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Articles

Supervision and assessment of Zirahuén Lake areas through a computational system implementation

Supervisión y evaluación de zonas lacustres en el lago de Zirahuén mediante la implementación de un sistema computacional

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Abstract

Mexico has numerous lakes with different characteristics and great importance for both biological and social aspects. This work shows the development of a computational system for water quality analysis in lake bodies by measuring relevant physicochemical parameters such as temperature, turbidity, and dissolved oxygen levels. Through the design and construction of a submersible measurement system, the water quality analysis process is automated. The development of specialized software for data management and measurement allows to speed up the process of water quality evaluations. Likewise, mathematical models are defined for the estimation of water quality parameters at different depths. The experimental measurements were carried out in Zirahuén Lake, located in Michoacán de Ocampo state, Mexico, due to the importance of the locality's ecosystem and the diversity of endemic species that reside there. As a result, a tool is obtained to facilitate decision-making to conserve water bodies, generating more advanced assessments.

Keywords: computational system, limnology, water quality, Zirahuén, automation, lake.

Resumen

México cuenta con una gran variedad de lagos de diferentes características y de gran importancia tanto para aspectos biológicos como sociales. El presente trabajo muestra el desarrollo de un sistema computacional para el análisis de la calidad del agua en cuerpos lacustres mediante la medición de parámetros fisicoquímicos de relevancia, como son temperatura, turbiedad y niveles de oxígeno disuelto. A través del diseño y construcción de un sistema de medición sumergible se automatiza el proceso de análisis de calidad del agua. El desarrollo de un *software* especializado para la gestión y medición de los datos obtenidos permite agilizar el proceso de evaluaciones de calidad del agua. Asimismo, se definen modelos matemáticos para la estimación de los parámetros de la calidad del agua a diferentes profundidades. Las mediciones experimentales realizadas se llevaron a cabo en el Lago de Zirahuén, localizado en el estado de Michoacán de Ocampo, México, debido a la importancia para el ecosistema de la localidad y a la diversidad de especies endémicas que habitan en él. Como resultado se obtiene una herramienta para facilitar la toma de decisiones con el propósito de conservar los cuerpos de agua, permitiendo realizar análisis más avanzados.

Palabras clave: sistema computacional, limnología, calidad del agua, Zirahuén, automatización, lago.

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Introduction

Limnology is a branch of ecology responsible for studying inland aquatic ecosystems by aquatic monitoring of water bodies to characterize them for their management and conservation (Banderas & González, 1996). Understanding the inland water bodies condition is important because they are basic human resources, and different economic and recreational activities are dependent on them. According to this, it is fundamental to establish indicators to conduct limnological studies towards the knowledge and evaluation of their physical and chemical processes and, for having tools that can guide the usage potential, linkage with management plans and water bodies conservation (Chacón, Rosas, Rendón, & Cruz, 2010). Through monitoring systems it is possible to carry out this orientation (Abarca, 2007); ecological monitoring is one of the most addressed topics by numerous authors in diverse geographical areas with different approaches over the last decades (Mudroch & MacKnight, 1994; Chapman, 1996; Díaz-Pardo, López-López, & Soto-Galera, 1996; López-Hernández & Guzmán-Arroyo, 1996; Shear, 1996; Bain & Stevenson, 1999; De-la-Lanza-Espino, 2000; Spellerberg, 2005; Abarca, 2007; Alippi, Camplani, Galperti, & Roveri, 2011; Carbajal-Hernández, Sánchez-Fernández, Villa-Vargas, Carrasco-Ochoa, & Martínez-Trinidad, 2013; Hongpin, Guanglin, Weifeng, Jie, & Qiuwei, 2015; Rahmat, Syahputra, & Lydia, 2016; Palani, Balasubramaniyan, & Durairaj, 2020). These works show the interest in ecological monitoring related to environmental quality in air and water. However, on lakes, efforts to establish guidelines and strategies for monitoring programs have been relatively recent (Secretaría de la Convención de Ramsar, 2013; Secretaría de la Convención de Ramsar, 2016).

Conventionally, samplings related to limnological parameters measurements are governed by different quality standards, both international (ISO) and national (NMX), used for water samples collection (ISO, 2018; Secofi, 1980), temperature (SE, 2014); dissolved oxygen levels by the electrochemical method (SE, 2010; ISO, 2012), and turbidity measurement (SE, 2001; ISO, 2016) in natural waters where the importance of collecting in situ samples in short periods prevails.

Studies related to analysis and evaluation of water bodies, indicates too high measurement times through sampling collections (Martínez-Almeida & Tavera, 2005; Ortiz & Rendón, 2010; Mendoza, Silva, Jiménez, Rodríguez, & Sol, 2015; Armendáriz & Martínez, 2016; Sigala *et al*., 2017), as a consequence, a few analysis points are obtained, affecting the parameters measured due to climate change, solar irradiation, atmospheric pressure, etc., since the samples collections are usually carried out over several days, By regulation, not making the measurements in a short period, affects the result accuracy in samples collected.

Currently, the market offers a variety of high-cost devices capable to measure different *in situ* parameters such as Van Walt's water quality meters (Van Walt, 2020), SIDMAR's 600 series multiparameter probes (SIDMAR, 2020), among others (Hanna Instruments, 2020). Nevertheless, specialists interested in water bodies conservation are forced to design new tools with diverse approaches that let them on-site sampling at low cost (Marcelli, Piermattei, Madonia, & Mainardi, 2014; Davis, 2016; Bhardwaj, Gupta, & Khatri, 2018; Wade & Ericksen, 2019). However, not all specialists know how to design their specialized tools, subsequently, most authors collect water samples through the vertical water body profile at different depths handling a Van Dorn's bottle, then, individually, they obtain the measurements for each parameter operating dedicated devices for temperature, oxygen levels, turbidity and so on. (Martínez-Almeida & Tavera, 2005; Ortiz & Rendón, 2010; Mendoza *et al*., 2015; López-Macías & Salas-Benavides, 2019). In these works, a post-processing information process is essential, since a GPS device is used to get the coordinate of the analyzed point, in other words, is necessary to find the coordinate, write it down, then make the measurements in situ through the process described above, preserve the samples, if necessary, send them to the laboratory and compute them using an electronic spreadsheet.

Most of the studies in hydrological basins are carried out manually. It is only supported using sensors and measurement equipment independently, where the sampling operator collects the samples, maneuvers the instruments, and at the same time, writes down their readings in logs usually made of paper. This methodology makes the measurement and data collection processes very slow and complex. Additionally, mobility problems within the water body must be considered, since the currents or the inland water jaggedness complicate this type of work, beholding high possibilities of suffering both, personal and high-cost equipment, accidents. Against this background, this paper presents the development and implementation of a computational system for the automated analysis of water quality in lake areas through multiparameter evaluation model programming. This will be done by the development and implementation of a virtual instrumentation software that let, graphically, visualize the geo-positioned coordinate, measure physicochemical parameters such as temperature, dissolved oxygen levels, and turbidity at different depths through a set of sensors. Subsequently, estimates the water quality, obtaining results on the behavior of the evaluated site. Finally, the measurements and results are recorded in a digital file. This will provide a digital log for the sampling operator, facilitating the samples database creation as Mexican standard PROY-NMX-AA-121/1-SCFI-2008 proposes (SE, 2009).

