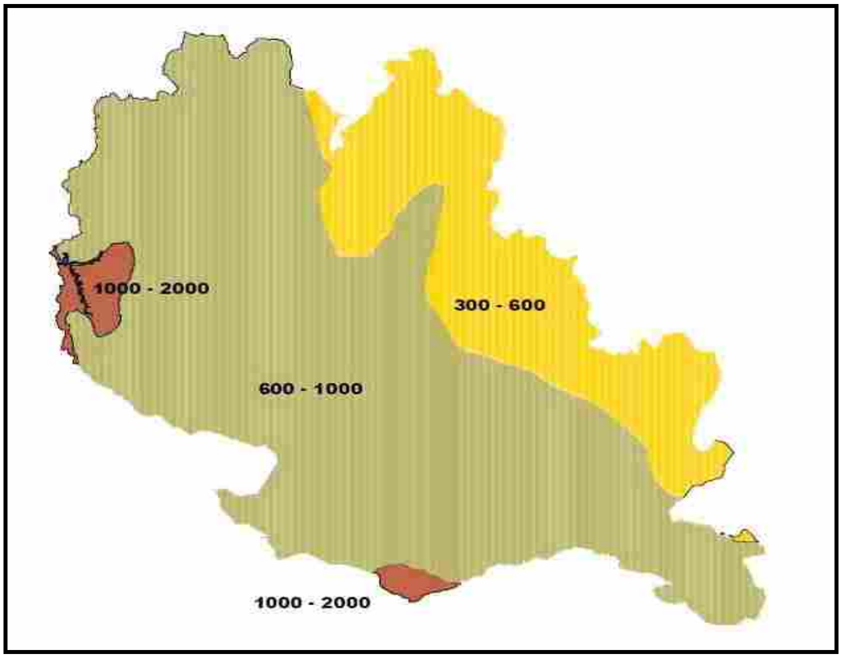


Figure 2-3: Rainfall in mm/yr of the Lerma-Chapala-Santiago Watershed (Potential Impacts, 2003)

2.1.2 Geology

The hydroelectric Aguamilpa project is located in the southern mountainous area of Mexico known as the Sierra Madre Occidental. The geology of this area is characterized by tertiary volcanic-ignimbrites rocks (CFE, 1991). The presence of small outcrops of slate, greywacke, and limestone exposed in the canyon of the Santiago River classifies the Aguamilpa dam area in the pre-Cenozoic geologic era. The rocks, mentioned above, are spatially associated with Oligocene to Early Miocene granitic intrusive bodies (INEGI, 2007; CFE, 1991). The main geologic structural characteristics found in the Aguamilpa dam area correspond to six faults with a general orientation from northeast to southwest, known as the Colorines system. Four of these faults are located on the right site of the dam and affect the power generation works. The other two faults are situated on the left site of the dam (see Appendix A); one of them in the Diversion works structure and the other one in the control and spillway structure (CFE, 1991).

2.1.3 Climatology

According to the Köppen climate classification, there are two main types of climates present in the region where the Aguamilpa reservoir is located: 1) Tropical rainy climate with no cool season and winter dry season (Aw); and 2) Middle latitude rainy climate with mild winters, winter dry season and hot summer with an average temperature over 22 °C /71.6 °F (Cwa) (INEGI, 2007). The dry season comprises seven months of the year, from November to May, and the wet season runs from June through October (Figure 2-4). The climatological station named "El Carrizal" (operated by CFE) and located close to the Aguamilpa dam (21°50'00" N and 104°48'00"W), has registered the maximum and minimum average annual temperatures as 35.2 °C and 21.4°C respectively, with an annual mean average temperature of 28.3°C. Moreover, this station (ID=18045) has registered a total monthly mean precipitation of 1,155 mm per year, with a total monthly mean evaporation of 2,086.5 mm per year, and a mean of 8.5 monthly storms per year.

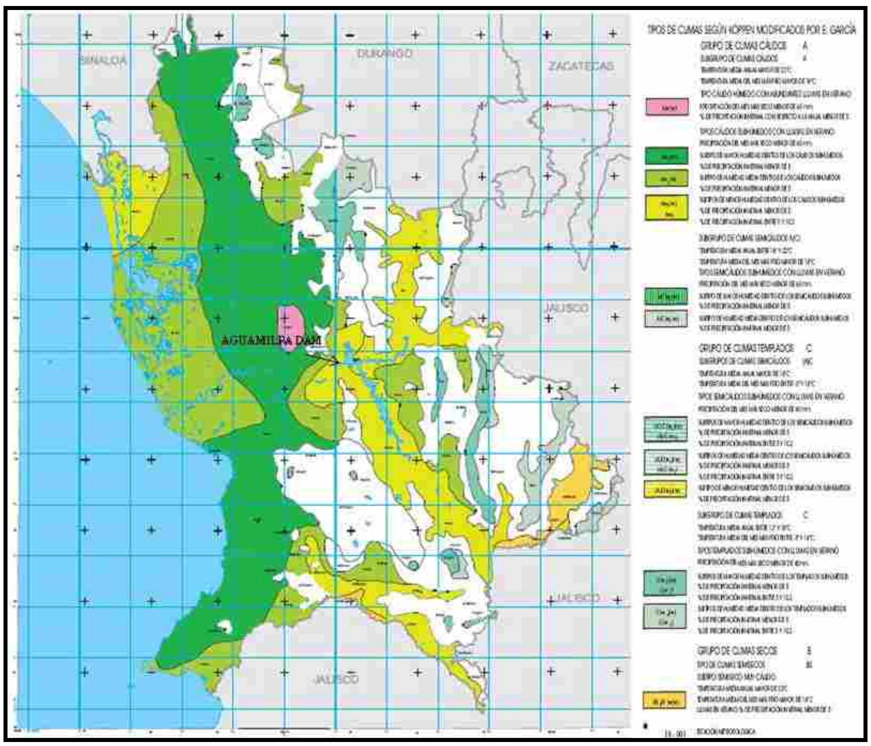


Figure 2-4: Types of Climates in Nayarit, Mexico (INEGI, 2007)

2.1.4 Power Generation

The Aguamilpa-Solidaridad hydroelectric project is one of twenty-seven projects along the Santiago River that have been planned and developed by the Mexican government to generate a hydro energetic potential of 4300 MW in Mexico. Marengo (2006) reported that the Aguamilpa-Solidaridad dam contains an underground hydroelectric power plant with three units of 320 MW of capacity each. Totaling 960 MW of installed power capacity, the Aguamilpa-Solidaridad dam ranks fourth in all of Mexico (Table 2-1). Moreover, this hydroelectric plant has an annual average generation rate of 2,131 GW*h and generates electricity for all of the states located in the northwestern region of Mexico (CFE, 1991; ROP, 1997).

Table 2-1: Hydroelectric Dams with Most Power Capacity in Mexico

Name	Power Capacity (MW)	Annual Average Generation Rate (GW*h)	Height (meters)
Chicoasen	1500	2500	251
Malpaso	1080	2800	138
Infiernillo	1000	3160	149
Aguamilpa	**960**	**2131**	**187**
Angostura	900	2200	147
El Cajon	680	1496	186
Caracol	594	1480	126
Penitas	420	1910	53
Villita	300	1180	60
Zimapan	290	1292	200
Mazatepec	208	790	92

2.2 Water Quality Issues

As mentioned before the Santiago River is one of the two main inflows for the Aguamilpa reservoir. Since middle of nineteen century, the construction of dams along the Santiago River began with different purposes like power production, irrigation and flow control. Nowadays, there are fifteen dams along the Santiago River in which the Aguamilpa-Solidaridad Dam is included. There are two other similar large dams located upstream of the Aguamilpa-Solidaridad Dam (Santa Rosa and El Cajon), and two additional dams are planned and under construction (Arcediano and La Yesca) to meet the energy demands. Three more dams (San Sebastian, Arroyo Hondo and San Francisco) are planned to increase the storage capacity of the main cities located in the central-northwest area of Mexico, Guadalajara, Leon and Tepic (Nelson et al., unpublished manuscript, 2008). The Santiago River has poor water quality due to non-point wastewaters discharges from Guadalajara city metropolitan area, the excessive use of fertilizers, and land use changes (de Anda et al., unpublished manuscript, 2007; Barlow and Obregon, unpublished manuscript 2007). In addition, the current and projected construction of dams along the Santiago River will potentially generate environmental impacts that can affect the water quality of the river and the built reservoir. Because, reservoirs can be used as indicators to examine the conditions of the watershed, it is necessary to find tools that let Mexican authorities and researchers assess the water quality conditions of the reservoirs that have been constructed along the Santiago River. These tools can include water quality models which are being used to better understand the degradation of water quality and the eutrophication of the reservoirs.

2.3 Water Quality Models

A water quality model is a representation of the water quality processes that occur in a particular studied waterbody. Water quality models and hydrodynamic models are derived by applying the laws of conservation to conservative properties such as momentum, heat energy, water mass, and contaminant mass. Water quality modeling simulates the interaction between the sources of contamination and the water quality of a given waterbody, known as cause-effect relationships. Based on how the cause-effect relationships are implemented, Chapra, (1997); Martin and McCutcheon, (1999) classify water quality models in two main categories:

1) *Mechanistic. -* Models that express their cause-effect relationships by using mathematic formulas.

2) *Empirical. -* Models (or statistical models) that describe the cause-effect relationships by using a minimum knowledge about how the studied system works.

In current practice, mechanistic models are used more than empirical models to predict water movement and water quality, because they have the ability to incorporate physical mechanisms that cause changes to the critical aquatic process. Further, mechanistic water quality models have three important advantages over empirical models that make them become more useful to test hypotheses about a particular waterbody, diagnose water quality problems and predict the impact of various environmental controls. The first advantage is that modeling allows water management experts to better understand how the water quality of a waterbody behaves. The second advantage refers to the calibration of the model that provides information about cause and effect relationships and indicates what parts of the model have the most uncertainty. The third advantage is the capability to predict responses, which the empirical models do not have (Martin and McCutcheon, 1999). However, it is important to remember that all current models still use empirical relationships to solve and understand complicated equations that are involved in the process affecting water moment and water quality.

There are many water quality models available to simulate surface water flows and water quality in rivers, lakes, estuaries, reservoirs or a combination of them. These models can be classified as one, two or three-dimensional according to their capabilities and limitations for simulating characteristics of a particular waterbody under study. Each water quality model has its own characteristics, limitations and requirements, and its selection depends on the studied waterbody and the goals that the modeler hopes to achieve.

Due to the fact that the goal of this project is not to describe all the existing water quality models, only the most common models that have been identified and used by the United States Environmental Protection Agency (EPA) are described in this work. The EPA (2007) defines in its website water quality models as tools for simulating the movement of precipitation and pollutants from the ground surface through pipe and channel networks, storage treatment units and finally to receiving waters. A brief description of the water quality models recognized by the USEPA is included below.

2.3.1 AQUATOX

AQUATOX is a water quality model used to predict the fate of nutrients and organic chemicals in waterbodies and their direct-indirect effects on the resident organisms. AQUATOX is used to identify and understand the cause-effect relationships between chemical water quality, physical environment, and aquatic life. Stratified lakes, reservoirs, ponds, and rivers can be represented using this model. Some possible applications of AQUATOX are: predicting effects of toxic substances on aquatic life, determining effects of land use changes on aquatic life, and estimating time to recovery of aquatic species after the contaminant loads are reduced. Its applicability has a range from riverine systems to small ponds which are within the scale of stratified pond, reservoir and lake ecosystems. AQUATOX assumes that the modeled waterbody is uniformly mixed, except where stratification occurs in reservoirs and lakes (EPA, 2007). Even though it is a one-dimensional model, AQUATOX can be a two-dimensional model when it is linked to another water quality model (Nielsen, 2005; EPA, 2007).

2.3.2 EPDRiv1

EPDRiv1 is a system of programs used to perform one-dimensional (cross-sectional) dynamic hydraulic and water quality simulations. The model was designed to simulate dynamic conditions in rivers and streams, to analyze existing conditions, perform waste load allocation, and allocate Total Maximum Daily Loads (TMDLs). EPDRiv1 contains two computational components which are run separately. These components are a hydrodynamic model EPDRiv1H and water quality model EPDRiv1Q. This model may be used for modeling a one-dimensional waterbody with issues that do not include metals, toxics or sediment transport (EPA, 2007).

2.3.3 WASP7

The Water Quality Analysis Simulation Program (WASP7) is a dynamic compartment-modeling program used for simulating aquatic systems, including both the water column and the underlying benthos. WASP7 is a water quality tool that helps users interpret, predict water quality responses generated by natural phenomena and anthropogenic pollution and formulate the best pollution control decisions (EPA, 2007; Hellyer, 2008). This model lets the user simulate one, two and three-dimensional systems, and different types of contaminants. Moreover, WASP can provide flows, depths, velocities, temperature, salinity and sediment fluxes when it is linked with hydrodynamic and sediment transport models.

2.3.4 QUAL2K

QUAL2K is a one-dimensional river and stream water quality model that assumes the channel is well-mixed vertically and laterally. This model represents a modernized version of the QUAL2E model (Brown and Barnwell, 1987). The QUAL2E model has been widely used by the USEPA and other global environmental agencies for modeling the water quality of rivers and channels (Salvai and Bezdan, 2008). In addition to the well known features of QUAL2E, the new QUAL2K contains new features such as model segmentation, carbonaceous Biochemical Oxygen Demand (cBOD) speciation, anoxia and denitrification, sediment-water interactions, bottom algae, light extinction, pH, and pathogens.

2.3.5 CE-QUAL-W2

Originally developed in 1975 by the U.S. Army Corps of Engineer (USACE) Waterways Experiment Station (WES), "CE-QUAL-W2 is a two-dimensional, laterally averaged, hydrodynamic and water quality model. Because the model assumes lateral homogeneity, it is best suited for relatively long and narrow waterbodies exhibiting longitudinal and vertical water quality gradients." (Cole and Wells, 2003) The definition given above can be explained in two parts. First, the term two-dimensional means that two of the three dimensions of the model are represented by a series of cells for which governing equations can be solved. The second part "laterally averaged," means that the two dimensions of CE-QUAL-W2 look for the longitudinal (reservoir length) and vertical (reservoir depth) dimensions of the studied waterbody. Yet, this model (called W2) was developed for reservoirs and narrow, stratified estuaries and it is efficient and cost-effective use in comparison with other two-dimensional models. CE-QUAL-W2 has been improved for the last three decades and it was originally known as LARM (Laterally Averaged Reservoir Model) developed by Edinger and Buchak in 1975 (Nielsen, 2005). LARM, renamed CE-QUAL-W2 Version 1.0 in 1986 for the addition of water quality algorithms, is a modification of the Laterally Averaged Estuary Model (LAEM) and later Generalized Longitudinal-Vertical Hydrodynamics and Transport (GLVHT) model (Martin and McCutcheon, 1999).

2.4 Model Selection

The increasing demand of water supply and overexploiting groundwater in the biggest cities in Mexico have made the Government search for new alternatives to supply potable water (Comision Nacional del Agua [CONAGUA], 2008). These new sources may be the surface waters which comprise rivers, lakes and reservoirs. However, the water quality of Mexican surface waters present high levels of pollution which make them unusable for human consumption. This is why the National Water Commission of Mexico (CONAGUA) and water management officials want to know the levels of eutrophication in the national waterbodies and what practices can be incorporated to improve their water quality. As described earlier, water quality models have been used for years as tools to interpret, predict and better understand the water quality changes, eutrophication and hydrodynamics in rivers, lakes, estuaries, reservoirs or a combination of them. In most of the cases, these models have been used to successfully simulate temperate waterbodies. After reviewing literature and understanding the characteristics of the Aguamilpa reservoir, the CE-QUAL-W2 model was chosen to simulate the water quality of the reservoir. CE-QUAL-W2 is a two-dimensional laterally-averaged hydrodynamic and water quality model that has been applied frequently to long-narrow reservoirs and estuaries (Cole and Wells, 2003). This model was selected not only because the Aguamilpa reservoir is characterized as long and narrow, but also based on the results of previous studies (Nielsen, 2005; Williams, 2008; de Victoria, 1996) that exhibit reservoir circulation and significant longitudinal and vertical variations in water quality and productivity. Since its creation, CE-QUAL-W2 has been improved by including new codes and algorithms. As a result of these improvements, different versions of CE-QUAL-W2 have been released in the market and they will be explained together to their capabilities and limitations as follows.

2.4.1 CE-QUAL-W2 Versions

Every released version of CE-QUAL-W2 has included changes which have improved the model. By the time this project was finished, the CE-QUAL-W2 version 3.6 became the newest version of the model but it has not been released yet. Previous versions of the model comprise:

- CE-QUAL-W2 v 3.5. - This is the current model release which includes capabilities to simulate zooplankton and macrophyte (Portland State University [PSU], 2008).
- CE-QUAL-W2 v 3.2. - Version 3.2 presented improvements such as the addition of a new algorithm which estimates suspended solids resuspension due to wind-wave action.
- CE-QUAL-W2 v 3.1 and v 3.0. - Numerical solution scheme and water quality algorithms were added to these versions which included algal groups and epiphyton/peripyton groups.
- CE-QUAL-W2 v 2.0. - In this version, the mathematical description of the prototype and the computational accuracy and efficiency of the model were improved (Cole and Wells, 2003).

The version used for this study is CE-QUAL-W2 v 3.2 which is the latest supported code from the USACE. Moreover, the executable named *w2_32agpm_tvd_weir.exe* has been modified to work with AGPM pre and post processors.

2.4.2 CE-QUAL-W2 Capabilities and Limitations

As mentioned in Section 2.3 (Model selection), specific criteria were used to select the most suitable model for this study. An important part of the selection process was reviewing the CE-QUAL-W2 capabilities and limitations in order to understand its application to the Aguamilpa reservoir. As with every other computational model, CE-QUAL-W2 has distinct capabilities and limitations in its application. The model has the ability to predict water surface elevations, velocities, temperatures, several water quality constituents and over sixty derived water quality variables. Waterbodies, which present a complex geometric shape, can be represented by using a finite difference computational grid. Most of the inflows and outflows of the waterbody are represented as precipitation, point/nonpoint sources, upstream/downstream branches, and other methods. Moreover, W2 is useful for long term simulations and water quality responses to different meteorological scenarios which are important points for this study.

The limitations of CE-QUAL-W2 are that the governing equations are laterally and layer averaged. In other words, lateral averaging assumes that lateral variations in velocities, temperatures, and constituents are not considered. This assumption may not be appropriate for large waterbodies showing significant lateral variations in water quality (Cole and Wells, 2003). The model may not provide accurate results where there is significant vertical acceleration because an algorithm for vertical momentum is not included. Also several water quality processes are not simulated such as dynamic sediment oxygen demand, sediment transport and accumulation, and toxics. The model does not simulate zooplankton and their effects on phytoplankton or recycling of nutrients. Macrophytes effects are not included either in the hydrodynamics and water quality parts of the model. In addition to these limitations, the model is also complicated and time consuming, requiring knowledge of hydrodynamics, aquatic biology, aquatic chemistry, numerical methods, programming, and statistics. However, improvements to the model are being continuously developed in order to decrease the limitations of the model. For more information about capabilities and limitations of the CE-QUAL-W2 version 3.2 can be found in the User Manual (Cole and Wells, 2003).