To address all the points of the system, the paper has been divided as follows: materials and methods in section 2, shows the study area characteristics (a); the parametric analysis characteristics (b); the submersible system characteristics (c); and the analysis software description (d). Section 3 shows the measurements of the results evaluated in the sampling site and discussions of the work regarding the art state. Finally, the conclusions show the relevant points of this work and the guideline of new objectives in the area.

Materials and methods

Study area

The study of endorheic lakes is of great importance for *Limnology* (Mendoza *et al*., 2015). In Mexico, specifically in the Michoacán state, there are three endorheic lakes: Cuitzeo, Pátzcuaro, and Zirahuén. During the last decades, the first two show deterioration signs (Chacón *et al*., 2010). Continuously, Cuitzeo Lake has been desiccated due to urban expansion and its constant pollution, coupled with the excessive use of the lake's water, and mainly to the infrastructures built that divide the lake in half; actions that have altered the lake capacity to carry out its natural cycle to recover itself, affecting the entire ecosystem of the place (Ortiz & Lassman, 2019; Maldonado-López, 2019). Patzcuaro Lake presents a deterioration because of overexploitation and pollution due to the immoderate deforestation and overpopulation of the place. On the other hand, Zirahuén Lake is of interest because it does not follow the pattern of the previous two despite being of smaller dimension and located nearby. Conversely, it is a lake of crystal-clear water which is protected by the government; however, residents, researchers of UMSNH University, and some institutional agencies request the federal authorities and legislators to maintain, clean, and rehabilitate this lake. Requests, such as the creation of legislation to avoid the use of prohibited agrochemicals, the use of detergents low in phosphates, the implementation of organic crops near population centers, and key areas are made. In addition, they request a monitoring and follow-up system implementation that let us know the quality of lake conditions, this is fundamental for its conservation since mainly, the use of the basin is the income source for the surrounding population. It is worth mentioning that the principal limitation to carrying out actions in favor of Zirahuén Lake are economic resources (Ayala, 2019), and derived from the above, it is proposed to select this Lake as a study area.

Zirahuén Lake is located at Salvador Escalante municipality, Michoacán de Ocampo, Mexico, with an area of almost 10 km^2. It has shallow regions near the shores and 40 to 45 m deep in the center of the lake (Bernal-Brooks & MaCrimmon, 2000). It is located between the coordinates 19°21'10" and 19°29'24" North Latitude and 101°29'37", 101°49'37" West Longitude, and belongs to the hydrological basin of Balsas River (Madrigal, Novelo, & Chacón, 2004) as shown in Figure 1. The Basin of Zirahuén Lake is endorheic type, covering an extension of 260 km2 of highlands, between 19 ° 22′ N to 19 ° 30′ N and 101 ° 30′ W at 101 ° 46′ W (José *et al*., 2018). Its altitude is 2075 m. above sea level (López, 1981; Madrigal *et al*., 2004).

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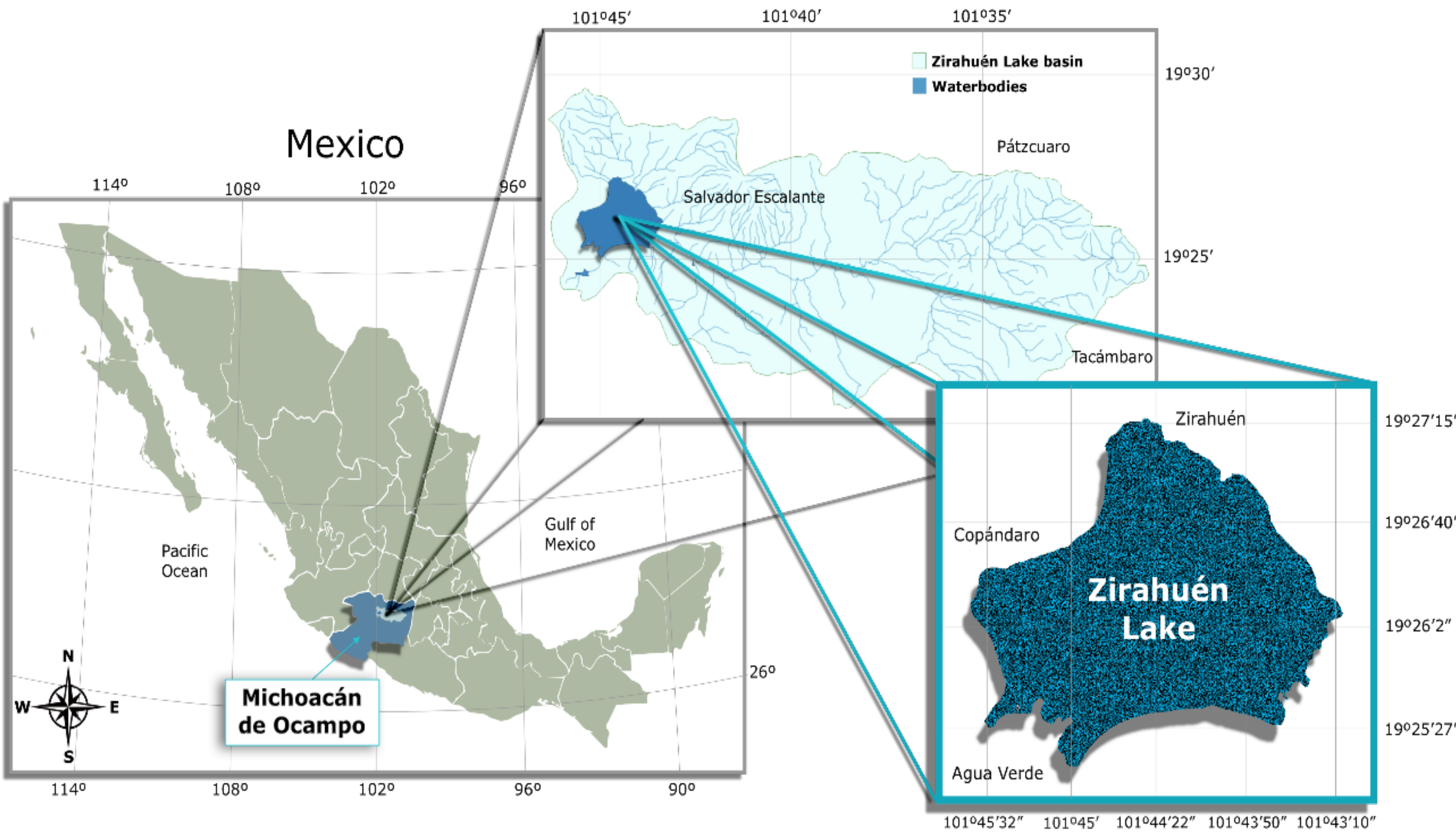

Figure 1. Zirahuén Lake Geographical location and graphic appreciation of its basin. Source: own elaboration with the help of hydrographic basins of Mexico geospatial archives, provided by Instituto Nacional de Estadística y Geografía (in Spanish) (INEGI, 2018).

Zirahuén Lake is one of the most important lakes in Michoacán; its fauna, flora, and the presence of pre-Hispanic human settlements in its basin identify it as a national heritage of ecological, economic, social, and cultural value with high possibilities for recovery and conservation; government agencies such as Instituto Nacional de Pesca (Inapesca,

2013) and Secretaría de Marina (Semar, 2018) among others (Gómez-Tagle & Gómez-Tagle, 2009; Chacón *et al*., 2010; Ortiz & Rendón, 2010; Lozano-García, Vázquez-Castro, & Israde-Alcántara, 2010; Barajas, 2017) are interested in. Currently, it encounters serious pollution and deterioration problems due to the immoderate deforestation of hundreds of hectares around the lake, proliferating avocado orchards, which accelerate the process of erosion (Chacón *et al*., 2010; Gómez-Tagle, Morales-Chávez, García-González, & Gómez-Tagle, 2019; Martínez, 2019). It is a problem that has been on the rise since the last decade, is possible that its current state of conservation still allows its recovery through concrete actions both, in the body of water and in its streams, to preserve its appearance improving its state (Maldonado-López, 2019).

Parametric analysis

The Limnology objective is to describe and analyze the structural and functional characteristics of inland waters in relation to the physical, chemical, and biological factors in the aquatic ecosystem (Margalef, 1983). The diagram of Rawson (1939), shown in Figure 2, exposes the essential factors that interact with each other to characterize a lake and thus determine its composition, distribution, density, and productivity.

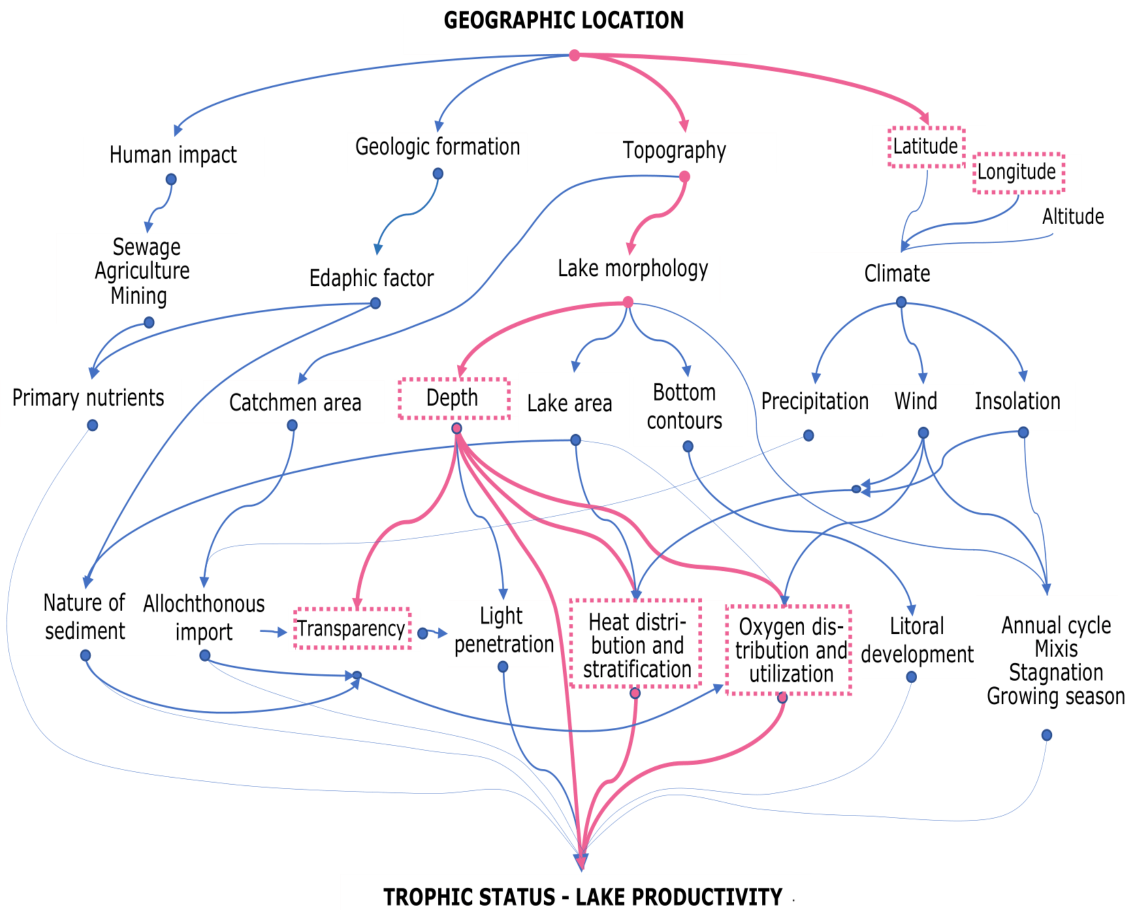

Figure 2. Rawson diagram and its relationship between essential factors that determine the trophic state of a lake. Source: own elaboration based on the original version (Rawson, 1939).

To obtain the geographical location of the lake, the present work considers the longitude and latitude, as well as the temperature, the levels of dissolved oxygen, and turbidity; factors dependent on the depth of the lake that are necessaries for its characterization. Also, through electronic sensors implementation, the measurements of physicochemical magnitudes values can be recorded. The main aim is to characterize the distribution of heat, oxygen, and transparency of the lake, by its interrelation through water quality models such as the index proposed by the National Sanitation Foundation (wQI_{NSF}) in 1970 (Brown, McClelland, Deininger, & Tozer, 1970; Brown, McClelland, Deininger, & O'Connor, 1972), letting know how contaminated the water body analyzed is.

The water quality index (wQI_{NSF}) determined by the Delphi method, is based on the weight of nine quantifiable parameters presented in Table 1. The results obtained by the index are interpreted on a scale from 0 to 100, where 0 indicates very poor water quality, while 100 indicates excellent water quality. Mitchell, Stapp and Beebe (1996) summarized a word descriptor scheme that corresponds to specific value ranges, presented in Table 2.

Table 1. Parameters used by wQI_{NSF} with the units represented by parameter and their respective associated weight.