2.5 Subtropical Reservoirs

The degree to which lakes and reservoirs are affected by pollution depends on whether they are deep or shallow, large or small, and tropical/subtropical or temperate (Hutchinson, 1957). Subtropical reservoirs have not been studied as much as temperate reservoirs, because they are located in developing countries where there is not enough technology that allows studying this type of reservoirs. Mexican reservoirs are classified as subtropical due to their geographical location. The Aguamilpa reservoir is classified as subtropical according to the climatological characteristics of the region. Man-made lakes or reservoirs located in subtropical areas present more complex thermodynamic, biologic and hydrologic characteristics than reservoirs located in temperate areas. This is because subtropical reservoirs are relatively abundant as compared with temperate reservoirs, and they also present higher temperatures that accelerate the biological and chemical processes occurring in them (Ayres et al., 1997). In general, subtropical reservoirs are less able to assimilate nutrients which accelerate eutrophication as nutrient loads are increased. Stratification and eutrophication processes in subtropical reservoir are described as follows.

2.5.1 Stratification

The most important and dominant physical process in a reservoir, is its thermal stratification which is the result from heating the water by the sun. This thermal process regulates the rates of chemical reactions and biological process. Thermal stratification occurs when the density of the upper water's reservoir is decreased by heating, and the water is subjected to wind, resulting in three main layers known as: *epilimnion* (upper and warm layer), *hypolimnion* (cool and denser layer), and *metalimnion* (zone of transition between the warm and cool layers). Most of the time there are large temperature differences between the top and bottom layers. Where a large temperature gradient occurs, the zone of temperature change is named a thermocline (Figure 2-5). Subtropical reservoirs have stable stratification with a thermocline of only 1°C to 3 °C. Stratification periods in subtropical reservoirs last approximately 10.5 months, and turnover (cooling of the surface relative to the bottom) occurs only once per year during the winter season (Reddy, 2005; MacKinnon and Herbert, 1996; Horne and Goldman, 1994). Because the Aguamilpa reservoir does not freeze over and it is classified as a subtropical reservoir, it conforms to the warm monomictic category presenting one long mixing period.

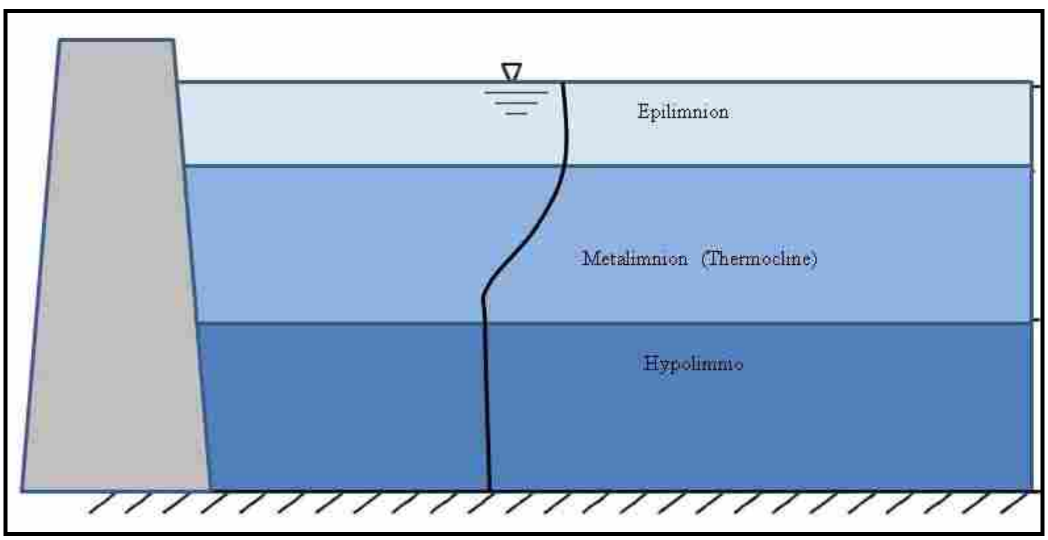


Figure 2-5: Reservoir Stratification

2.5.2 Eutrophication

The quantity of nutrients found in a reservoir in addition to the environmental factors such as temperature and light soluble gases in relation to the amount of reservoir phytoplankton defines its trophic level. Ortiz et al., 2006 describes the trophic state as the quantity of organic matter in aquatic ecosystems, and this trophic state is used as an indicator of the pollution level in a reservoir. The concentration of nutrients (phosphorous and nitrogen) and chlorophyll α as well as transparency are used to classify a waterbody's trophic state. Depending on the reservoir's trophic state, the studied reservoir is classified as oligrotrophic, mesotrophic or eutrophic.

- *Oligotrophic reservoirs*: They are generally deep with low nutrient levels and clear blue water.
- *Mesotrophic reservoirs*: These reservoirs present intermediate nutrient levels between oligotrophic and eutrophic conditions.
- *Eutrophic reservoirs*: High nutrients and rates of primary productivity (net photosynthesis) are primary characteristics of eutrophic reservoirs. The presence of surface blooms of blue-green algae is a typical.

However, subtropical reservoirs can be eutrophic when nutrient concentrations are low, due to the high water temperatures. Problems with eutrophication occur frequently for subtropical reservoirs, particularly those recently constructed. For instance, Lake Volta (Ghana), Lake Kariba (Zimbabwe) and Lake Brokopondo (Surinam) (Reddy, 2005) all fit this category. It is important to remember that the most common primary limiting nutrient in subtropical reservoirs may be the nitrogen produced by denitrification. This denitrification is generated by the anoxic conditions in the hypolimnion and bottom sediments which occur with high frequency in deep-subtropical reservoirs. These conditions and the better relationship observed between chlorophyll α-nitrogen than chlorophyll α-phosphorus suggests nitrogen as the primary limiting nutrient for subtropical reservoirs (Huszar et al., 2006; Lewis, 2002; Mazumder and Havens, 1998).

3 Model Development

In this part, a description of the CE-QUAL-W2 model development for the Aguamilpa reservoir is presented. It is important to mention that due to the availability of data, the 1995 and 1996 years were chosen to develop the initial model. However, the process for developing the model would be the same for any period of record that adequate data can be obtained. The following sections of this chapter discuss the model input files including bathymetry, boundary and initial conditions, and the associated assumptions for their creation. Depth, length, width and other physical characteristics of the reservoir are represented by its bathymetry which is described in the bathymetry section (Section 3.1). The description of the control file which manages requisite files is given in the initial conditions section (Section 3.2). The meteorological file section (Section 3.3) describes the climatological data used and where they can be obtained. The boundary conditions section (Section 3.4) consists of a description of how inflow, outflow, and inflow temperatures files were created as well as their use.

3.1 Bathymetry

The development of the CE-QUAL-W2 model began by creating the reservoir's bathymetry data. Bathymetry includes the depth, width, length, orientation and storage capacity of the reservoir. Getting a high-quality bathymetry of the reservoir is important to create an accurate model. The bathymetry of the Aguamilpa reservoir was created by using 1:50000 scale Digital Elevation Models (DEMs) obtained from The National Institute of Statistic, the Geography and Information Technology of Mexico (INEGI) and the Watershed Modeling System version 8.0 (WMS) software (Nelson, 2006). The codes of the necessary DEMs to cover the Aguamilpa reservoir are: F13D11, F13D12, F13D13, F13D21, F13D22, F13D23, F13D31, F13D32 and F13D33 (INEGI, 2008). WMS, which processes the DEM data to produce a CE-QUAL-W2 bathymetry file was developed by the Environmental Modeling Research Laboratory (EMRL) which is part of the Civil and Environmental Engineering Department at Brigham Young University. Presently WMS is maintained by Aquaveo LLC. WMS is defined by Aquaveo (2008) as "a comprehensive graphical modeling environment for all phases of watershed hydrology and hydraulics." WMS provides a variety of capabilities which include cross-section extraction from terrain data, watershed delineation, calculation of the geometry watershed and others. DEMs were converted to Triangulated Irregular Networks (TINs) using WMS to define the boundaries and storage capacity of the Aguamilpa reservoir (Figure 3-1). The reservoir's boundaries were set at a maximum elevation of 232 meters (corresponding to the high-water level in the reservoir), resulting in an extension of the reservoir approximately 60 Km along the Santiago River and 25 Km along the Huaynamota River.

The bathymetry of the Aguamilpa reservoir CE-QUAL-W2 model includes a total of 3 branches and 74 segments. The three created branches are identified as: Branch 1 (Santiago River), Branch 2 (Huaynamota River) and Branch 3 (Ensenada or ungauged branch) with Branch 1 being the largest and Branch 3 the shortest (Figure 3-2).

The average segment length and width are 1215.1 meters and 1349.4 meters respectively. The largest segment length is 1724.3 meters and the maximum segment width is 3032.0 meters. The shortest segment measures 487.0 meters and the narrowest segment measures 217.5 meters.

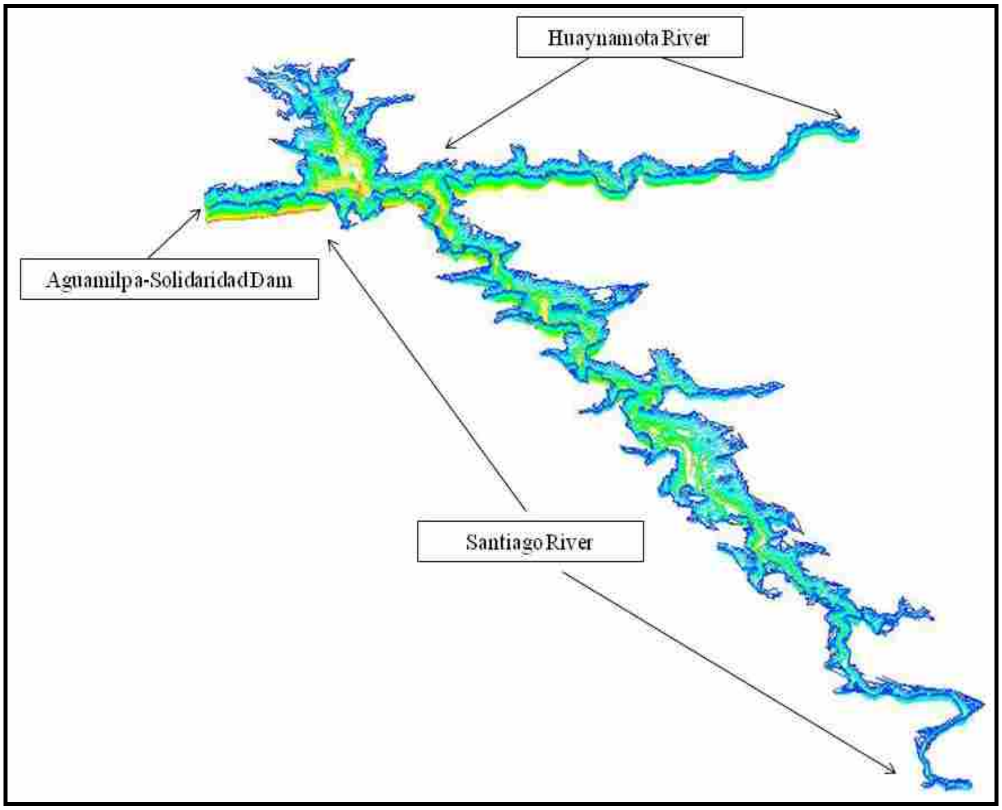


Figure 3-1: TIN of the Aguamilpa Reservoir Digitized by WMS

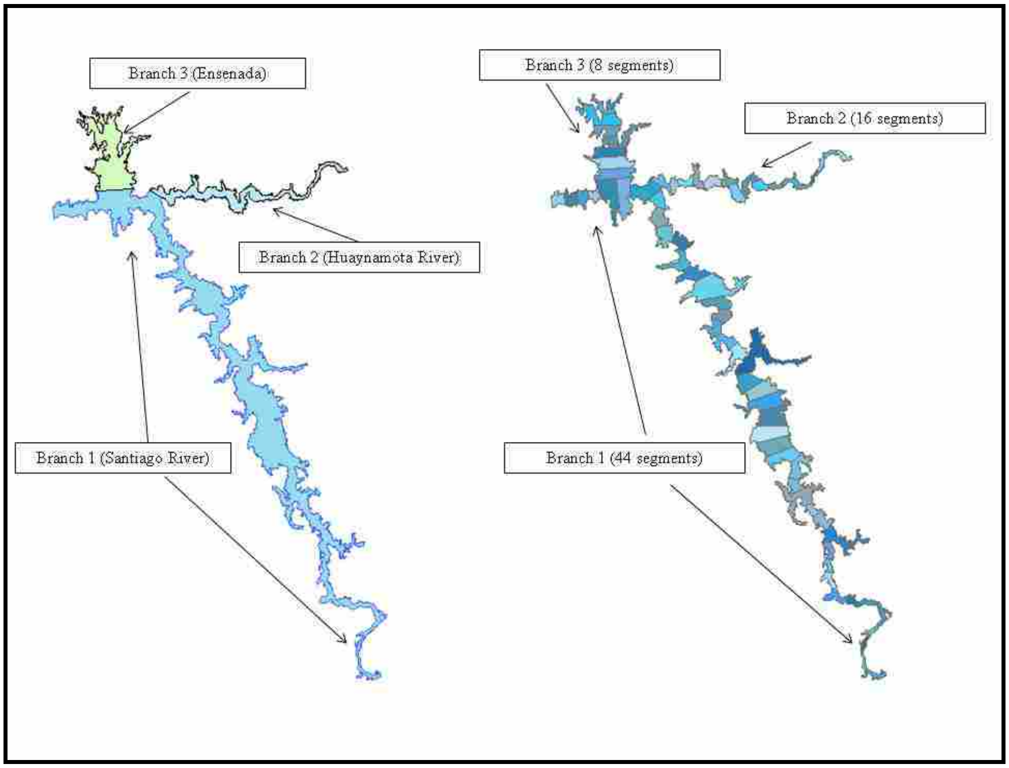


Figure 3-2: Branches and Segments of the Aguamilpa Reservoir

WMS generated a maximum number of 155 layers at the beginning with one meter thickness each because the minimum elevation of the used DEM's was 80 meters. The segments widths were automatically calculated from the TIN developed for the Aguamilpa reservoir by using the length, depth and volume of the segments (see equation below).

$$Width = \frac{Volume}{Depth * Length} \qquad \textbf{(3-1)}$$

With this information WMS generated the CE-QUAL-W2 bathymetry file for the Aguamilpa reservoir. A storage capacity curve was then created from the bathymetry file and compared with the field data obtained from CFE and GRUBA to check the accuracy of the bathymetry data. As shown in Figure 3-3, the created storage capacity curve is similar to the observed proving the accuracy of the bathymetry file of the Aguamilpa reservoir. This comparison showed that the DEM 1:50,000 available from INEGI (2008) is adequate to develop an accurate bathymetry for the Aguamilpa reservoir. The storage capacity curves created for the branches and segments are shown in Appendix A. These storage capacity curves show the storage of the reservoir at different elevations and locations.

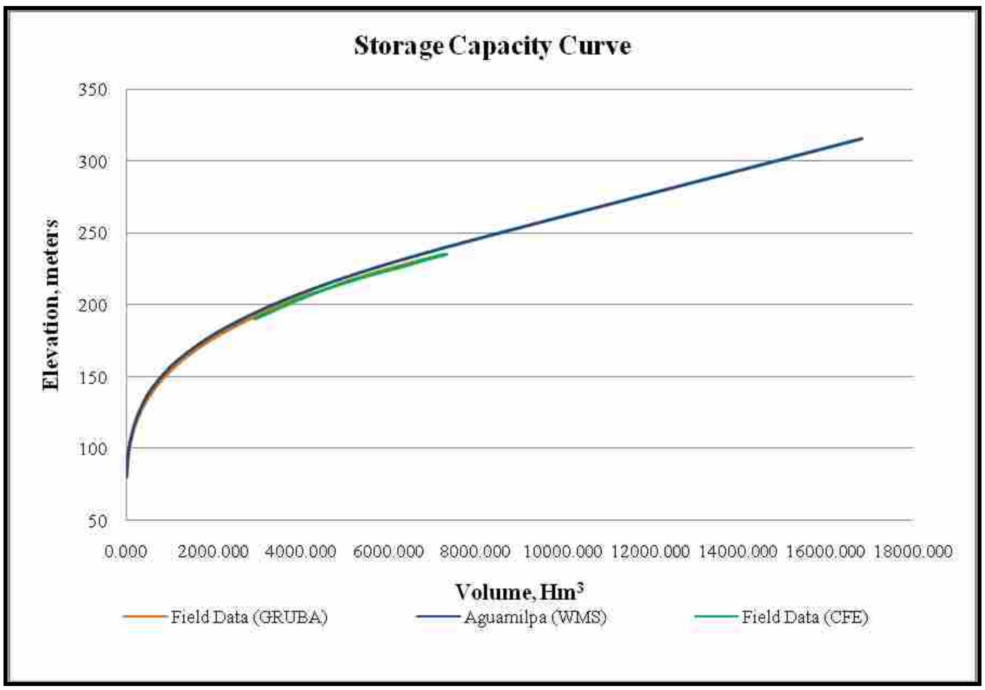


Figure 3-3: WMS Total Storage Capacity Curve vs. Field Data

However, 13 more layers were added by hand to the 155 generated layers (1 meter) to obtain 168 layers of a maximum number for each single segment. This is because the maximum reservoir's depth is 187 meters (613.5 feet) not 155 meters (508.5 feet). Besides, a bathymetry made by GRUBA S.A. de C.V. [GRUBA] (1997) reported the minimum elevation of the reservoir at 64.3 meters (211.0 feet) with a volume of 0.001 Hm^3 (0.81 acre-feet).

A pre-processor named W2i, included in the W2i-AGPM Modeling System UI for CE-QUAL-W2 v3.2 software, is a powerful water quality modeling tool created and managed by Loginetics, Inc (Loginetics, 2008). W2i was used in several occasions for developing this study. One of its uses was to view the created bathymetry of the Aguamilpa reservoir. Viewing the bathymetry in W2i pre-processor allowed an improvement in the bathymetry created by WMS. The minimum layer width in the bathymetry file was limited to 10 meters to increase model stability and decrease model run times. The final bathymetry grid of the branch 1 (Santiago River) is presented in Figure 3-4, and the final bathymetry grids of branch 2 and branch 3 are shown in Appendix A.