Parameter	**Units**	wQI_{NSF} **Weight**
Dissolved Oxygen Saturation	%	0.17
Fecal coliform density	lb/100 ml	0.15
pH	-	0.12
$BOD_{5\ days}$	mg/l	0.10
Nitrates	mg/l	0.10
Phosphors	mg/l	0.10
Temperature	°C	0.10
Turbidity	NTU	0.08
Total solids	mg/l	0.08

Source: own elaboration based on the original version (Ichwana, Syahrul, & Nelly, 2016).

Table 2. Descriptive words associated with the wQI_{NSF} index with their respective range.

Word	*very bad*	*bad*	*media*	*good*	*excellent*
Numerical range	0 – 25	26 - 50	51 - 70	71 - 90	91 -100

Source: own elaboration based on the original version (Ichwana *et al*., 2016).

It is worth mentioning, that WQI_{NSF} can be adjusted even if does not have the nine proposed parameters; adding the results of the parameters with their respective weights and adjusting the index by normalizing it with the total of parameters analyzed.

Using a Venn diagram, an intersection analysis was performed, which is described graphically in Figure 3, between Rawson diagram factors, parameters used by wQI_{NSF} index and industry sensors that can be coupled to obtain physicochemical magnitudes related to both, the wQI_{NSF} and Rawson diagram factors. So, only dissolved oxygen levels, turbidity, as well as temperature, are the parameters that simultaneously, are involved in the three sets considered of utmost importance.

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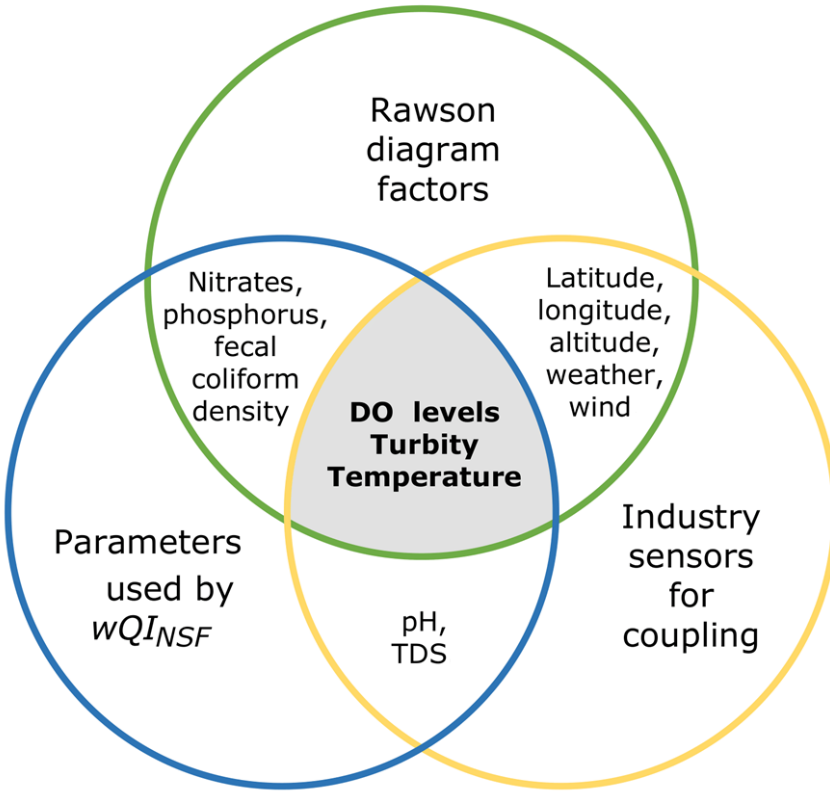

Figure 3. Graphical description of the three sets analysis intersection took into consideration: 1) Rawson diagram factors; 2) parameters used by the NSF water quality index, and 3) industry sensors that allow the measurement of the physicochemical parameters. Source: own elaboration.

The water quality assessment performed by the proposed system use three of the nine parameters set out in the index. As mentioned above, the computation of the wQI_{NSF} can be estimated by adding the results and then adjusting the number of parameters, which means, normalizing the result according to the recommendations suggested by the National Sanitation Foundation when a smaller number of parameters are analyzed than the complete proposed set (BASIN, 2005).

Analysis and evaluation system

For the Aquatic Measurement System (SAM, Sistema Acuático de Medición in Spanish) design, described in Figure 4, the intersection analysis of Venn diagram shown in Figure 3 was considered. The design consists of the Submersible Container Device (DCS, Dispositivo Contenedor Sumergible in Spanish) and the Limnological Parameter Measurement System (SMP-L, Sistema de Medición de Parámetros Limnológicos in Spanish). The DCS includes a data acquisition card (DAQ), sensors for dissolved oxygen, temperature, turbidity, and water level, as well as a Multiparameter Container Module (MCTR, Modulo Contenedor multiparamétrico in Spanish). The system is considered scalable by coupling other measurement sensors.

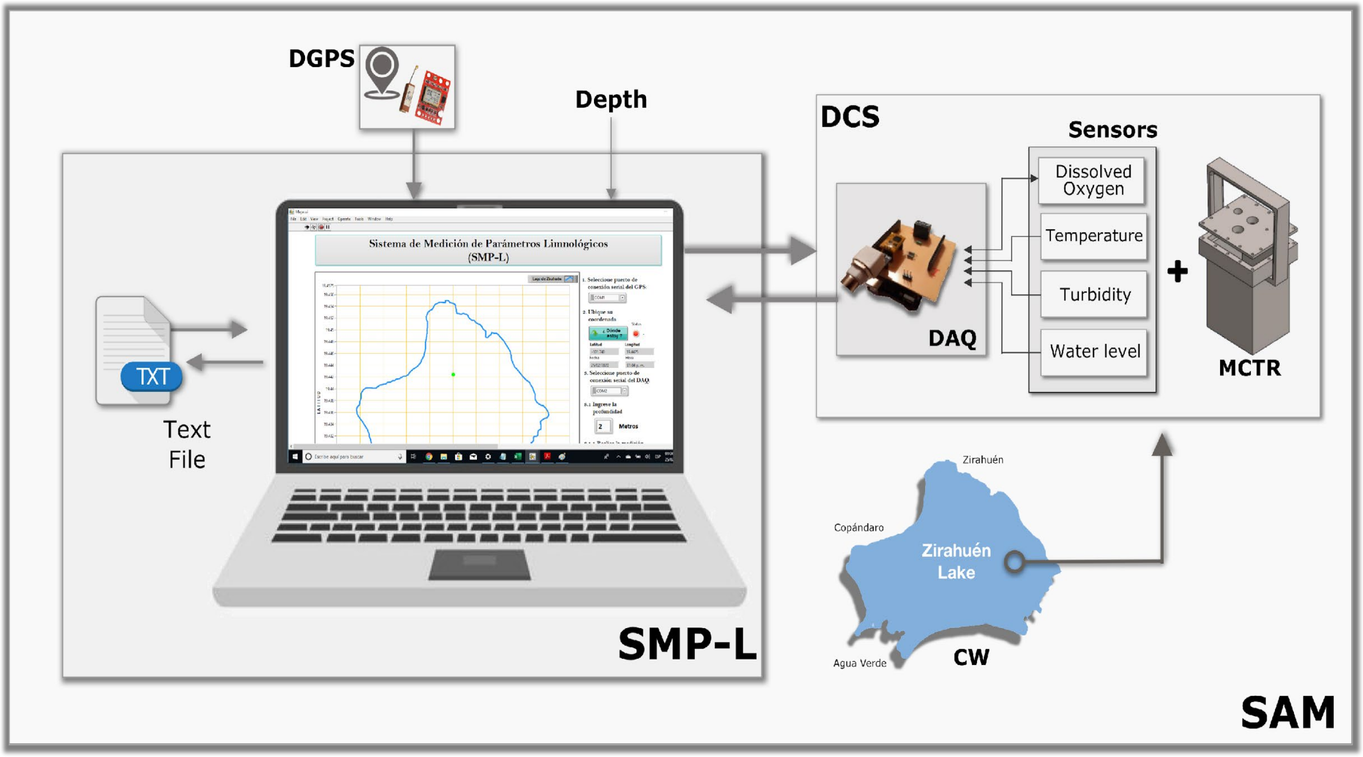

Figure 4. General diagram of interaction and operation of the Aquatic Measurement System (SAM). Source: own elaboration.

Data acquisition card and sensors

For the DAQ Card, Arduino Uno microcontroller based on ATmega328 microcontroller was used. Arduino Uno is a development card of low cost and high precision, as it contains the necessary resources to support the operation of the microcontroller (Newmark, 2020), since it has 14 digital

I/O pins, 6 analog inputs, a 16 MHz glass oscillator, a reset button with an operating voltage of 5 V through a USB connection or with an external power supply, a Flash memory of 32kB, an SDRAM of 2kB, an EEPROM of 1kB. It has an RS232 communication protocol via a USB serial port with a transmission rate from 300 to 115200 baud with the computer (Arduino, 2020). The Arduino Uno system was assembled with a printed circuit board coupling the sensors used and was designed using Proteus 8 software, as shown in Figure 5. The data transmission distance between the Arduino Uno card and the computer for the present project was by 15-meter-long USB cable.

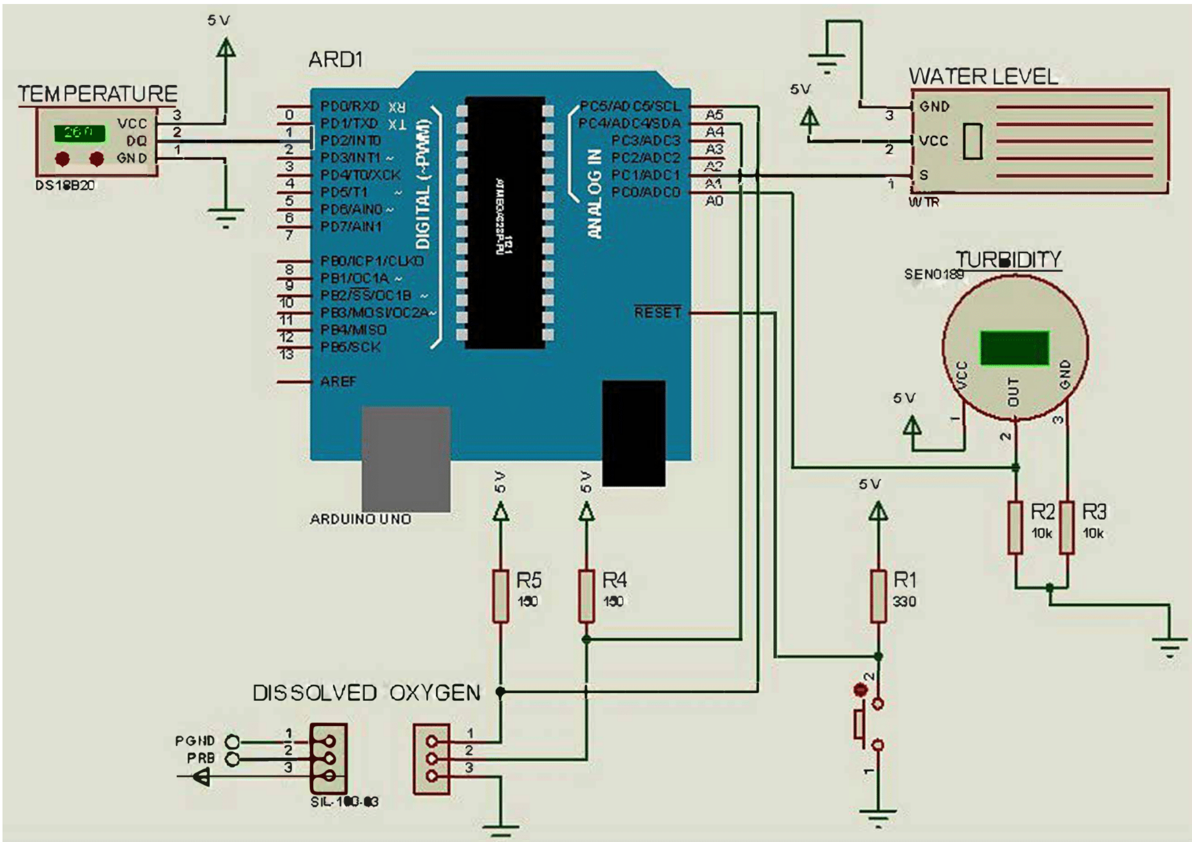

Figure 5. Data acquisition card schematic diagram implemented with Arduino Uno. The design was developed using Proteus 8 simulator. Source: Own elaboration with the help of Proteus 8 simulator.

Parameters such as temperature, dissolved oxygen levels, water turbidity, and water level can be measured with relative precision. Mainly, this depends on sensor characteristics described by the manufacturer, indicating the error margin introduced by the device (Table 3). It is necessary to mention that the water level sensor is considered to detect leaks inside the MCTR module that could threaten the integrity of the electronic system.

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Table 3. Sensors General characteristics used for temperature, dissolved oxygen levels, turbidity, and water level measurement.