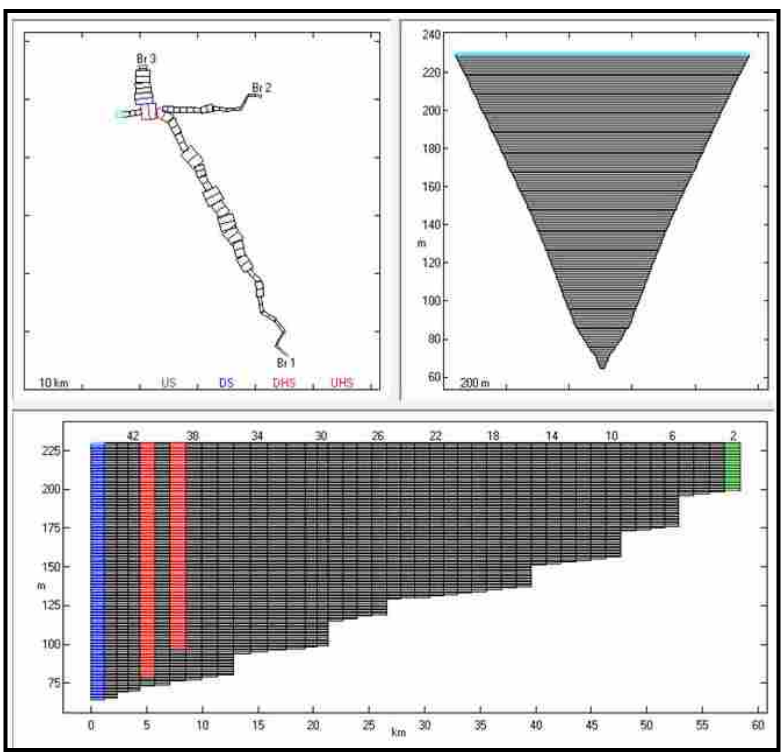


Figure 3-4: W2 Bathymetry Grid of Branch 1 (Santiago River)

3.2 Initial Conditions

Initial conditions were specified in the control file which manages all the other required files. Number of waterbodies (1), number of branches (3) and segments (74), bottom elevation of the reservoir (64.30 meters), elevation of the spillway (210 meters) and power generation releases elevation (180 meters) are the initial conditions specified for the Aguamilpa reservoir model. These initial conditions were input in the control file shown in Appendix C.

In addition to these initial conditions, water surface elevations were required for each computational segment and layer before starting the model simulation. The model simulation was set to begin on January 1, 1995 and finish on December 31, 1996. These dates were converted to Julian Days (JDAYS) which is format required for the CE-QUAL-W2 model for all the input files. These years were selected because their data were the most complete available to develop the required files of the CE-QUAL-W2 model for the Aguamilpa reservoir. The initial water surface elevation on January 1, 1995, was set at 218.32 meters or 716.3 feet (above sea level) and it was measured at the Aguamilpa-Solidaridad dam site of the Aguamilpa reservoir. The observed daily water surface elevations data for the modeling years were obtained from a water quality study prepared by GRUBA (1997). These daily average water surface elevations data were used to create an observed elevation file used for the water balance calibration of the model, which will be described on section 4.1.

3.3 Meteorological File

The meteorological file of the Aguamilpa reservoir includes hourly data of air temperature, dew point temperature, wind speed, wind direction, and cloud cover. Air temperatures and dew point temperatures were input in the model in degrees Celsius, wind speed in meters per second, wind direction values were converted from degrees to radians, and cloud cover assigned values between 0 and 10. Data from ten climatological stations, located around the Aguamilpa reservoir and managed by the State of Nayarit and CFE, were obtained. However, these stations were not used because the meteorological data gathered from them only had daily average temperature and in some cases the data were incomplete. However, the climatological station located at the Tepic airport (NOAA, 2008), gathered hourly climatological data it was chosen to create the meteorological file. Modifications and assumptions (described in section 3.5.1) were made to the Tepic climatological data in order to represent the meteorological conditions at the Aguamilpa reservoir. The W2i-AGPM utility helped identify that the Tepic airport station was the closest climatological station that included hourly data. This was found by using the “Find Met” option. The climatological data of the Tepic airport was downloaded from the National Oceanic and Atmospheric Administration (NOAA) International Data Centers, and the general information of this station is described on the following Table 3-1.

Table 3-1: Climatological Station Information

Station Information
Name: Tepic airport
ID: 765560
Dates of data: 1995 – 1996 (hourly)
Location: ~ 31 kilometers (19.262 miles) from the Aguamilpa reservoir • 21°31'1.20"N • 104°52'58.80"W

3.4 Boundary Conditions

In order to run the CE-QUAL-W2 model for the Aguamilpa reservoir, the following boundary conditions files were required: inflows, outflows, inflow temperatures, inflow constituents and distributed tributaries inflows. These boundary conditions were important for the model to represent the behavior of the reservoir. The development of the required boundary conditions files are described in this section and the adjustments made for these files are presented in section 3.5.2

3.4.1 Inflows

There are approximately nine gauging stations useful for defining the boundary conditions that are located on the three main branches of the Aguamilpa reservoir (Santiago, Huaynamota and Ensenada). These gauging stations, shown in Figure 3-5, are La Playa, Cerro Blanco, El Capomal, Despeñadero, Huaynamota, Chapalagana, Jesús María, Paso de la Yesca and El Caiman. The National Power Commission (CFE) or the National Water Commission (CONAGUA) operates the gauging stations. Data from these gauging stations were provided by CIATEJ and CFE Mexico City. The La Playa and Cerro Blanco gauging stations were used to create the inflow file for branch 1 (Santiago). Inflow files for branch 2 (Huaynamota) and branch 3 (Ensenada) were estimated by using water velocities and are described in section 3.5.2. The other gauging stations were not used to create the inflow files for branches 2 and 3 because they were not operational, or the data were incomplete for the period being modeled.

Figure 3-5: Location of Gauging Stations

3.4.2 Outflows

The outflow boundary conditions were defined from the discharge records taken at the Aguamilpa-Solidaridad Dam from 1995 to 1996. Hourly outflow data were gathered from the water quality study prepared by GRUBA (1997). However, these data only included water releases used to generate energy, and did not include other outflows from the reservoir, such as the minimum ecological flows and irrigation intakes. These data were the only hourly outflow data available at the time this work was concluded. After the outflow data were analyzed, it was observed that most of the hourly water releases for power generation from the dam occur between 7:00 PM and 10:00 PM local time at night, being this period of time the daily peak power generation (Alvaro Perez, phone communication, September 30, 2008).

3.4.3 Inflow Temperatures

Upstream inflow temperature data for the Aguamilpa's branches were not available. These data had to be estimated by using daily average air temperature from climatological stations, located close to the inflow of the three branches, and by making the assumptions which will be discussed in section 3.5.2. There were 3 climatological stations used:

- Paso la Yesca and Cerro Blanco for branch 1 (Santiago River)
- Jesús María and Chapalagana for branch 2 (Huaynamota River)
- Capomal and Carrizal for branch 3 (Ensenada River)

The daily average temperature data from the climatological stations mentioned above were gathered from CFE and CONAGUA. The unrecorded inflow temperatures data is the primary weakness of the developed model, and it is important to include these data in future monitoring programs to create more accurate models.

3.4.4 Inflow Constituents

The inflow constituent files for the main branches of the Aguamilpa reservoir could not be created by using water quality data from the reservoir. This is because there were no water quality data available or the data were not sufficient to be used for simulation. Due to the lack of water quality data, the initial model development for the Aguamilpa reservoir was focused on water temperature. However, in order to demonstrate the possibility and utility of simulating water quality parameters, some data from a separate reservoir were used. While the data are useful as a demonstration, they should not be used to infer specific results, but rather to develop appropriate guidelines for future monitoring. These example water quality simulations will be shown and described in section 4.3.

3.4.5 Distributed Tributary Files

Distributed tributary inflows are used to develop nonpoint source loadings adjacent to the branches along the length of the reservoir. The distributed tributary option provides the user with means to account for contributions that are not included as inflows to the reservoir. These unaccounted sources generally represent smaller, ungauged tributaries, precipitation on the lake, groundwater inflows and wastewater discharges. This option distributes inflows into every branch segment weighted by the segment surface area (Cole and Wells, 2003). Three different types of distributed tributary files were created inflow, inflow temperature and inflow concentration for each branch of the Aguamilpa reservoir. The distributed tributary inflow files contained the values calculated from the water balance which is described in section 4.1. As explained in section 3.4.3, the inflow temperature data had to be estimated and their monthly average values were used as source of data to create the distributed tributary inflow temperature files.

3.5 Data Gaps

As mentioned in previous sections, the best available data were used to create the input files for developing the CE-QUAL-W2 model of the Aguamilpa reservoir. Several gaps were identified made in the input data in order to get a more accurate model. The data gaps, along with the assumptions made to complete the setup of the initial model for the Aguamilpa reservoir are discussed in the following sections.

3.5.1 Meteorological Adjustments

The hourly climatological data, obtained from the Tepic airport station were modified before being used to create the meteorological file of the Aguamilpa reservoir. Adjustments on the climatological data were necessary because the Aguamilpa reservoir is located at an elevation of 240 meters (787.4 ft) and the Tepic airport climatological station is at 915 meters (3000 ft) above sea level. This difference in elevation produces variability on weather conditions that affect the mixing and thermal effects on the Aguamilpa reservoir. For instance, wind speed will generally be higher and air temperature colder at the higher elevation Tepic station than the reservoir. The modifications to the meteorological file began by adjusting time. The downloaded data uses Greenwich Mean Time (GMT) and the model required the local time in Aguamilpa, which is seven hours less than the GMT during standard time and six hours less than GMT during daylight saving time (Holiday-Weather, 2008). As shown on Figure 3-6, 4.5 degrees Celsius (°C) were added to the air temperature gathered from the Tepic airport station in order to be more representative of air temperature at the Aguamilpa reservoir. An adjustment of 4.5 °C was chosen after an air temperature comparison analysis was performed. This analysis included comparing historical average air temperature data of the Tepic and El Carrizal climatological stations located at Tepic and the Aguamilpa-Solidaridad Dam respectively (Figure 3-7). It is important to remember that the climatological data gathered from the El Carrizal station was not complete and it was only average daily data. Also, the dew point temperatures were adjusted for conditions at the Aguamilpa reservoir. They were calculated by using the calculated air temperatures at Aguamilpa and estimating the percentage of relative humidity, which was calculated with equation below (Wanielista et al., 1997).

$$T_D = f^{\frac{1}{8}}(112 + 0.9T_{AIR}) - 112 + 0.1T_{AIR} \tag{3-2}$$

where:

f = Percentage Relative humidity, frictionless

T_{AIR} = Air Temperature, °C

T_D = Dew Point Temperature, °C

Other meteorological data such as wind speed, wind direction, and cloud cover from the original meteorological file were not modified because they were assumed to be the same at the Aguamilpa reservoir. This assumption reveals an important need to collect the data locally at that dam for the final model, because these factors produce effects on thermal conditions and mixing processes occurring in the reservoir.

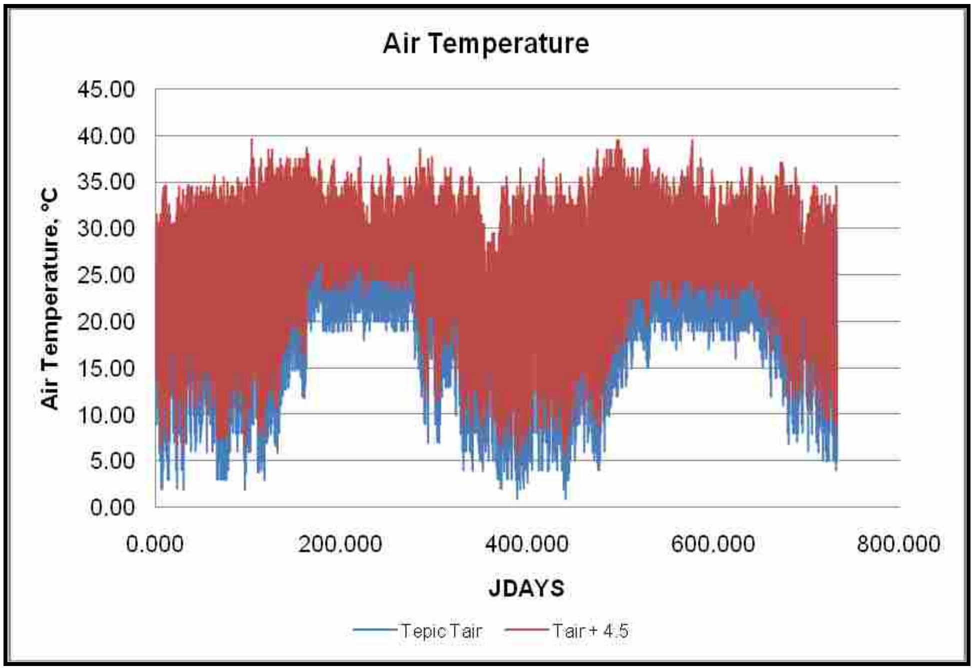


Figure 3-6: Tepic Air Temperatures and Aguamilpa Air Temperatures (Estimated)

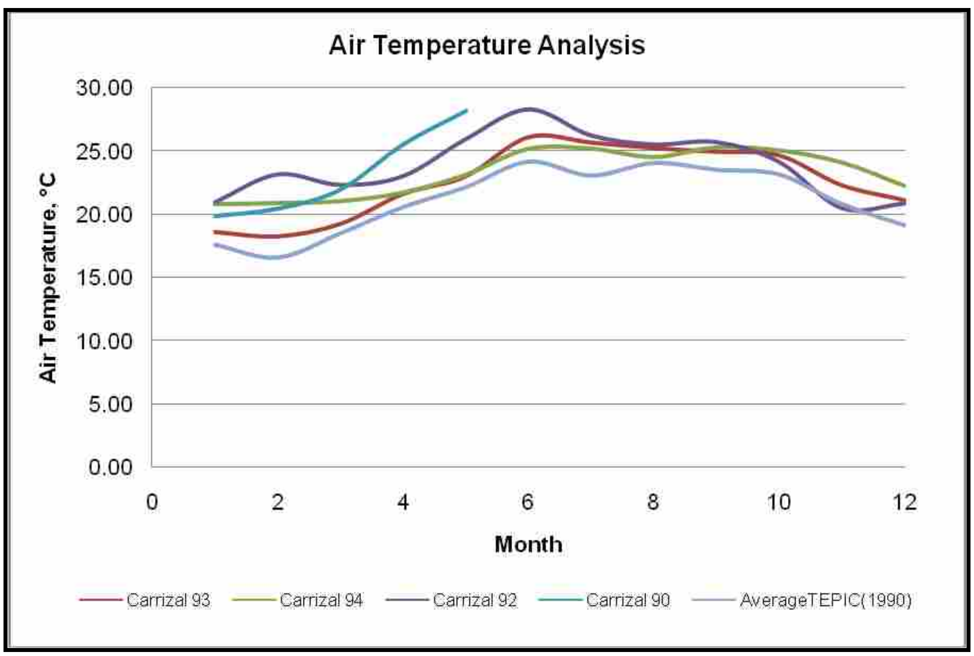


Figure 3-7: Air Temperature Analysis (Tepic-Carrizal)

3.5.2 Boundary Condition Modifications

In order to create the most accurate model of the Aguamilpa reservoir, several assumptions were made with the available data to create the boundary conditions files. First of all, due to incomplete or unavailable data, inflow data for two of the three main branches of the reservoir had to be estimated. Inflow calculations for branch 2 (Huaynamota River) and branch 3 (Ensenada), were completed by using water velocity values derived from a study titled "Water Quality Impacts for the Hydroelectric Project Aguamilpa, Nayarit" which was prepared by de Victorica et al., (1993). Inflow velocities were measured during the beginning of the rainy season (August) at the inflow locations of the Santiago River (0.124 m/s), and Huaynamota River (0.089 m/s). Flow velocities were also measured close to the Aguamilpa-Solidaridad Dam (0.004 m/s). These velocities ($V = m/s$) together with cross sectional areas ($A = m^2$) of the three branches of the Aguamilpa reservoir, calculated from the reservoir bathymetry data (central narrowest layer multiply by the segment depth), were used to estimate the stream inflow ($Q = m^3/s$) data for branch 1, branch 2 and branch 3. This stream flow data was estimated using continuity equation ($Q = V*A$).

These estimated stream flows for branch 1, branch 2 and branch 3 were used to calculate the flow ratios of branch 2 and branch 3 with respect to the gauged flow of branch 1 (La Playa and Cerro Blanco gauging stations). As a result of the assumptions, it was found that the branch 2 inflow is approximately 27 % of the inflow for branch 1. The inflow for branch 3 was found to be 4 % of the inflow for branch 1.

Similar to the inflow, assumptions were used to develop the inflow temperature files and the distributed tributary inflow temperature files as well. There were no inflow temperature data available that could be used for the CE-QUAL-W2 model for the Aguamilpa reservoir. For the purposes of developing an initial model air temperature data from climatological stations, described in section 3.4.3, were used as the basis for the inflow temperature files and the distributed tributary inflow temperature files (Figure 3-8). Air temperatures were increased 5 °C to better represent the water temperatures in the inflow branches of the reservoir. The 5 °C value was chosen after running several thermal simulations and comparing them with field data reported by GRUBA (1997) and the current readings that are being monitored by CIATEJ (section 4.2). As mentioned before this estimation is one of the primary weaknesses of the model and recording daily water inflow temperatures are essential to develop a more accurate model. The distributed tributary inflow temperature files were created by using the average monthly estimated inflow temperature data for the three branches of the Aguamilpa reservoir.

Since the distributed tributary inflow files were created from the results obtained in the water balance, which is described in section 4.1, their assumptions are described in the same section. The assumptions made for the inflow constituents files and distributed inflow constituents files, are described in section 4.3.

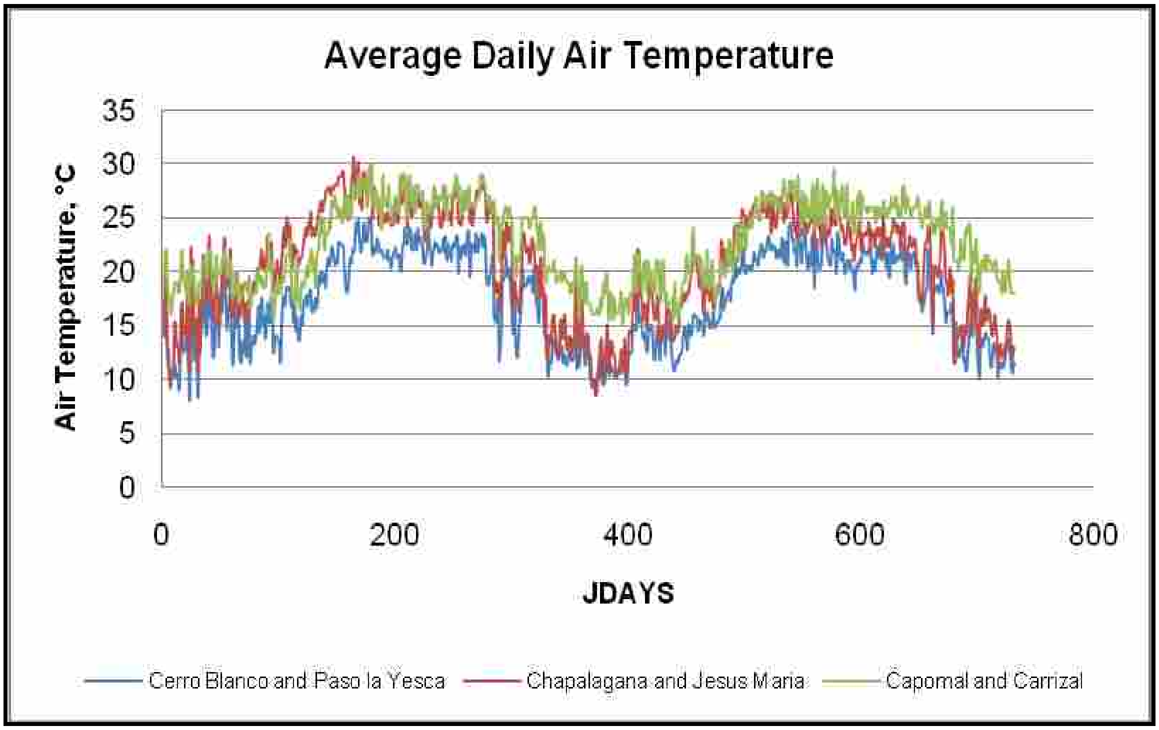


Figure 3-8: Air Temperature Data Used to Create Inflow Temperature Files

4 Results

In this section, results of the water balance calibration, temperature simulations, and example water quality simulations for the Aguamilpa reservoir are presented. The data preparation required to develop the model has been presented in the previous chapters. The process of creating a CE-QUAL-W2 water quality model for the Aguamilpa reservoir with both a thermal and example water quality simulation identified the available sources for information as well as the design of a monitoring and data acquisition plan to obtain the minimum required data. The monitoring and data acquisition plan is also explained in this section.