Sensor	**Measurement parameter**	**Unit**	**Operating range**	**Precision**	**Supply voltage**	**Main features**
DS18B20	Temperature	*°C*	55 to 125	±0.5	3 *V* - 5.5. *V*	- Digital communication via its DQ data cable - 12 bits resolution
EZO-DO	Dissolved oxygen levels	*mg/L*	0.01 - 35.99	±0,05	3 *V* - 5.5. *V*	- Digital communication via I2C or RS232 protocol. - Requires pressure compensation. - It has a galvanic membrane, where oxygen molecules adhere obtaining a small potential difference.
SEN0189	Turbidity	*NTU*	5000 to 0	-	5 *V*	- communication (equivalence between 0 V to 4.5 V) - Detects total solids suspended in water by measuring light transmittance
HR0043	Water level	*Volts*	0 – 5	-	5 *V*	- Analog communication (0 V and 5V) - Indicates if there is any water filtration inside the electronic device

Source: own elaboration with collected information from datasheets sensors (DFROBOT, 2008; Maxim Integrated, 2019; SDR, 2019; Atlas Scientific, 2020).

Measurements are made by sensors calibration and coupling for sampling and obey the official Mexican standards NMX-AA-007-SCFI-2013 and NMX-AA-012-SCFI-2001 for temperature and dissolved oxygen levels measurement respectively, while there is no official Mexican standard for turbidity measurement on site.

Submersible container

The multiparameter analysis must be carried out at different depths in the Continental Water Mass (MAC, Masa de Agua Continental in Spanish), for this, a container with enough weight to fall by gravity was designed, guaranteeing the security of the data acquisition system. The main manufacturing material was a stainless-steel plate type 316 with 3/8" thickness, due to its high corrosion resistance to saline substances (CIMA, 2015). Through the plate manufacturing, it was possible to design the container lid according to each sensor dimensions including the cable that were exposed to the aquatic environment; i.e. the temperature sensors (ø 5 mm), dissolved oxygen (ø 15 mm), turbidity (ø 20 mm) and the USB 2.0 Hi-Speed Active Extension Repeater (A M/F) communication cable of 15 meters (ø 20 mm), while the water level sensor will be kept inside the container to detect leaks. The MCTR module was designed according to the DAQ dimensions, specifically, it can store a volume of up to 67 cm^3 approximately. Each part of the container was joined with stainless steel welding using 316-16 1/8" electrodes. Subsequently, the sensors were coupled with the container lid, to be precise, each sensor was adhered to the lid with automotive silicone Loctite SI 593 Black, without interfering with its operation. Finally, by placing a square 3/16" Chesterton 1400 R carbon-reinforced graphite package between the lid and the container, both pieces were assembled and adjusted with the 14 screws that fit perfectly between each piece as shown in Figure 6 views. The MCTR also has a sill that allows the manipulation and fastening of the module. The total weight of the MCTR is 3.4 kg.

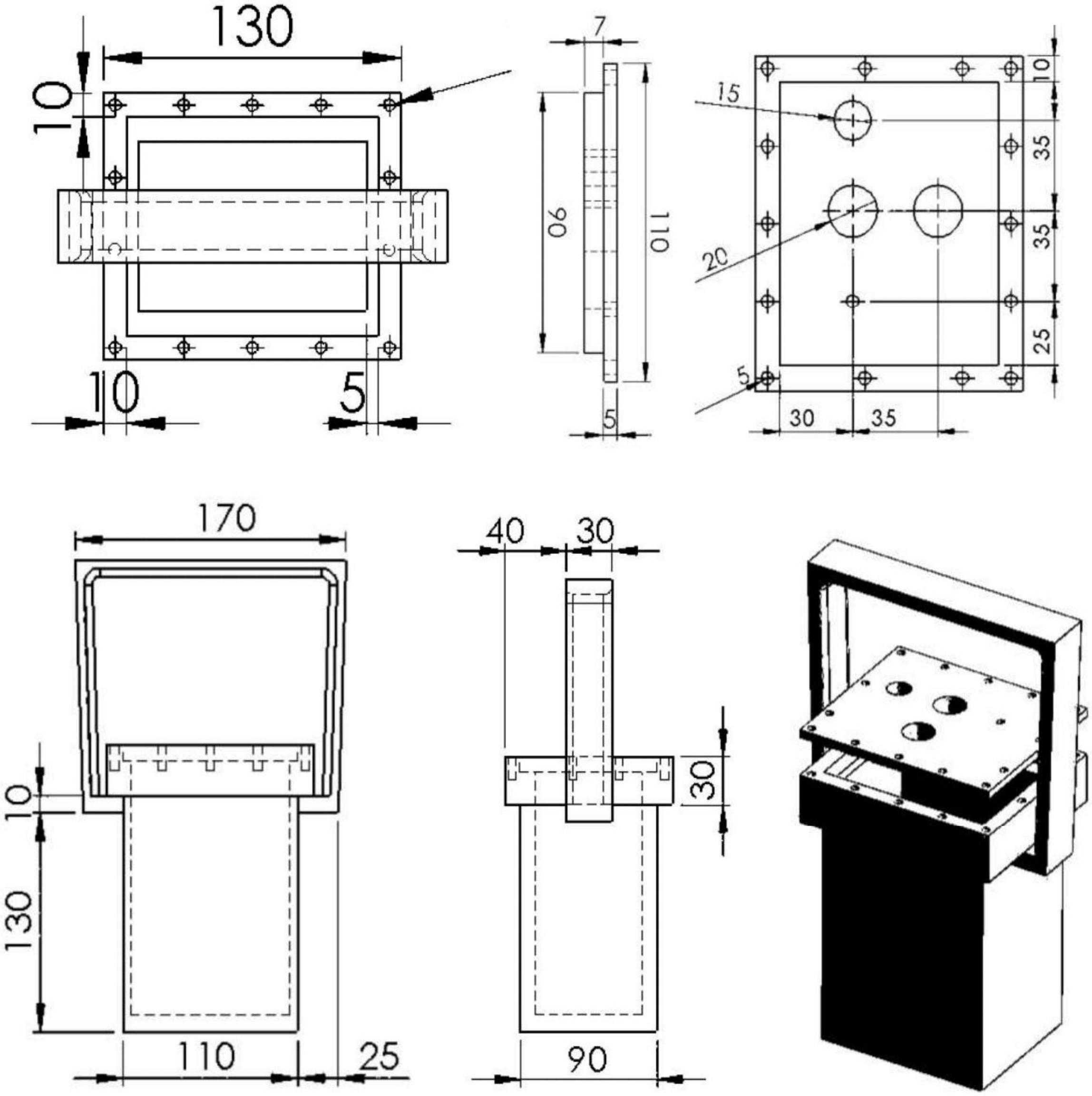

Figure 6. Front, side, upper and isometric views of MCTR with their respective dimensions. Source: own elaboration with the help of Solidworks software.