4.1 Water Balance Calibration

The first step in the Aguamilpa water quality simulation was to perform a water balance. An accurate accounting of the water budget for a reservoir is essential for a simulation and the calibration of the model. All the recorded and estimated inflow and outflows data (described in sections 3.4 and 3.5.2) for 1995 and 1996 were used to establish the water balance of the Aguamilpa reservoir. As shown in Figure 4-1, the reservoir's water budget was checked by comparing predicted elevations with observed elevations. This comparison was formulated by using the CE-QUAL-W2 V3.2 and the water balance tools that generate the inflows needed to establish an accurate water balance (Figure 4-2). The water surface elevation differences were converted to daily volumes which were positive or negative.

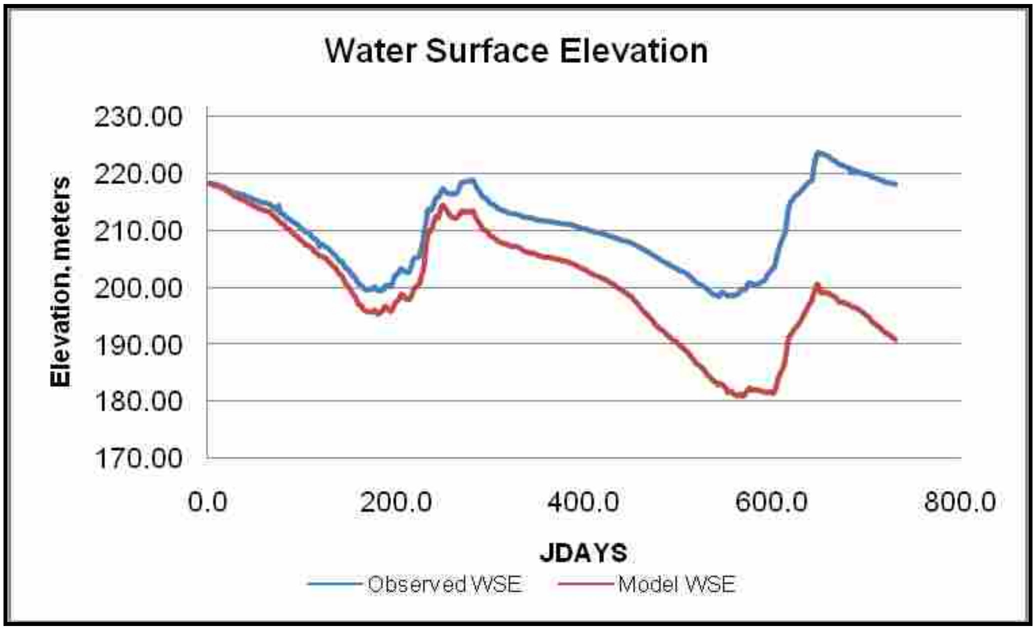


Figure 4-1: Observed and Modeled Water Surface Elevations Comparison

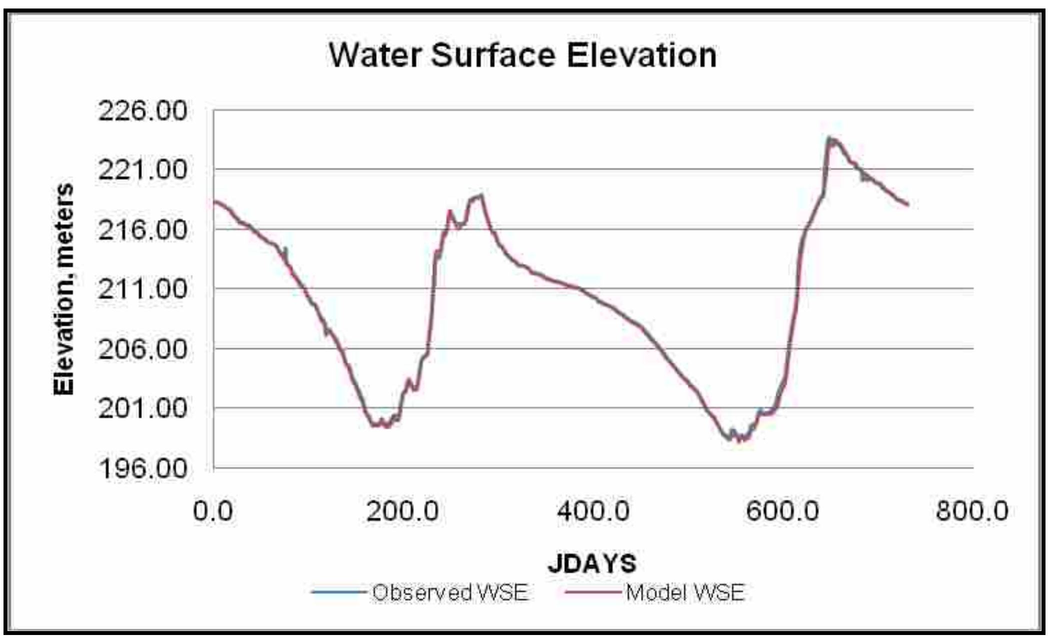


Figure 4-2: Water Balance Calibration of the Aguamilpa Reservoir

The volume differences were added to the inflows of the model through the three distributed tributary inflows files, which represent all the ungauged inflows and outflows for the Aguamilpa reservoir (ecological flow, irrigation intakes, precipitation, evaporation, seepage, bank storage and ungauged tributaries inflows). These three distributed tributary inflow files were estimated from the inflows and outflows generated in the water balance. The maximum difference between the observed and modeled water surface elevations was approximately 12.5 %, meaning that most of the distributed tributary inflows may correspond to the ungauged tributaries inflows. However, large negative flow values were obtained for some days of simulation, meaning that there could be some water releases from the reservoir that were not taken into account (evaporation, irrigation intakes, and ecological flows). In order to decrease the large negative values, a five-day average inflow calculation was performed to reduce the error generated by the ungauged outflows of the Aguamilpa reservoir. This five-day inflow calculation was randomly chosen trying to distribute the error throughout a week. Because this average reduced the large negative values, it was not necessary to try other average days. The allocation of the error in simulated versus measured volumes to the distributed tributary inflow through the three main branches of the reservoir used the following criteria: The distributed tributary inflows for branch 3 and branch 2 were estimated to be 4 % and 27 % respectively of the inflows contributing to the water balance. The distributed tributary inflows for branch 1 were estimated by subtracting the sum of the distributed tributary inflow estimated for branch 1 and branch 2 from the total distributed tributary inflows generated in the water balance.

4.2 Thermal Simulation

As mentioned in section 2.5.1 the mixing regime in deep subtropical reservoirs is warm monomictic, meaning that the reservoir only turns over once per year (during winter season). These high temperatures in the subtropical reservoirs accelerate the rates of chemical reactions and biological processes. The thermal simulations run for the Aguamilpa reservoir proved that CE-QUAL-W2 is suitable for deep subtropical reservoirs. Insufficiency of *In-Situ* water temperature data and inflow water temperature prohibits an accurate thermal calibration for the Aguamilpa reservoir. However, making some assumptions such as increasing the wind sheltering coefficient (1.45), wind function coefficients, solar radiation shading (0.85) and increasing/decreasing the estimated inflow temperatures, allow the simulation of similar thermal conditions that have been recorded by CIATEJ in the Aguamilpa reservoir (Figure 4-3).

The wind sheltering coefficient has the most effect on temperature during calibration and it is necessary to adjust it before changing any other coefficient. According to Cole and Wells (2003), previous applications varied the wind sheltering coefficients have found that values from 0.5-0.9 are used for reservoirs located at mountainous and/or dense vegetative canopy areas. Values of 1.0 are used for open terrain areas and values over 1 should be used for funneling effects on systems with steep banks, like Aguamilpa reservoir's area in which, after several runs, a value of 1.45 was chosen. The wind function coefficients have effects in the surface heat exchange and evaporation of the reservoir.

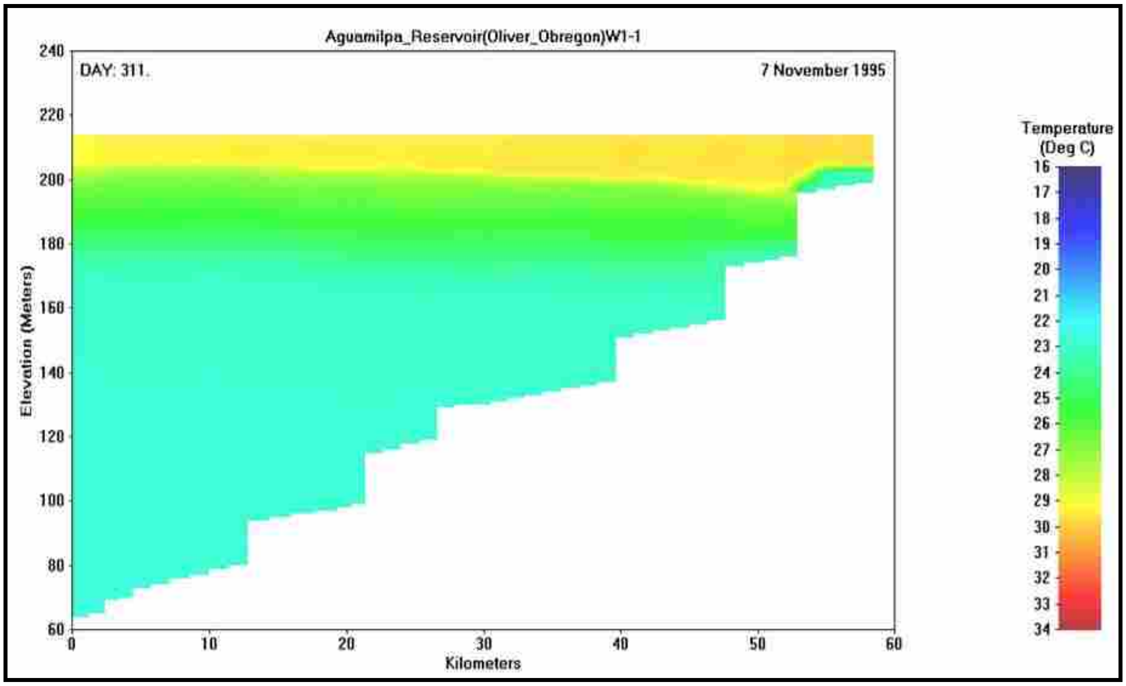


Figure 4-3: Water Temperature Simulation for Branch 1 (Santiago River)

Even though, there were not enough water temperature data for the years that the model was developed (1995-1996), an attempt of thermal calibration for the Aguamilpa reservoir was performed using the estimated water temperatures. As shown in Figure 4-4, this thermal calibration resulted in simulated water temperature values that matched the limited measured water temperatures values that were recorded in the study prepared by GRUBA (1997). These field water temperature values were collected during the third week of October and first and third week of November in 1995 close to the Aguamilpa-Solidaridad Dam.

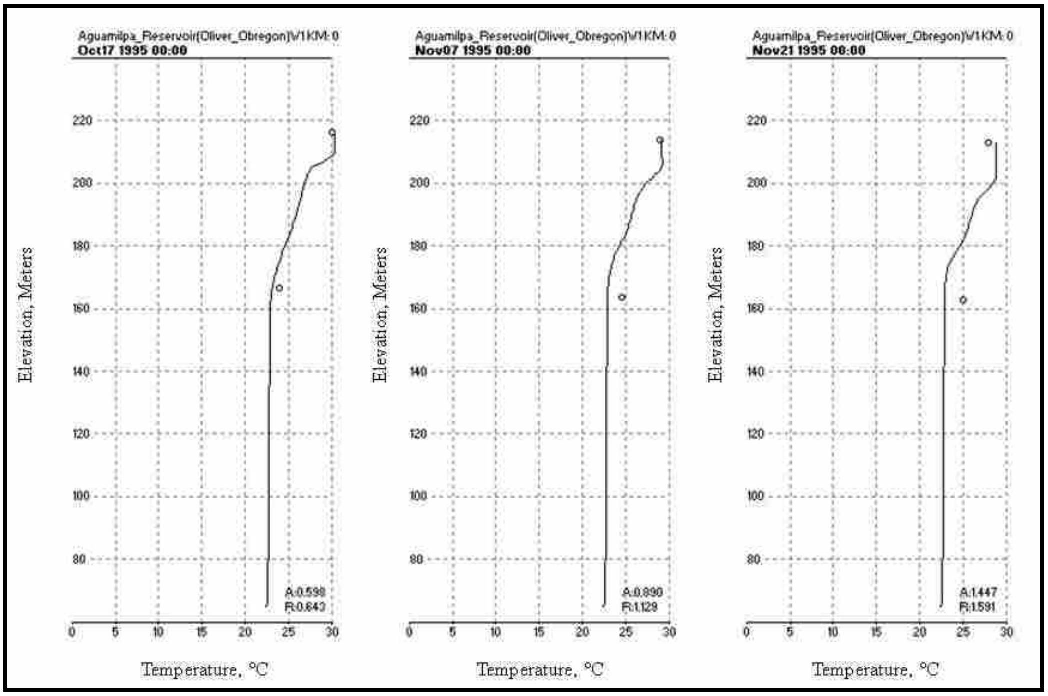


Figure 4-4: Field vs. Modeled Water Temperature Data (1995)

4.3 Example Water Quality Simulations

As explained in section 3.4.4, there were not enough available water quality data from the three main branches of the Aguamilpa reservoir to run constituent simulations. Nevertheless, to demonstrate how a CE-QUAL-W2 water quality model for the Aguamilpa reservoir may work, water quality simulations were run using input data from a different reservoir.

The water quality input data used to create the inflow constituents files and the distributed tributary inflow concentration files were gathered from the East Canyon reservoir located in the state of Utah, in the western United States. It is important to mention that the Aguamilpa reservoir and East Canyon reservoir are not similar in characteristics. The example water quality simulations included twenty water quality parameters, such as total dissolved solids (TDS), dissolved oxygen (DO), inorganic suspended solids group 1 (ISS1), dissolved silica (DSI), dissolved inorganic phosphorous (PO_4), ammonium (NH_4), nitrate-nitrite (NO_3), dissolved iron (Fe), labile dissolved organic matter (LDOM), refractory dissolved organic matter (RDOM), labile particulate organic matter (LPOM), refractory particulate organic matter (RPOM), total inorganic carbon (TIC), alkalinity (ALK) and six algal groups (ALG), chlorophyll α, and diatoms.

Example simulations of water quality parameters, used to define the trophic level in a reservoir, were run to show what the water quality of the Aguamilpa reservoir may look like and how the CE-QUAL-W2 model may be used to evaluate it. The simulated water quality parameters, chosen to define the trophic level were: dissolved oxygen (Figure 4-5), phosphorous (Figure 4-6) and chlorophyll α (Figure 4-7). Also, as shown in Figure 4-8, a simulation of cyanobacteria was performed, because this algal group is usually present in subtropical reservoirs like Aguamilpa (Reddy, 2005). These example water quality simulations showed that the Aguamilpa reservoir is a clinograde reservoir with low dissolved concentrations (anoxic) on the hypolimnion.

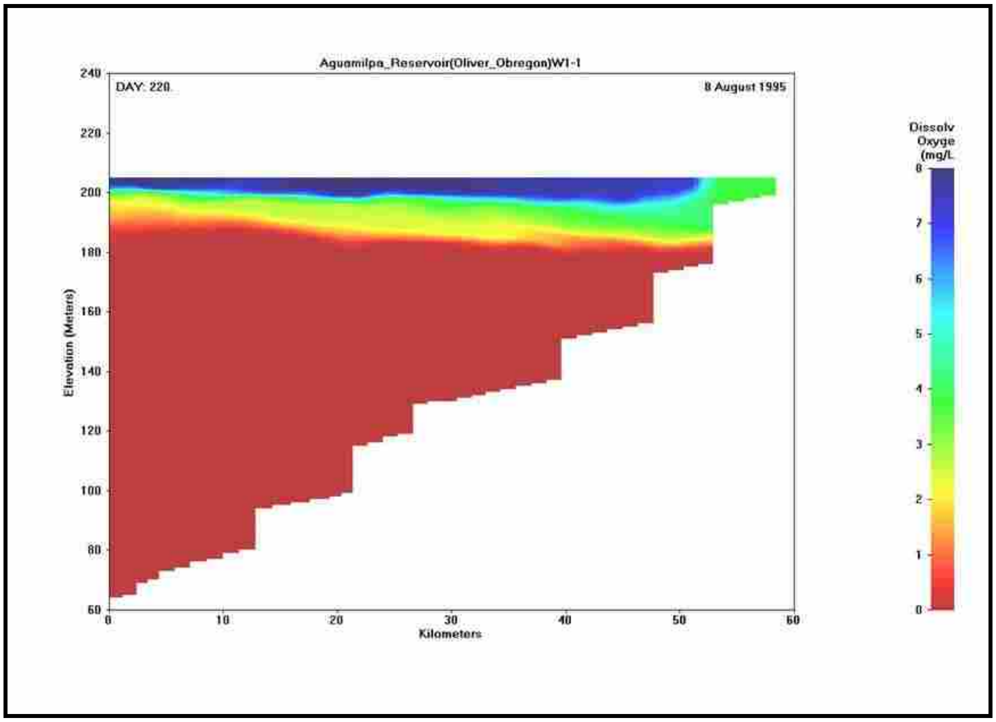


Figure 4-5: DO Example Simulation Branch 1 (Santiago River)

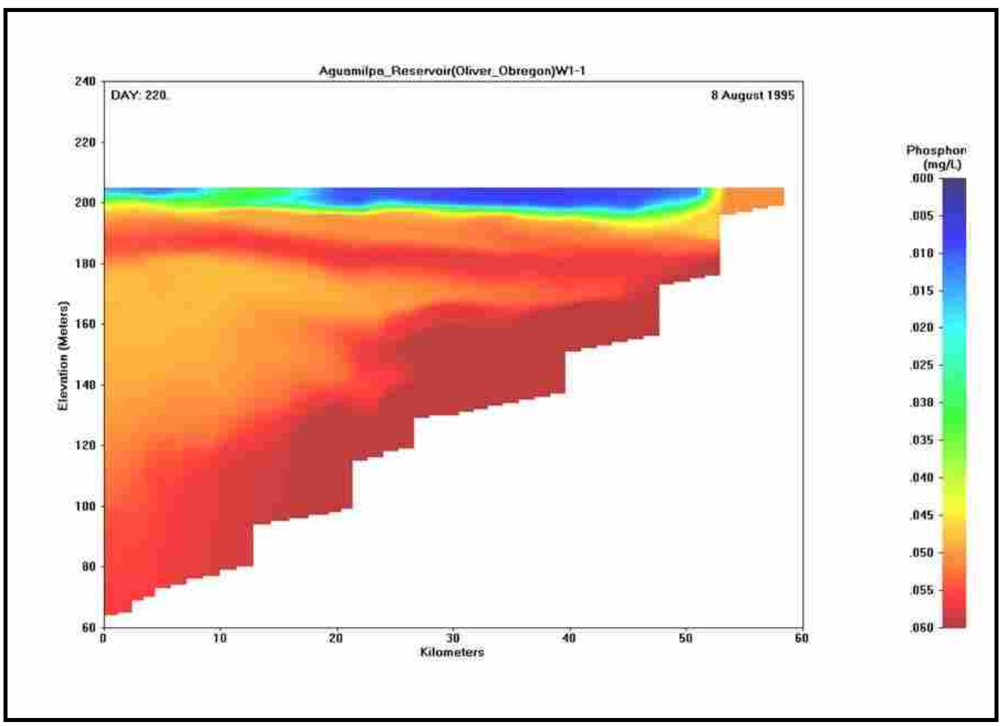


Figure 4-6: Phosphorous Example Simulation Branch 1 (Santiago River)

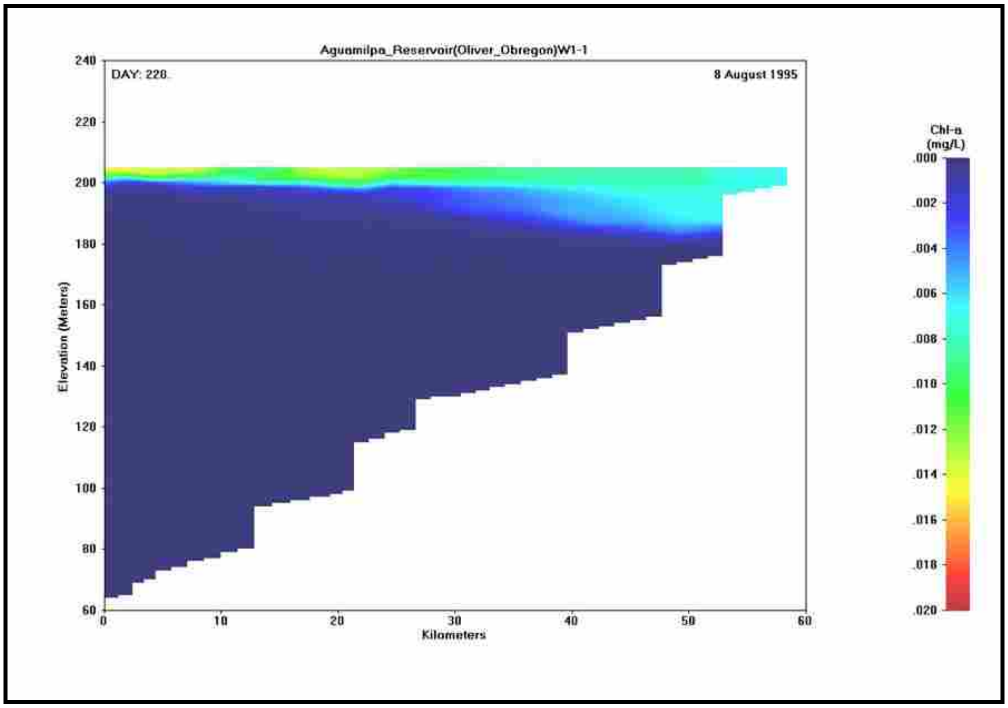


Figure 4-7: Chlorophyll α Example Simulation Branch 1 (Santiago River)

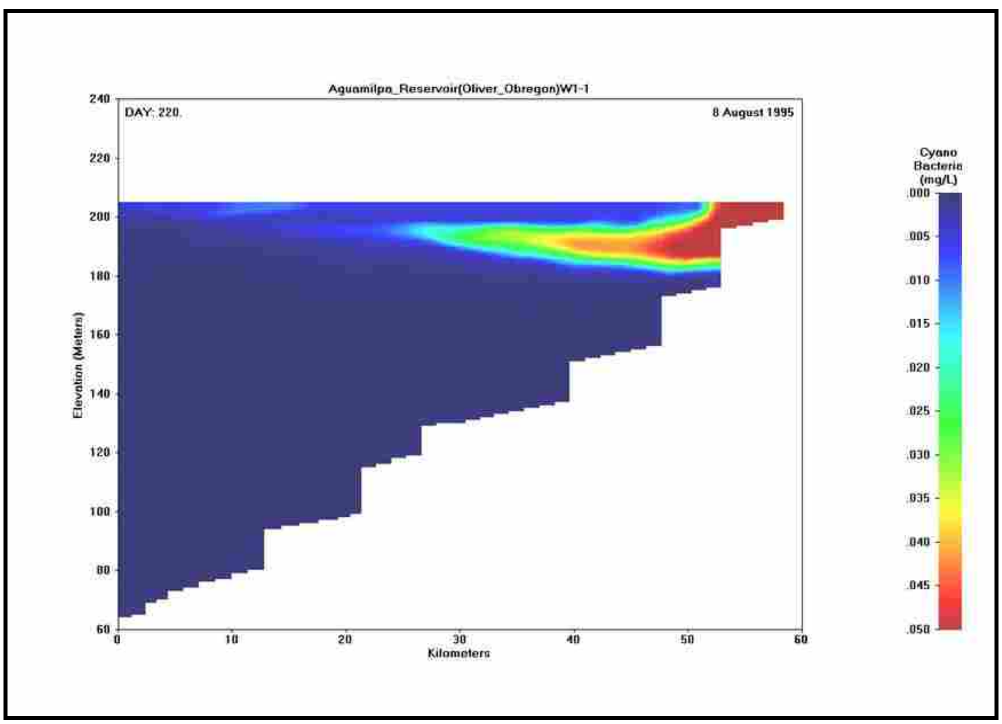


Figure 4-8: Cyanobacteria Example Simulation Branch 1 (Santiago River)

4.4 Monitoring and Data Acquisition Plan

As a result of developing the CE-QUAL-W2 water quality model for the Aguamilpa reservoir, a monitoring and data acquisition plan was designed to obtain the minimum required data necessary to support water quality modeling with CE-QUAL-W2 for the Aguamilpa reservoir. This monitoring and data acquisition plan includes the following data:

- Hourly climatological data from the station located in the Aguamilpa-Solidaridad Dam. This station is known as Aguamilpa or Carrizal and the acquisition of this data from 1994 to 2007 is still in process. These data can be obtained from CFE (Tepic) and from the website created by CFE: <http://h06814.iie.org.mx/presascfe/semanapresaCaracol.aspx?estacion=Agu>. It is important to mention that this website was uploaded on the last week of July 2008 and it only has climatological data from October 2007 to the present.
- Daily inflow data from the gauging stations known as La Playa, Huaynamota II (or Jesús María and Chapalagana), Cerro Blanco and the average daily outflow data from El Cajon Dam which is located upstream of the Aguamilpa reservoir (see Appendix A). All these data can be obtained from CFE (Tepic station and Mexico City) and CONAGUA. The acquisition of these data is still in process.
- Hourly releases and observed surface water level values from the Aguamilpa-Solidaridad Dam. These data were obtained from CFE (Tepic) and CFE (Mexico City) for the initial model, and should continue

to be available for subsequent modeling efforts from the website mentioned above and CFE (Tepic).

- It is necessary to identify the ecological release that is normally discharged from the Aguamilpa-Solidaridad Dam or any other outflow points in which water from the reservoir is being discharged. These outflow points can be irrigation intakes and the use of the spillway. If the spillway has been used, it will be necessary to gather the discharged flows and the height that the gates were opened. This information can be obtained from CFE (Tepic) and CONAGUA. The acquisition of these data is still in process.
- Daily inflow temperatures and inflow constituents from branch 1 (Santiago River), branch 2 (Huaynamota River) and branch 3 (Ensenada). These data can be gathered by installing temperature and water quality loggers at the most upstream parts of the three main branches in the Aguamilpa reservoir (see Figure 4-9). These loggers are used to record daily inflow temperatures and inflow constituents such as pH, turbidity, DO, and conductivity.
- Bimonthly water quality boundary conditions such as total organic carbon (TOC), total phosphorous (TP), nitrite-nitrate-nitrogen (NO_2+NO_3-N), ammonium-nitrogen (NH_4-N). It is recommendable to monitor these values every week but due to location of the Aguamilpa reservoir and the available budget for this project bimonthly data will be enough to run accurate simulations. The acquisition of these data is pending.

- Bimonthly *In-Situ* water quality data that has been collected from eight sampling points (see Figure 4-9) along the entire reservoir. The collection of these data began on the first week of June, 2008 and is being taken by CIATEJ every two months for a two-year period. Also, water quality data collected by the National Fishery Department of Mexico (NFD) from the Santiago River should be obtained.

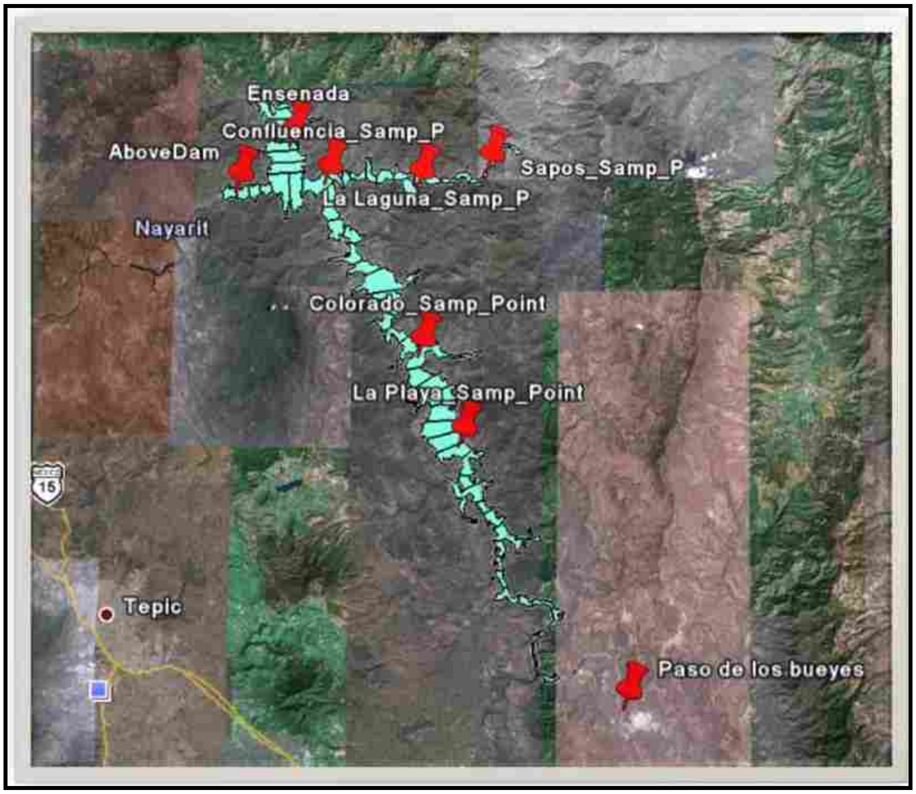


Figure 4-9: *In-Situ* Water Quality Sampling Points Location

5 Summary and Conclusions

A water quality model was identified and assessed for a subtropical reservoir, Aguamilpa. The Aguamilpa reservoir, located in the State of Nayarit, Mexico, is important for the northwest area of the country for power generation, irrigation, and fishing. Furthermore, the government's future plans show that it may be used for water supply. Because most of the Mexican reservoirs present different levels of pollution, the use of a two-dimensional CE-QUAL-W2 water quality modeling tool might help authorities, researchers, and private institutions better manage the reservoirs. This study concluded that the CE-QUAL-W2 water quality model is applicable to large-narrow-deep subtropical reservoirs, like Aguamilpa, if the minimum required data are available. Objectives were established for this study and their realization is explained below as well as future work for this study.

First of all, developing the CE-QUAL-W2 water quality model for the Aguamilpa reservoir demonstrated that this model is appropriate to simulate the Aguamilpa reservoir (subtropical). The characteristics of the area where it is located and the capabilities of the model were useful to conclude the CE-QUAL-W2 suitability. The model was built for 1995 and 1996 due to the availability of data.

The minimum required data and gaps for modeling the Aguamilpa reservoir were identified during and after the construction of the CE-QUAL-W2 water quality model. As discussed in previous sections, there were unavailable or incomplete data required for modeling the reservoir and it was necessary to make several assumptions that could affect the accuracy of the model. In this study, it was found that most of the required data can be obtained from Mexican governmental agencies such as INEGI, CFE (Tepic and Mexico City) and CONAGUA. Obtaining data is a time consuming task because the data are spread throughout the offices previously mentioned. However, this study explained what kind of data are needed and where it can be gathered or requested.

Even though the unavailable inflow water temperature data, thermal simulations, illustrated in the results section, were run to model the water temperatures in the reservoir during different weather seasons over a two-year simulation period. These thermal simulations showed that the Aguamilpa reservoir is stratified during most part of the year, turning over once per year during the month of December (monomictic reservoir) which is a typical behavior for a deep subtropical reservoir. These simulations were compared with the few water temperature data collected in the field and show these thermal simulations are close to what was happening in the reservoir. This preliminary thermal calibration reinforced the fact that CE-QUAL-W2 is suitable for the Aguamilpa reservoir. This study also concluded that it is important to frequently monitor the inflow water temperature for the three main modeled branches (Santiago River, Huaynamota River and Ensenada) to have enough data for thermal calibrations. Running the example water quality simulations illustrated what water quality data are required for modeling the reservoir. Like thermal simulations, the example water quality simulations helped design a water quality-quantity monitoring and data acquisition plan used to obtain all the minimum required data to run an accurate model.

The monitoring and data acquisition plan designed in this study detail when, where, and what data should be collected. This plan should be implemented as soon as possible and followed to update and calibrate the model. It may be challenging to follow this monitoring plan because the current budget for this project may be insufficient to finance the field trips to the reservoir and purchase the required equipment. Nevertheless, if this monitoring and data acquisition plan is correctly followed, the model can be updated and calibrated. Once the model is calibrated, it may be a useful monitoring tool to simulate the water quality changes in the Aguamilpa reservoir (subtropical) and be used to evaluate the environmental, climatological and anthropogenic effects of various management choices. It also serves as a guideline for developing similar water quality models at other reservoirs in the region.

The developed CE-QUAL-W2 water quality model for the Aguamilpa reservoir requires continuing work. The results from this study have generated new options for future research work which include: 1) Optimizing the proposed water quality monitoring plan, 2) Updating the CE-QUAL-W2 water quality model based on the ongoing water quality data being collected at Aguamilpa, 3) Continue collecting *In-Situ* water quality data, 4) Calibration of the model, 5) Simulating different water quality scenarios to provide information for management plans, 6) Identifying and adding algal groups to the model, 7) Providing guidelines for development of models for similar reservoirs located along the Santiago River and other locations in Mexico.

References

Aquaveo. (2008). "AQUAVEO Water Modeling Solutions." http://www.aquaveo.com/wms (October/15, 2008).

Arredondo, J. L., Diaz, G., and Ponce, J. T. (2008). Limnologia de Presas Mexicanas: Aspectos Teoricos y Practicos. Universidad Autonoma Metropolitana and Agt Editor SA.

Avery, R. E. (2007). "Evaluating the impact of nutrient input reductions on chlorophyll a concentrations using CE-QUAL-W2 at Lake Eucha, Oklahoma." MS thesis, University of Arkansas, Arkansas, United States.

Ayres, W.S., Busia, A., Dinar, A., Hirji, R., Lintner, S.E., McCalla, A.F., and Robelus, R. (1997). "Integrated Lake and Reservoir Management. World Bank Approach and Experience." Rep. No. 358, The World Bank, Washington, D.C.

Bowen, J. D., and Hieronymus, J. W. (2003). "A CE-QUAL-W2 Model of Neuse Estuary for Total Maximum Daily Load Development." J.Water Resour.Plann.Manage., 129(4), 283-294.

Chapra, S. C. (1997). Surface Water Quality Modeling. McGraw-Hill, New York, United States.

Cloern, J. E. (2001). "Our evolving conceptual model of the coastal eutrophication problem." Mar Ecol Prog Ser, 210 223-253.

Cole, T.M., and S.A. Wells. (2003). "CE-QUAL-W2: A two-dimensional, laterally averaged, Hydrodynamic and Water Quality Model, Version 3.2." Rep. No. Instruction Report EL-03-1, US Army Engineering and Research Development Center, Vicksburg, MS.

Cole, T.M., and Tillman, D.H. (2001). "Water Quality Modeling of Allatoona and West Point Reservoirs Using CE-QUAL-W2." Rep. No. ERDC/EL SR-01-3, Environmental Laboratory U.S. Army Engineer Research and Development Center.

Comision Federal de Electricidad [CFE]. (2002). "Informe Final de los Estudios Hidrologicos e Hidraulicos." Comision Federal de Electricidad, Nayarit, Mexico.

Comision Federal de Electricidad [CFE]. (1991). "Proyecto Hidroelectrico Aguamilpa, Nay. Mexico 1991." Comision Federal de Electricidad.

Comision Nacional del Agua [CONAGUA]. (2008). "National Water Program 2007-2012." Secretaria de Medio Ambiente y Recursos Naturales, D.F., Mexico.

de Victorica, J. L. (1996). "Modelo para Simular la Evolucion del Oxigeno Disuelto en Embalses." Ingenieria Del Agua, 3(2), 63-74.

de Victorica, J.L., Galvan, M., and Rojas, M.N. (1993). "Impacto a la Calidad del Agua por el Proyecto Hidroelectrico Aguamilpa, Nay." Rep. No. 1303, Comision Federal de Electricidad, Mexico.

Friedler, E., Juanico, M., and Shelef, G. (2003). "Simulation model of wastewater stabilization reservoirs." Ecol.Eng., 20(2), 121.

GRUBA, S.A. de C.V. [GRUBA]. (1997). "Estudio de Calidad del Agua en el Embalse de la Presa Aguamilpa, Nayarit." Rep. No. GSCA 007/97, Comision Nacional del Agua Subdireccion General Tecnica Gerencia de Saneamiento y Calidad del Agua, Nayarit, Mexico.