Measurement and evaluation software

The SMP-L measurement software was developed by obtaining the vector map of Zirahuén Lake using geospatial files (.shp) provided by the National Institute of Statistics and Geography (INEGI, 2018). The .shp files processing was carried out using QGIS 3.0 software, allowing .txt format conversion and subsequently including them within LabVIEW 14.0 2014 SP1 (National Instruments, 2020) as a graphical user interface module shown in Figure 7. Protocols for data transmission were implemented using the VISA component, which uses COM communication ports, the sampled parameters visualization, as well as the result of the estimated evaluation. The measurement system displays the location in the interior of the delimited study area and stores data in a file .txt as date, time, estimated evaluation, dissolved oxygen levels values, temperature, depth, turbidity, latitude, longitude, and water level if there are leaks inside the MCTR. The communication protocol used between the GPS and the computer, as well as the MCTR with the computer, was the RS232 protocol, via SERIAL USB 2.0. The GPS module used was NEO-6M since its communication with the computer is simple and altitude and longitude readings are easy to obtain. It is worth mentioning, that a Dell computer model Inspiron 14 series 5000 with a 4th generation Intel (R) Core (TM) i5-4210U CPU @ 1.70 GHz, 8.00 GB of RAM, internal solid-state drive Adata Ultimate SU650 ASU650SS-240GT-R of 240 GB of storage, and a 64-bit operating system with Windows 10 Home Single Language, version 17763.1282 was used.

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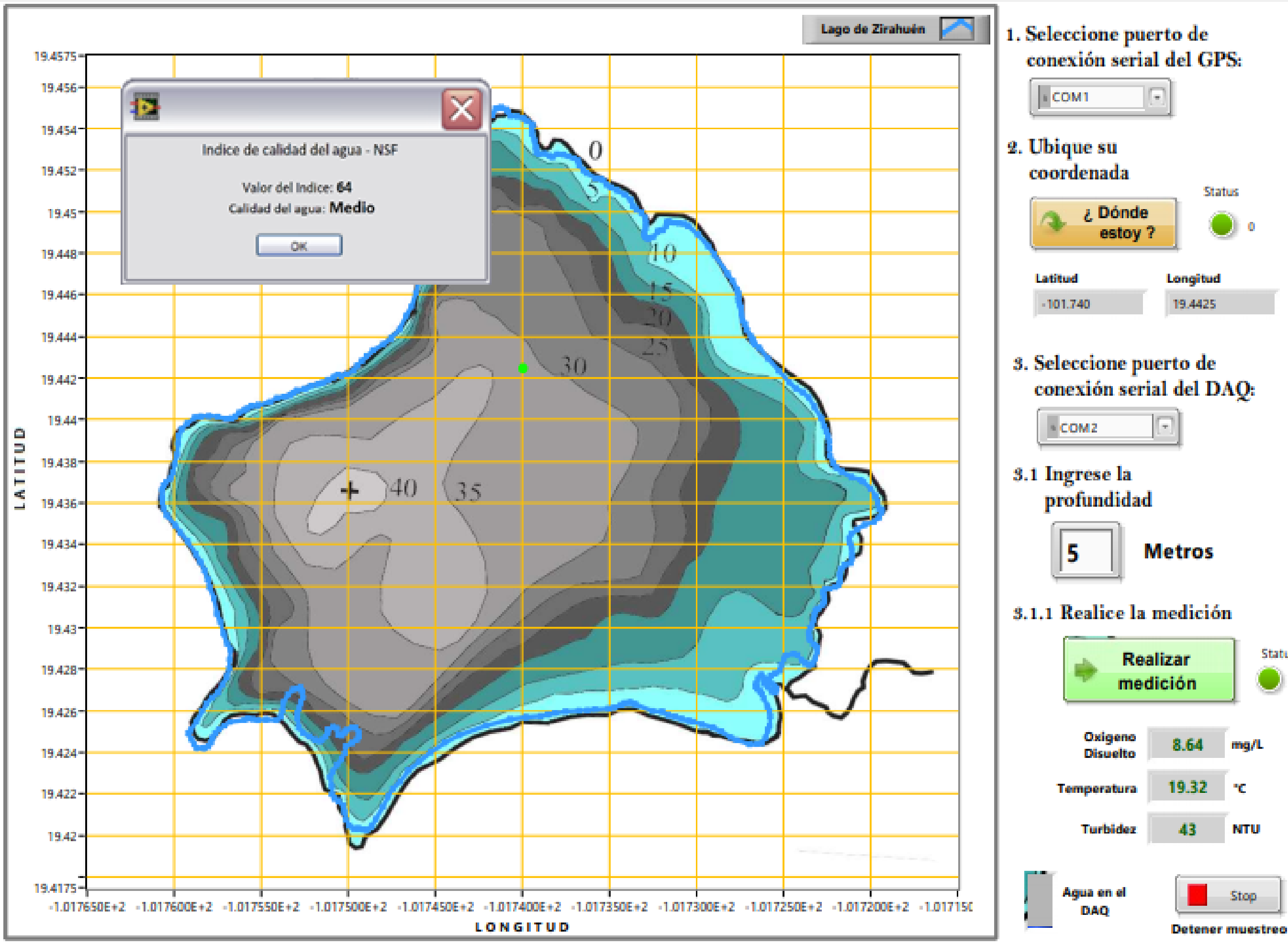

Figure 7. Graphical User Interface: the place and position of the GPS at sampling time, the interest parameters values and the estimated evaluation result of the water quality index can be seen. Source: own elaboration, screenshot of the measurement and evaluation software.

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Water quality assessment

Water quality index

The water quality index provided by the National Sanitation Foundation (wQI_{NSF}) is the most used indicator that standardizes a method to compare international water bodies water quality, demonstrating to be efficient for the evaluation and conservation of them.

The wQI_{NSF} calculations were made by applying the presented formula in Equation (1) (Brown *et al*., 1970):

$$wQI_{NSF} = \sum_{i=1}^{n} Q_i(W_i) \tag{1}$$

Where wQI_{NSF} is the water quality index which varies between 0 and 100, Q_i is the quality assessment of each parameter according to its behavior graphs (Universidad de Pamplona, s.f.) see ANNEX I. W_i is the weight assigned per parameter (refer to Table 1) when the condition $\sum_{i=1}^{n} W_i = 1$ is true; while n is the number of parameters analyzed. In case of not fulfilling the unitary condition in the sum of the weights, we proceed to normalize the result (BASIN, 2005) adding the biased weights by the sum of the unbiased weights to obtain the following (Equation (2)):

$$wQI_{NSF} = \frac{\sum_{i=1}^{n}(Q_i)(W_i)}{\sum_{i=1}^{n}(W_i)} \quad (2)$$

Directly, the proposed system obtains the temperature values, turbidity, and dissolved oxygen levels, however, it is necessary to perform a preprocessing to identify the dissolved oxygen saturation percentage in the water and the temperature variation from one measurement point to another. To obtain the dissolved oxygen saturation in water, the equations of the standard method are considered to determine the concentration of oxygen in temperature values and non-standard pressure by means of equations (3) to (9) (Forstner & Gnaiger, 1983):

$$DO_{SAT} = \frac{(100)(DO_{mg/L})}{C_p} \quad (3)$$

$$C_p = C^* P_{abs} \left(\frac{\left(\frac{1-P_{wv}}{P_{abs}}\right)(1-\theta P_{abs})}{(1-P_{wv})(1-\theta)} \right) \quad (4)$$