Hellyer, G. (2008). "Some Landscape and Spatial Analysis Tools and Datasets for Rapid Watershed Assessment - Short Version." United States Environmental Protection Agency, New England, United States.

Holiday-Weather. (2007). "Holiday-Weather.com. Daily Worldwide forecasts for your holiday." http://www.holiday-weather.com/aguamilpa_mx/index.html (May/30, 2008).

Horne, A.J., and Goldman, C.R. (1994). Limnology. McGraw-Hill, United States.

Huszar, L. M., Caraco, N. F., Roland, F., and Cole, J. (2006). "Nutrient–chlorophyll relationships in tropical–subtropical lakes: do temperate models fit?" Biogeochemistry, 79(1/2), 239.

Hutchinson, G. E. (1957). A Treatise on Limnology. John Wiley and Sons, New York, NY.

INEGI. (2008). "Instituto Nacional de Estadistica y Geografia. Sistema Nacional de Informacion Estadistica y Geografia. Sistema de Descarga del Continuo de Elevaciones Mexicano." http://mapserver.inegi.org.mx/DescargaMDEWeb/?s=geo&c=977 (January/7, 2008).

INEGI. (2007). Sintesis de Informacion Geografica Estatal SIGE Nayarit. Instituto Nacional de Estadistica Geografia e Informatica (CD-ROM), Mexico.

INP. (2006). "Dictamen para la implementacion de la veda 2006, Aguamilpa, Nayarit. Instituto Nacional de la Pesca. Centro Regional de Investigacion Pesquera Bahia de Banderas, Nayarit. Secretaria de Agricultura, Ganaderia, Desarrollo Rural, Pesca y Alimentacion." http://www.inp.sagarpa.gob.mx/Dictamenes/2006/dictamenvedatilapiaaguamilpa2006.pdf. (January/7, 2008).

IUCN., and. WB. (1997). "Large Dams. Learning from the Past Looking at the Future. Workshop Proceedings. Gland, Switzerland." The World Conservation Union and the World Bank, Gland, Switzerland.

Kuo, J., Lung, W., Yang, C., Liu, W., Yang, M., and Tang, T. (2006). "Eutrophication modelling of reservoirs in Taiwan." Environmental Modelling & Software, 21(6), 829-844.

Lewis, W. M. J. (2002). "Causes for the high frequency of nitrogen limitation in tropical lakes." Verh. Internat. Verein. Limnol, 28 210-213.

Loginetics. (2008). "Reservoir Modeling Tools." http://www.loginetics.com/modtools/2DMOD.html (August/30, 2008).

MacKinnon, M.R., and Herbert, B.W. (1996). "Temperature, Dissolved Oxygen and Stratification in a Tropical Reservoir, Lake Tinaroo, Northern Queensland, Australia." Mar. Freshwater Res, 47(7), 937-949.

Marengo, H. (2006). "Case Study: Dam Safety during Construction, Lessons of the Overtopping Diversion Works at Aguamilpa Dam." J.Hydraul.Eng., 132(11), 1121-1127.

Martin, J.L., and McCutcheon, S.C. (1999). Hydrodynamics and Transport for Water Quality Modeling. Lewis Publishers, Boca Raton, Fla.

Mazumder, A., and Havens, K.E. (1998). "Nutrient-chlorophyll-Secchi relationships under contrasting grazer communities of temperate versus subtropical lakes." Can. J. Fish. Aquat. Sci, 55 1652-1662.

McLachlan, A. J. (1974). "Development of Some Lake Ecosystems in Tropical Africa, with Special Reference to the Invertebrates." Biol. Rev, 49(3), 365-397.

Nelson, E. J. (2006). WMS 8.0 HTML Help Document. Environmental Modeling Research Laboratory, Brigham Young University, Provo, UT.

Nielsen, E. J. (2005). "Algal Suscession and Nutrient Dynamics in Elephant Butte Reservoir." MS thesis, Brigham Young University, Provo, UT.

NOAA. (2008). "NOAA Satellite and Information Service." http://www.ncdc.noaa.gov.erl.lib.byu.edu/oa/ncdc.html (April/25, 2008).

OEPA. (2008). "TMDLs for the Black River Watershed, Ohio. Appendix D: CE-QUAL-W2 Modeling Report." Ohio Environmental Protection Agency, Ohio, US.

Ortiz, M.A., de Anda, J., and Maniak, U. (2006). "Estimation of Trophic States in Warm Tropical Lakes and Reservoirs of Latin America by Using GPSS Simulation." Interciencia, 31(5), 345-350.

Portland State University [PSU]. (2008). "Water Quality Research Group. CE-QUAL-W2 Hydrodynamic and Water Quality Model." http://www.ce.pdx.edu/w2/ (August/2, 2008).

Potential Impacts. (2003). "Potential Impacts of the Rio Lerma-Lago Chapala-Rio Santiago Watershed on the Presa de Aguamilpa Fishery. Interim Report."

PSOMAS. (2002). "Deer Creek Reservoir Drainage TMDL Study." Prepared for Utah Department of Environmental Quality Division of Water Quality. Prepared by PSOMAS, Salt Lake City, UT.

Raftis, R. R. (2007). "Internal Cycling in an Urban Drinking Water Reservoir." MS thesis, Indiana University-Purdue University, Indianapolis, IN.

Reddy, M. V. (2005). Restoration and Management of Tropical Eutrophic Lakes. Science Publishers, Inc, Enfield, NH.

ROP. (1997). "Ficha Tecnica: Central Hidroelectrica de Aguamilpa." Revista de Obras Publicas, 3(363), 116-117.

Shrestha, R. (2006). "Water Temperature Simulation in Amistad Reservoir." MS thesis, Lamar University, Beaumont, Texas.

U.S. Environmental Protection Agency [EPA]. (2007). "Water Quality Models and Tools." (July/27, 2008).

Wanielista, M., Kersten, R., and Eaglin, R. (1997). Hydrology Water Quantity and Quality Control. John Wiley and Sons, Inc, United States of America.

Williams, T. N. (2007). "Modeling Dissolved Oxygen in Lake Powell using CE-QUAL-W2." PhD thesis, Brigham Young University, Provo, Utah.

Appendix A. Scheme of the Aguamilpa-Solidaridad Dam

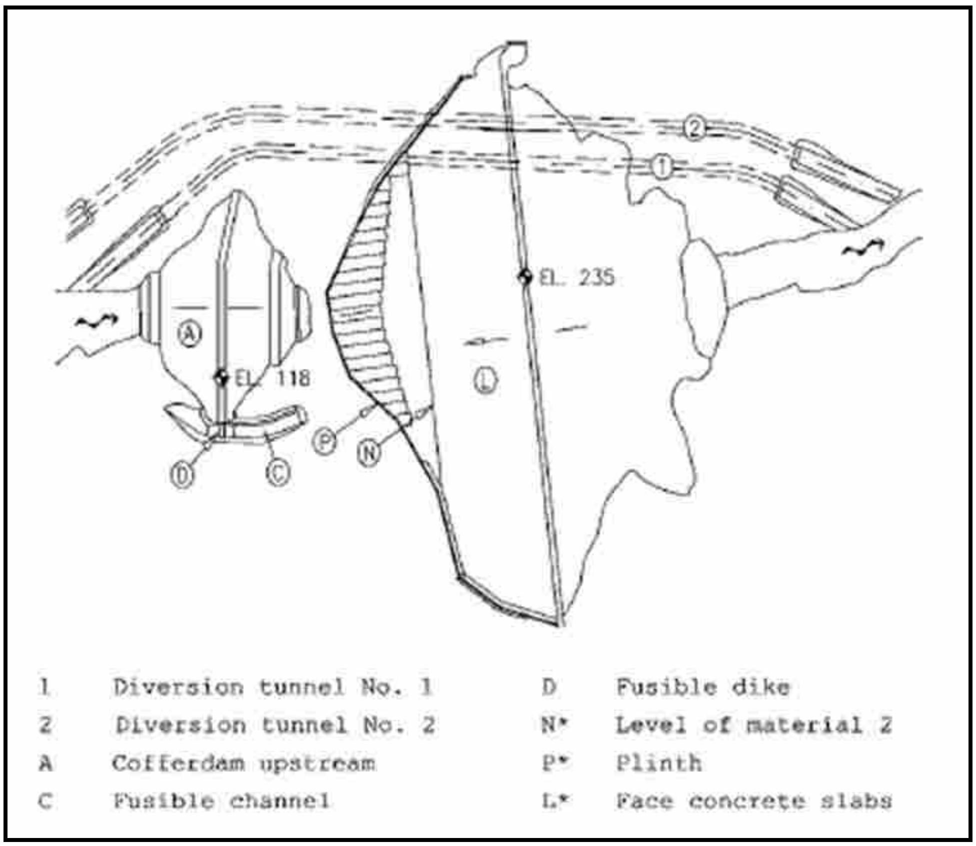


Figure A-1: Scheme of the Aguamilpa-Solidaridad Dam (Marengo, 2006)

Appendix B. Bathymetry

In this appendix the storage capacity curves and the final bathymetry grids for branch 2 and branch 3 are presented. The first graph (Figure B-1) compares the storage capacity curves generated by WMS for branch 1 (Santiago River), branch 2 (Huaynamota River), and branch 3 (Ensenada), with the storage capacity curves created from the field data obtained by GRUBA and the National Power Commission (Comisión Federal de Electricidad or CFE). The second graph (Figure B-2) shows the storage capacity curves for the segments created by WMS.

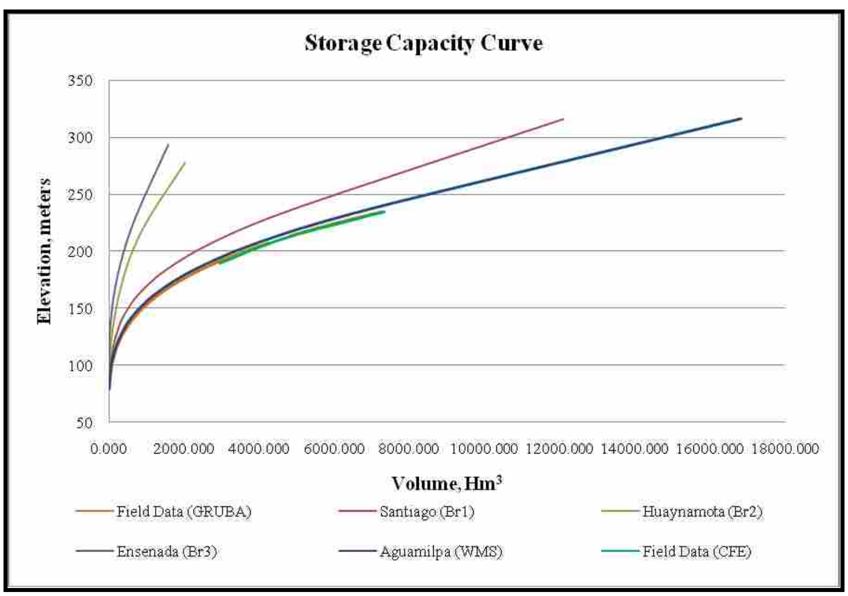


Figure B-1: Storage Capacity Curves for the Aguamilpa Reservoir

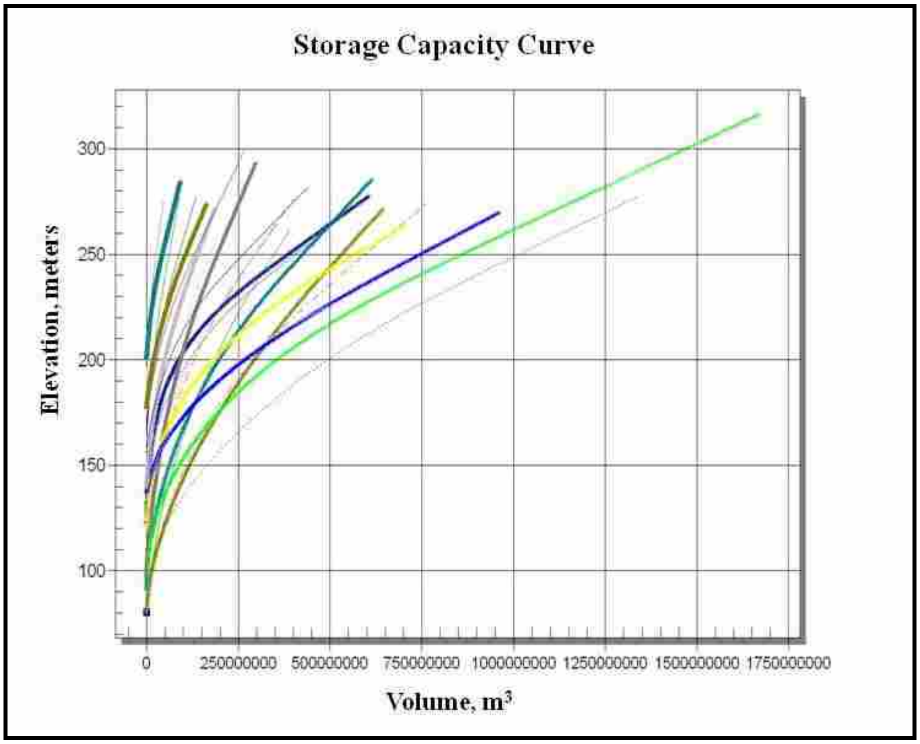


Figure B-2: Segments Storage Capacity Curves Generated by WMS

The final bathymetry grids of the Aguamilpa reservoir model are shown in Figure B-3 and Figure B-4.

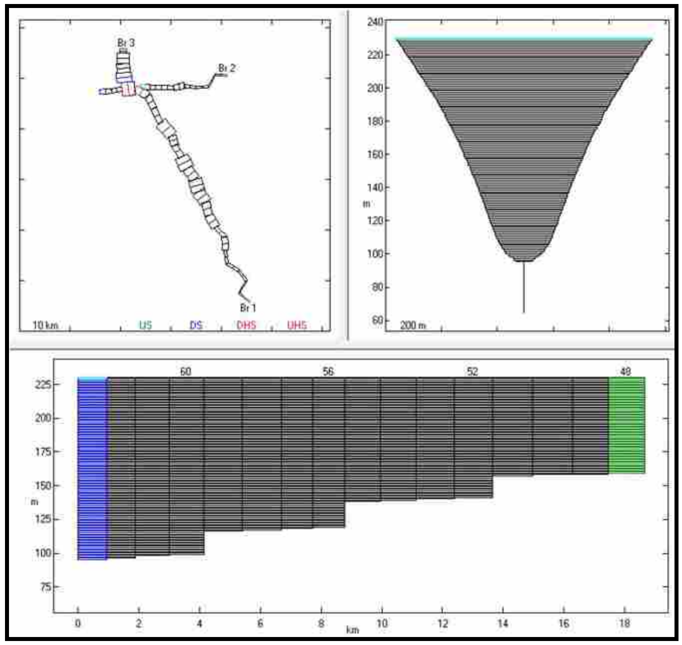


Figure B-3: W2 Bathymetry Grid of Branch 2 (Huaynamota River)

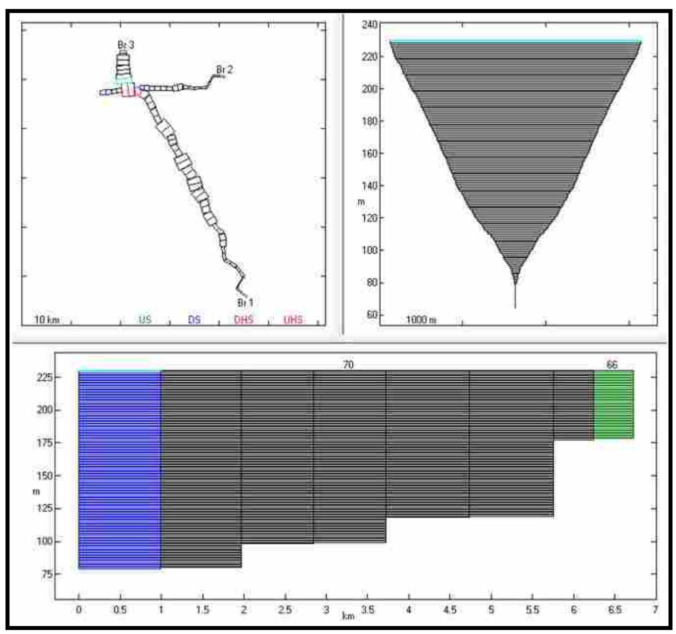
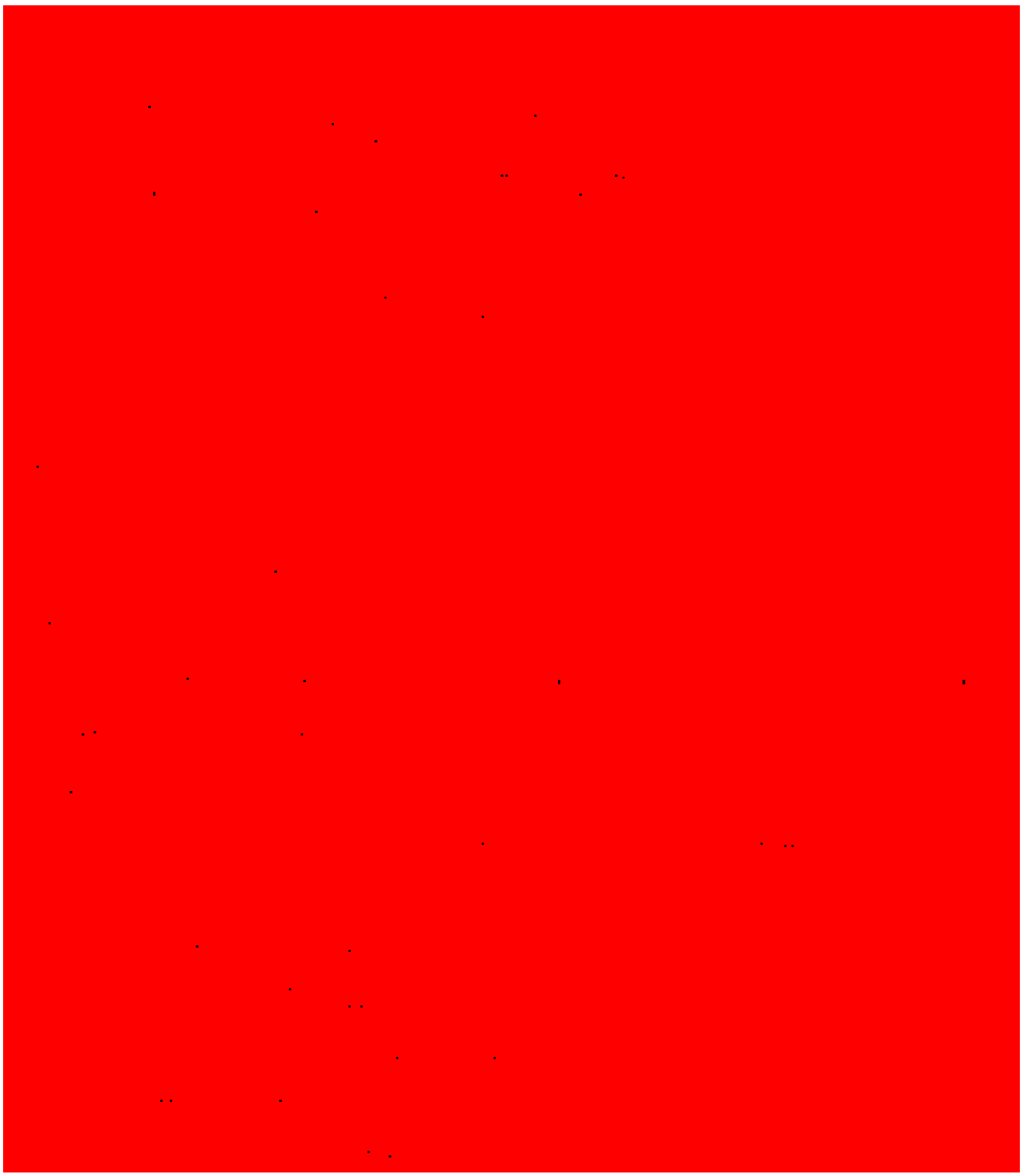
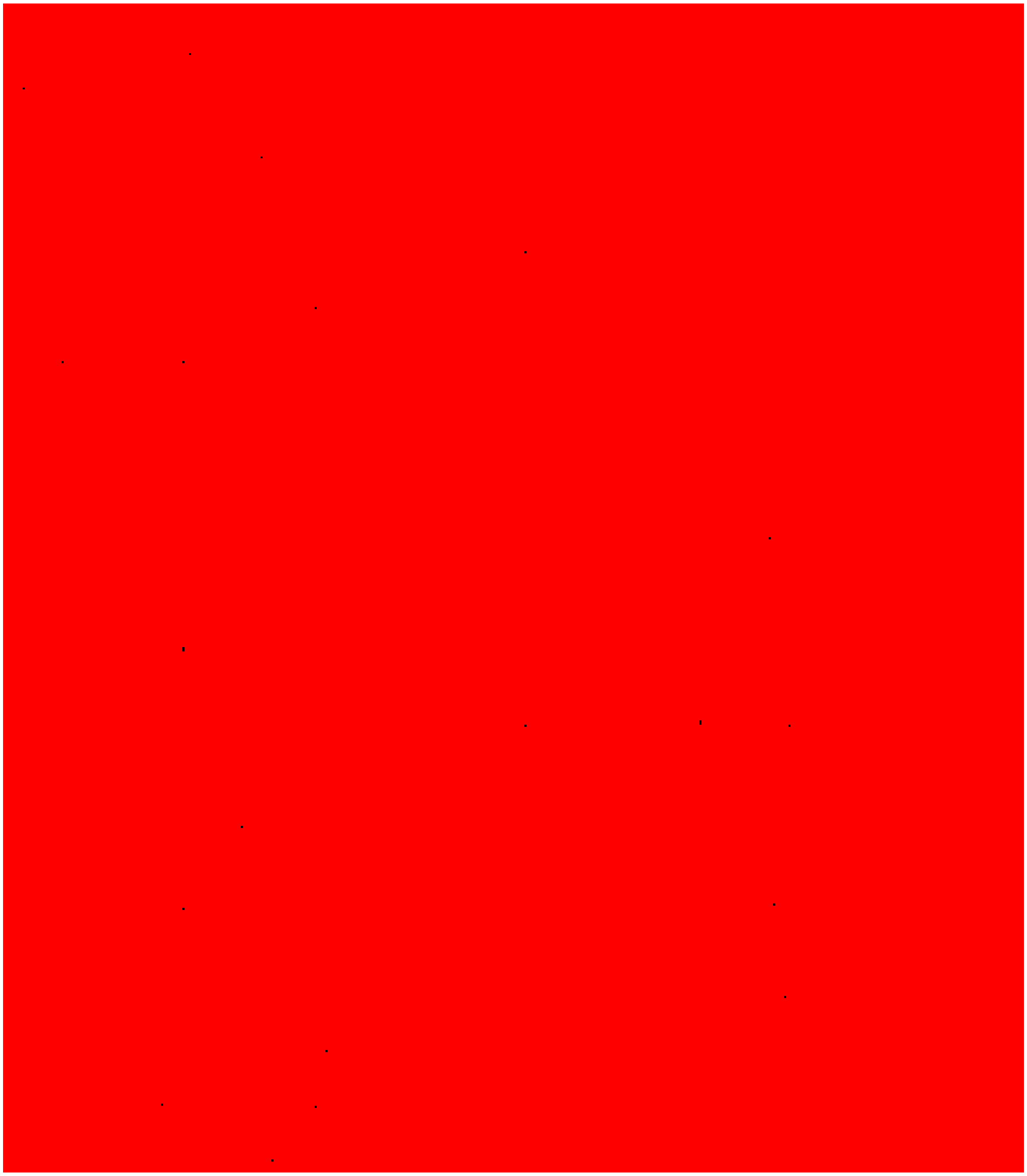
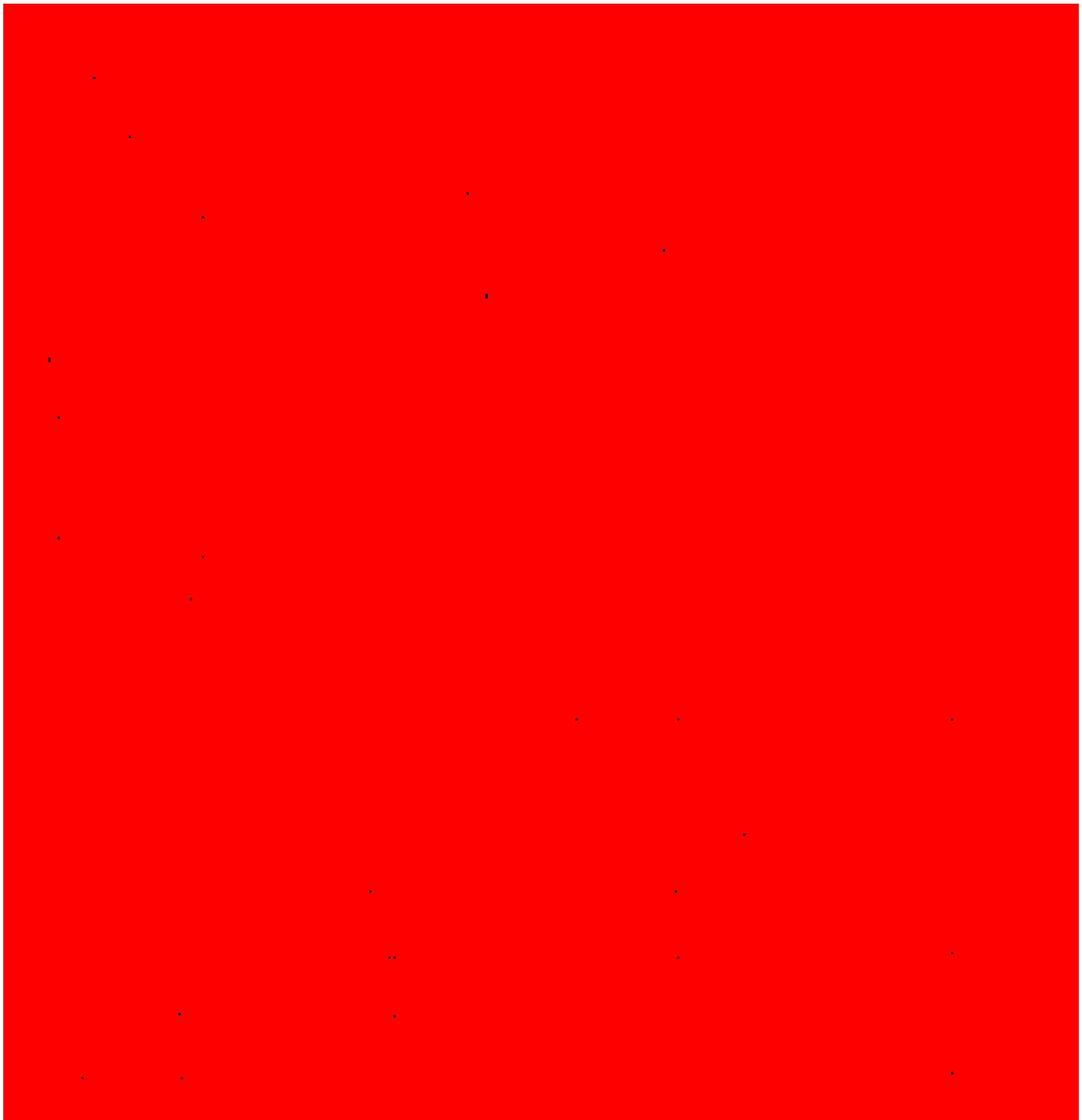


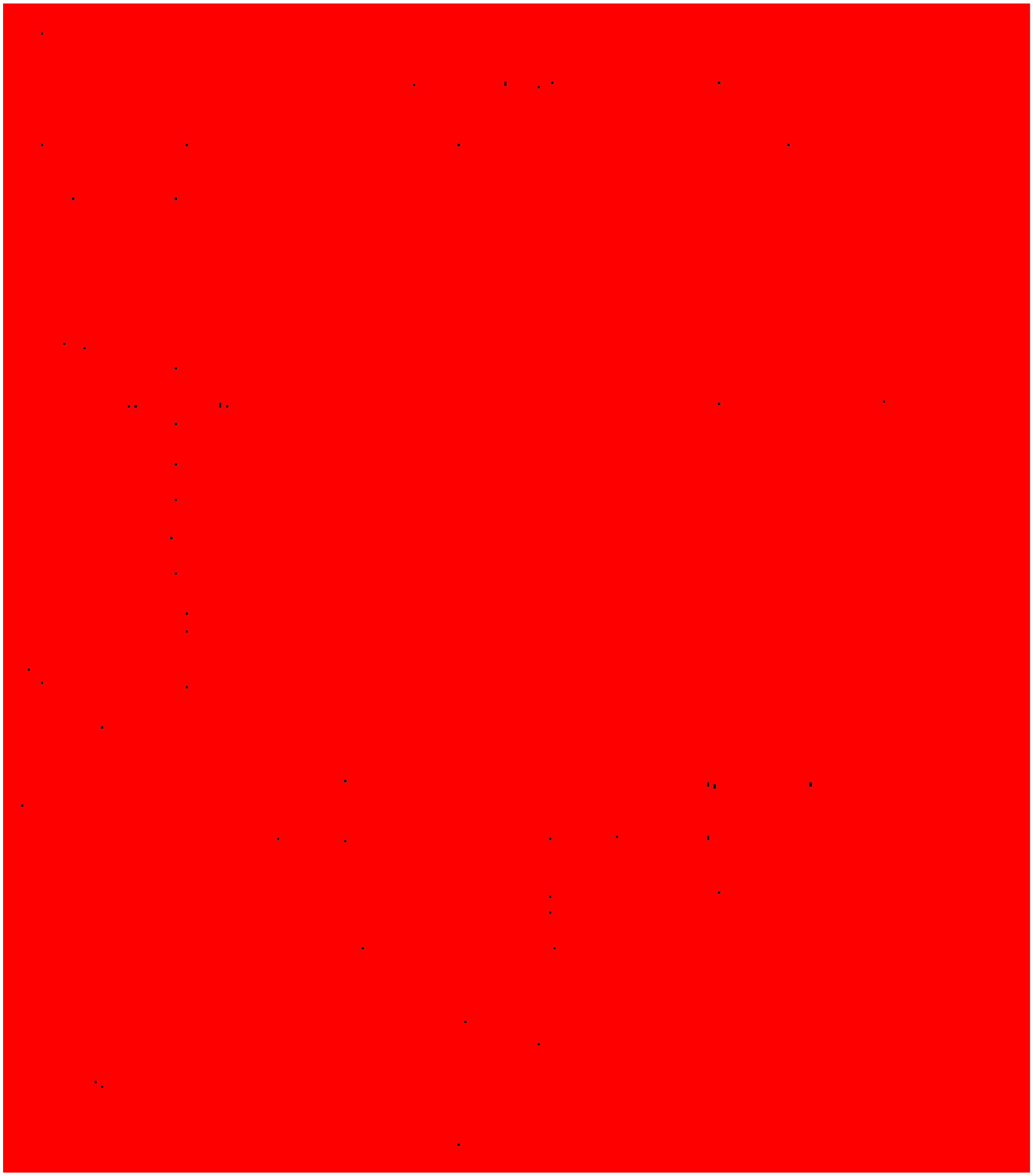
Figure B-4: W2 Bathymetry Grid of Branch 3 (Ensenada)

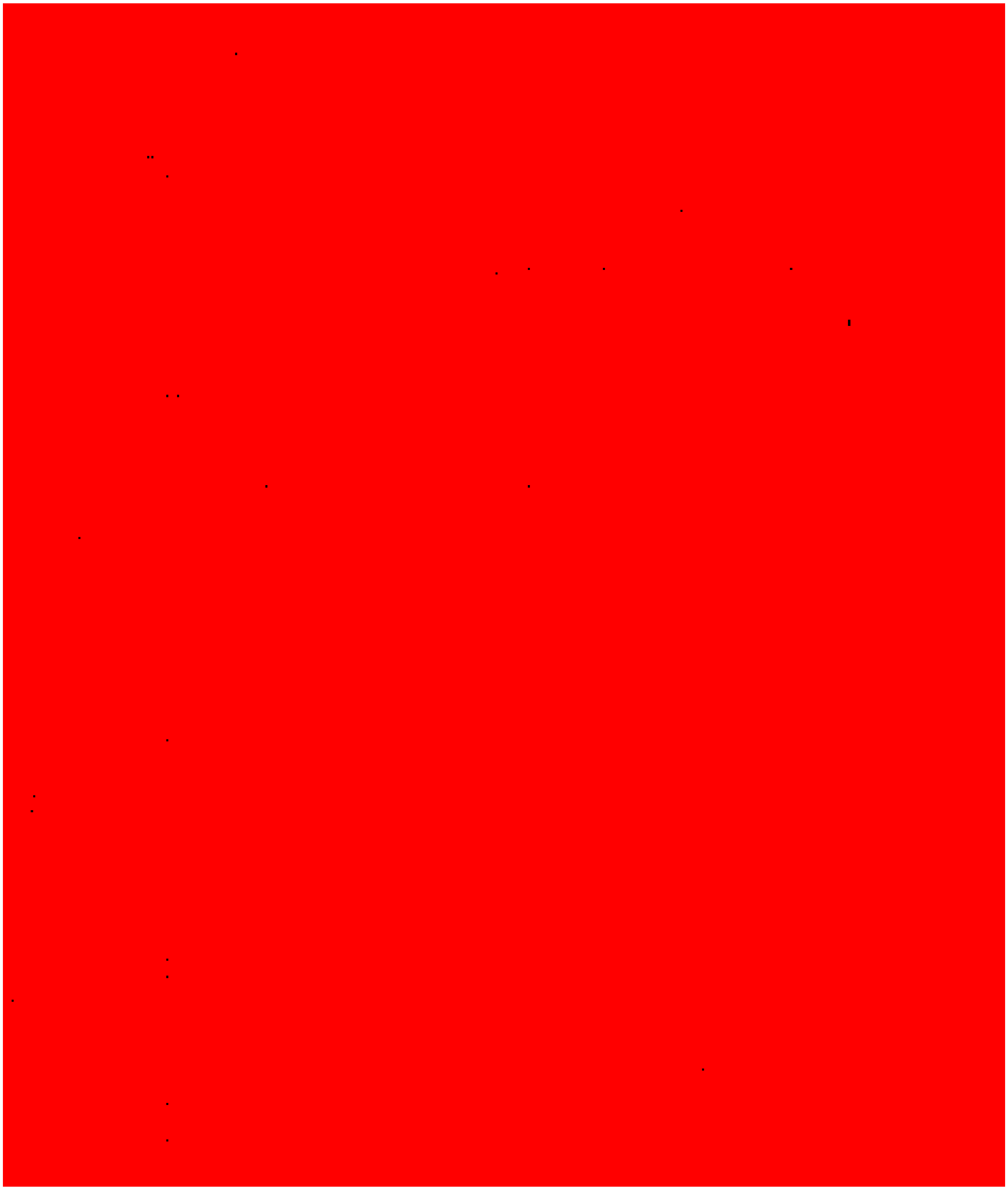
Appendix C. Control File

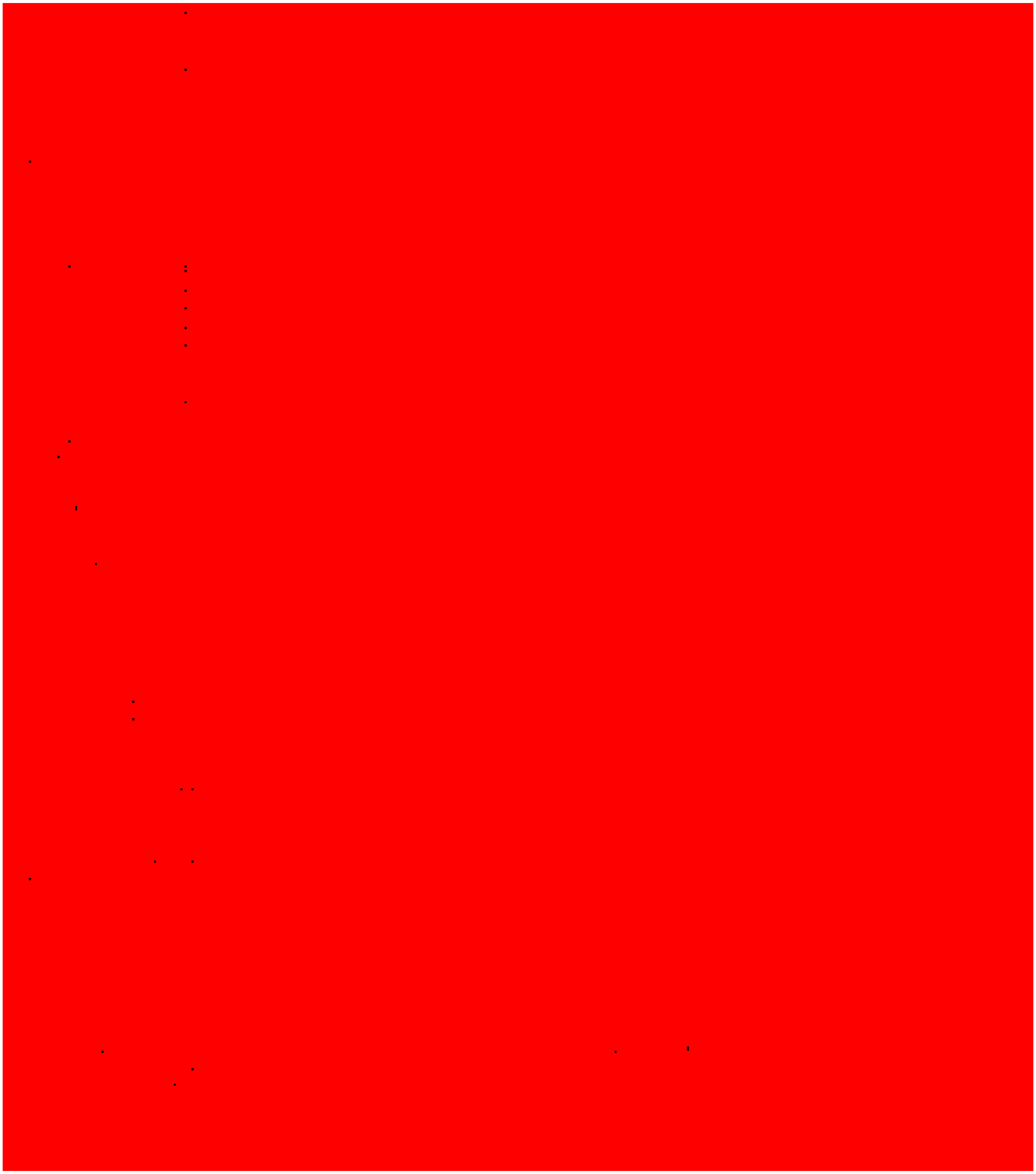












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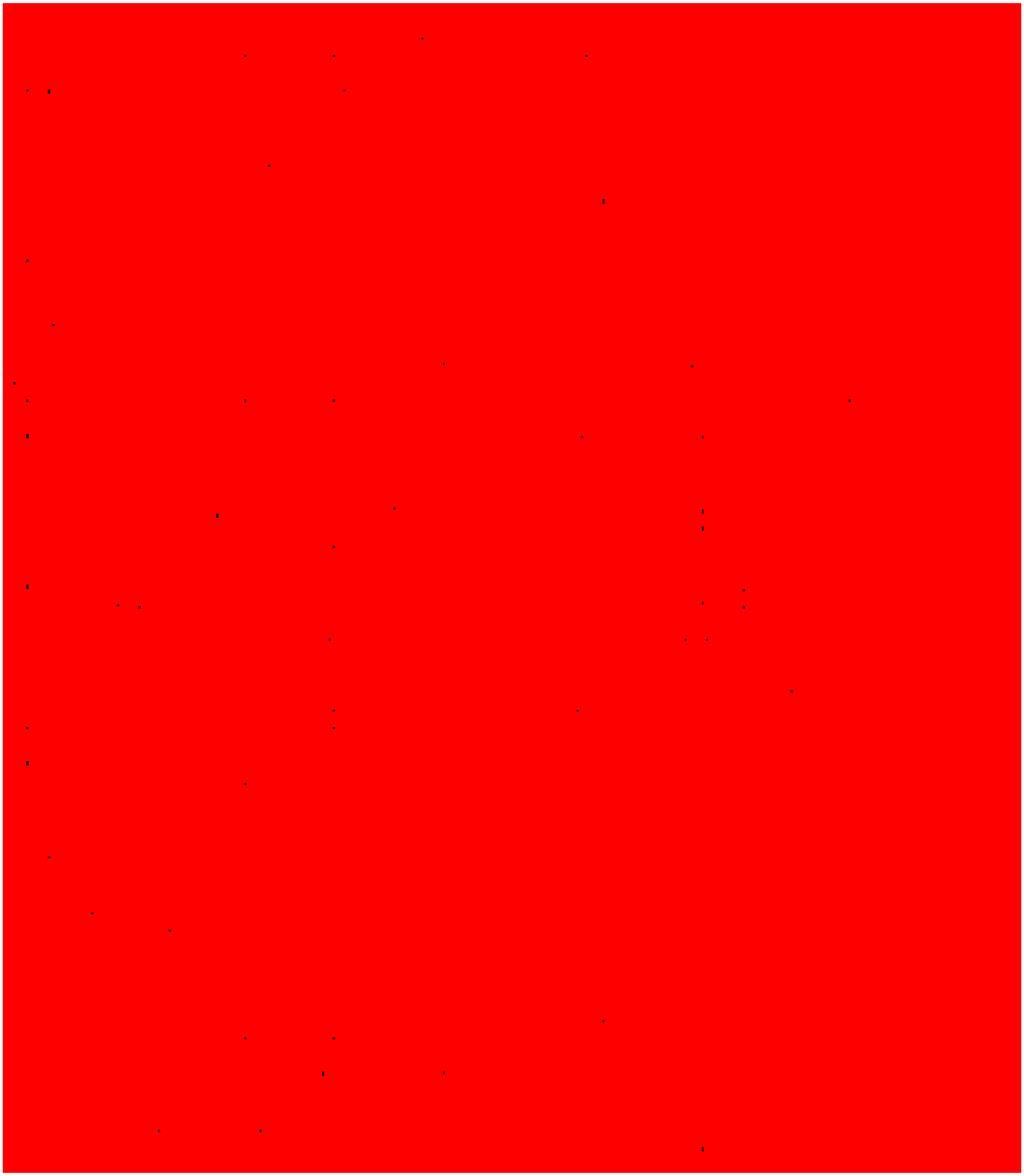

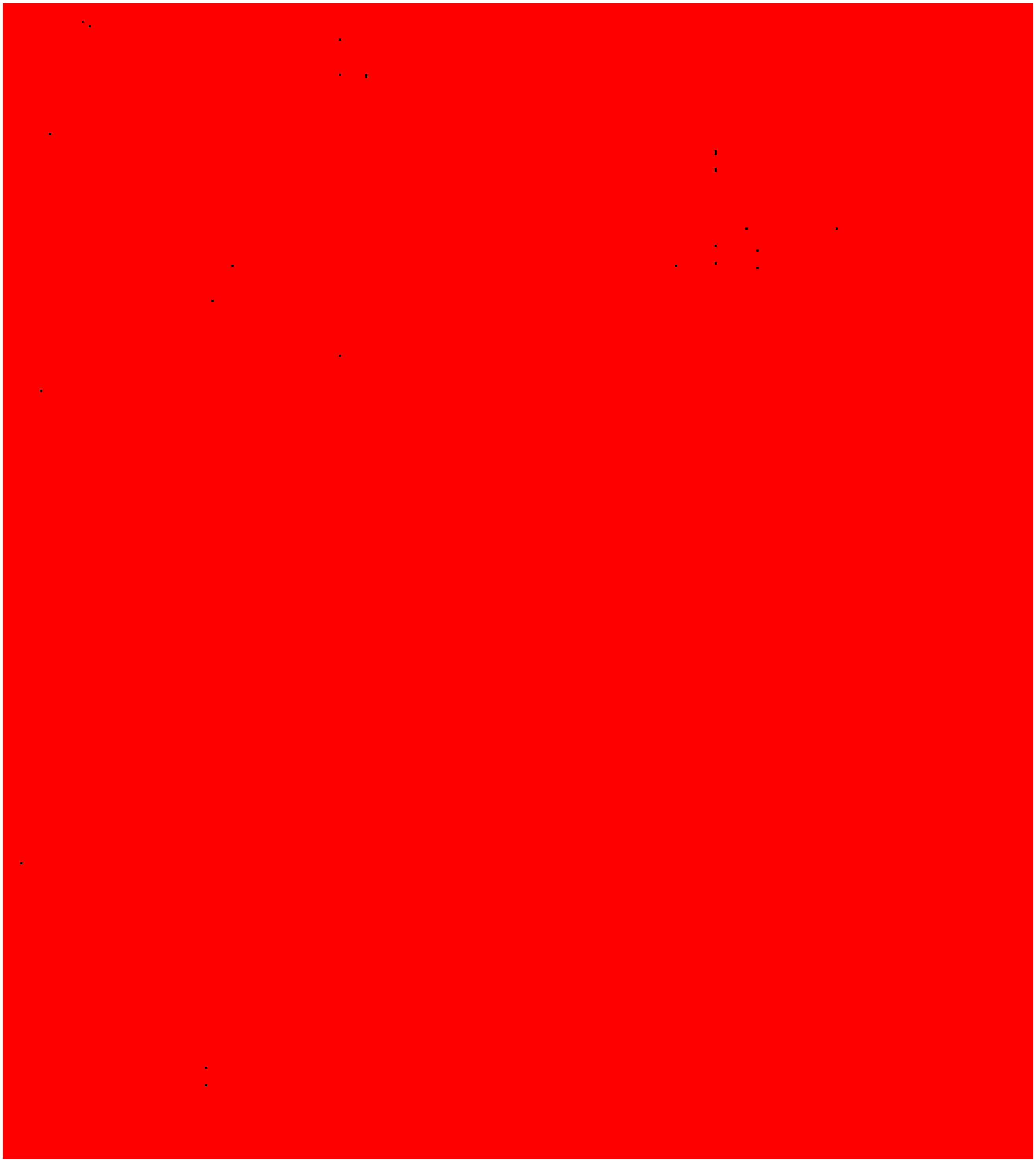

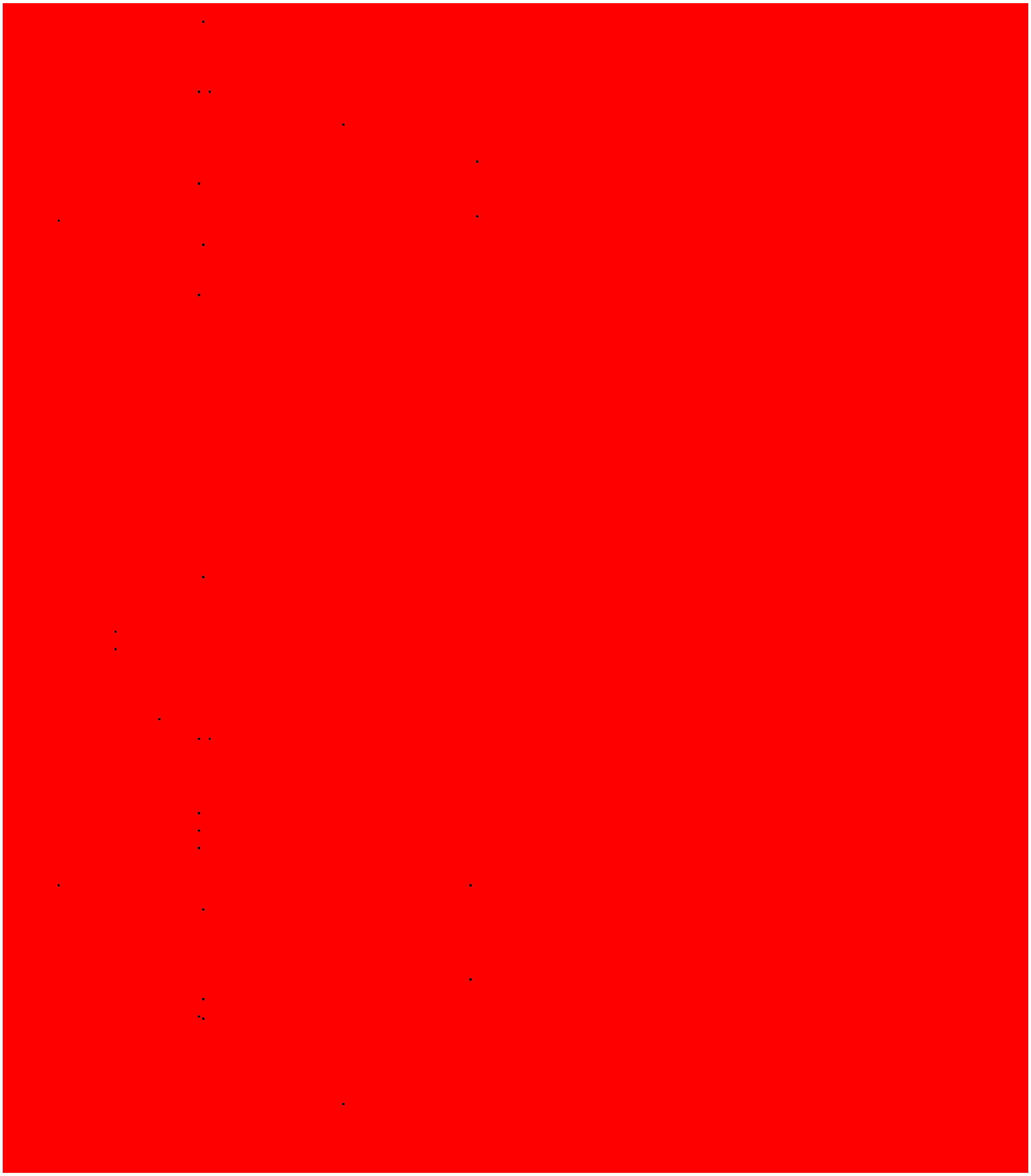

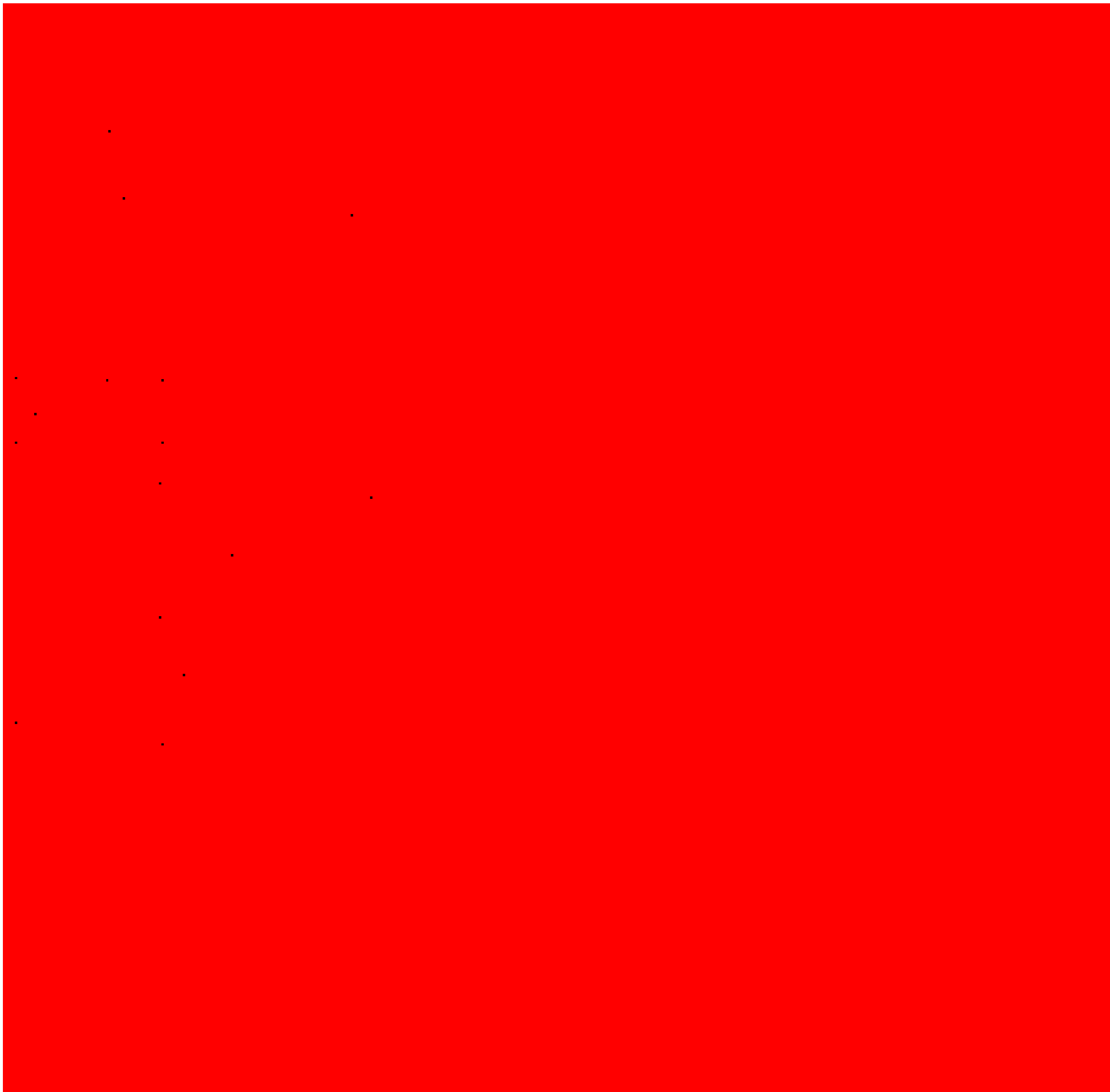

Appendix D. CFE Dams and Gauging Stations Location

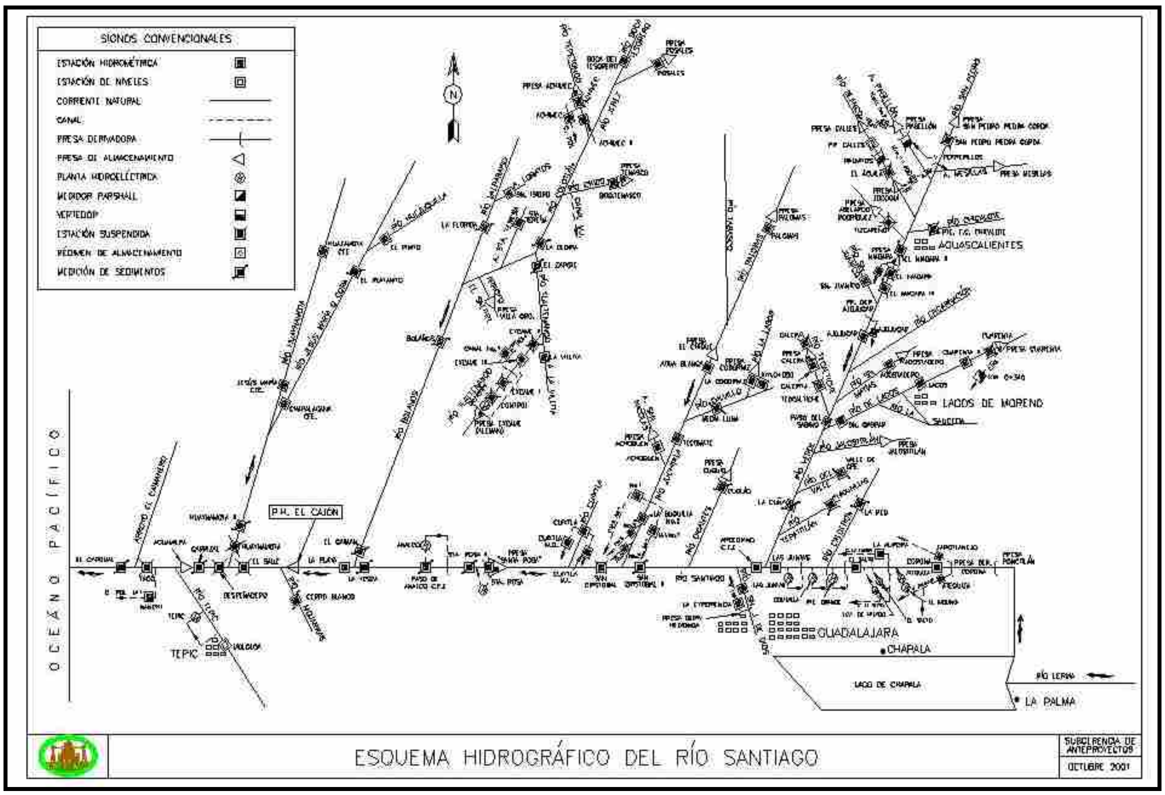

Figure D-1: Hydrographic Scheme of the Santiago River