$$C^* = \exp[7.7117 - 1.31404 \ln(t + 45.93)] \quad (5)$$

$$P_{abs} = \frac{P_{ATM} + pgh}{101325} \quad (6)$$

$$P_{wv} = \exp\left[11.7591 - \left(\frac{3840.70}{T}\right) - \left(\frac{216961}{T^2}\right)\right] \quad (7)$$

$$\theta = 0.00975 - (1.426 \times 10^{-5} t) + (6.436 \times 10^{-8} t^2) \quad (8)$$

$$T = t + 271.150 \quad (9)$$

where $DO_{mg/L}$ is the level of dissolved oxygen measured; C_p is the equilibrium concentration of oxygen at non-standard pressure in mg/L; DO_{SAT} is the oxygen dissolved saturation in water; C^* is the standard pressure oxygen equilibrium concentration of 1 atm in mg/L; t is the measured temperature in °C; P_{abs} is the non-standard absolute pressure in atm; P_{wv} is the water vapor partial pressure; θ is the determination coefficient; P_{ATM} is the sampling site atmospheric pressure; p is the water density; g the gravitational constant value; h the sample point depth and T is the temperature in °K.

The temperature parameter evaluation requires a difference between temperatures to be used in the wQI_{NSF}, in this case, the surface temperature minus the bottom temperature is considered. However, about lakes, this consideration is ephemeral, since they could be stratified according to the seasonal stage (Boehrer & Schultze, 2008). If stratification happens, the surface temperature variation respects the bottom will be great compared to the circulation or mixing stage, which is usually constant. In our case, sticking to wQI_{NSF}, we obtain the difference between the zero meters depth and the last measurement obtained according to the maximum depth reached.

Implementation methodology

In compliance with NMX-AA-007-SCFI-2013 (SE, 2014) and PROY-NMX-AA-012/2-SCFI-2009 Mexican standards, a measurement methodology was implemented as shown in Figure 8; the process begins when the card receives the instruction to perform a measurement, then an average of 5 measurements is made for each parameter involved and the averaged values are sent to the SMP-L using the serial communication cable. Finally, the estimation of the wQI_{NSF} is calculated, and the results are shown owing to the estimated evaluation.

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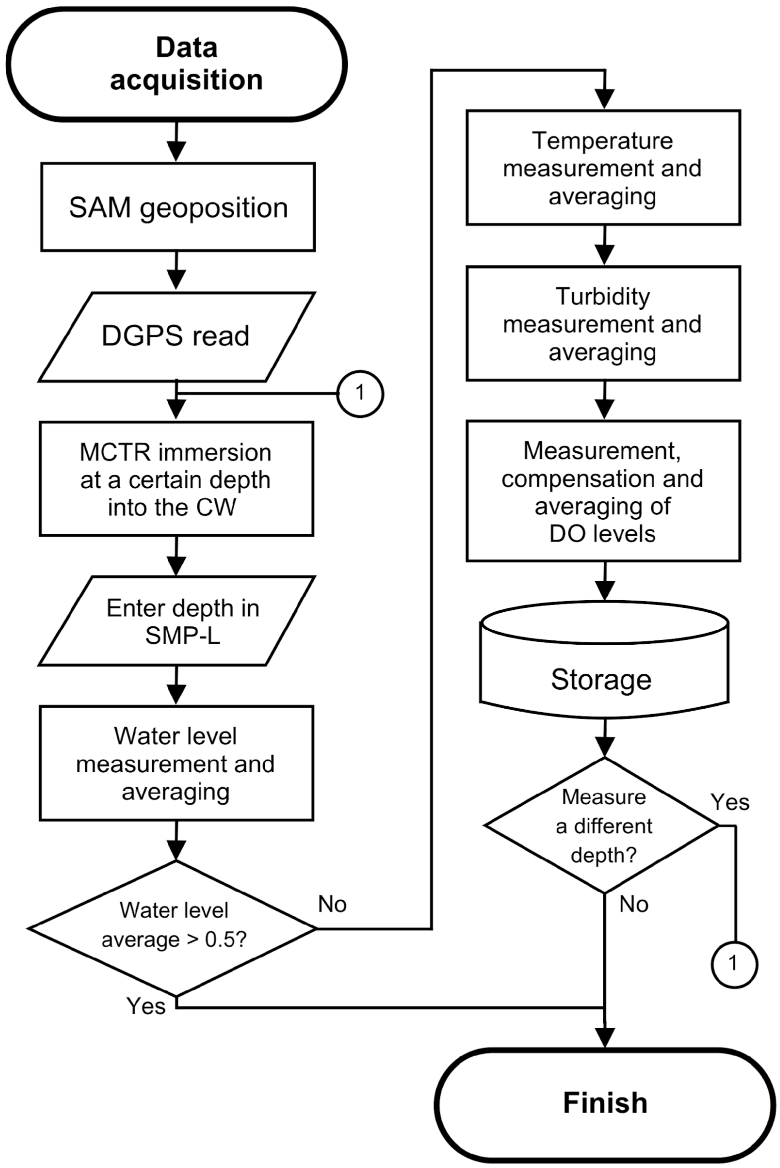

Figure 8. Data acquisition process flowchart. Source: own elaboration.

Results and discussions

Databases

In Zirahuén Lake, to obtain information about water quality analysis, a sampling of 8 geographical points was carried out considering the 8 points are the average amount used when a sampling lake of these characteristics is performed (Madrigal *et al*., 2004; Madrigal & Chacón, 2010; Mendoza *et al*., 2015). For this work, we sought to select geographical points (P0, P2, P6, P7; Figure 9) that match with previous research measurement sites (Vergara, Rendón, Chacón, Bernal, & Rosas, s.f.; Bernal-Brooks, Dávalos-Lind, & Lind, 2002; Martínez-Almeida & Tavera, 2005; Mendoza *et al*., 2015). Likewise, there was an interest of INAPESCA to study the area, since it is a non-motorized recreational water vehicle transited area, facilitating the equipment operation tests. The measurements obtained will allow identifying the dissolved oxygen levels, temperature, and turbidity at different depths, limited only by the serial cable length used for communication between devices.

Figure 9. Sampled geographical points of Zirahuén Lake with their respective labels. Source: own elaboration with the help of Google Maps.

The measurements set was performed on May 4, 2018, from 12:03 to 13:47 hours, to not mix the water of the sampling site, a rowboat was used as shown in Figure 10. The eight geographical points described in Figure 9 were measured with their respective coordinates and labels. Each point sampling was performed for about an average of 2 minutes, and through the MCTR immersion in Zirahuén Lake as the graphical simulation described in Figure 10, 4 to 8 measurements per site were achieved. The resulting database has a total of 49 measurements sampled during the time interval mentioned.

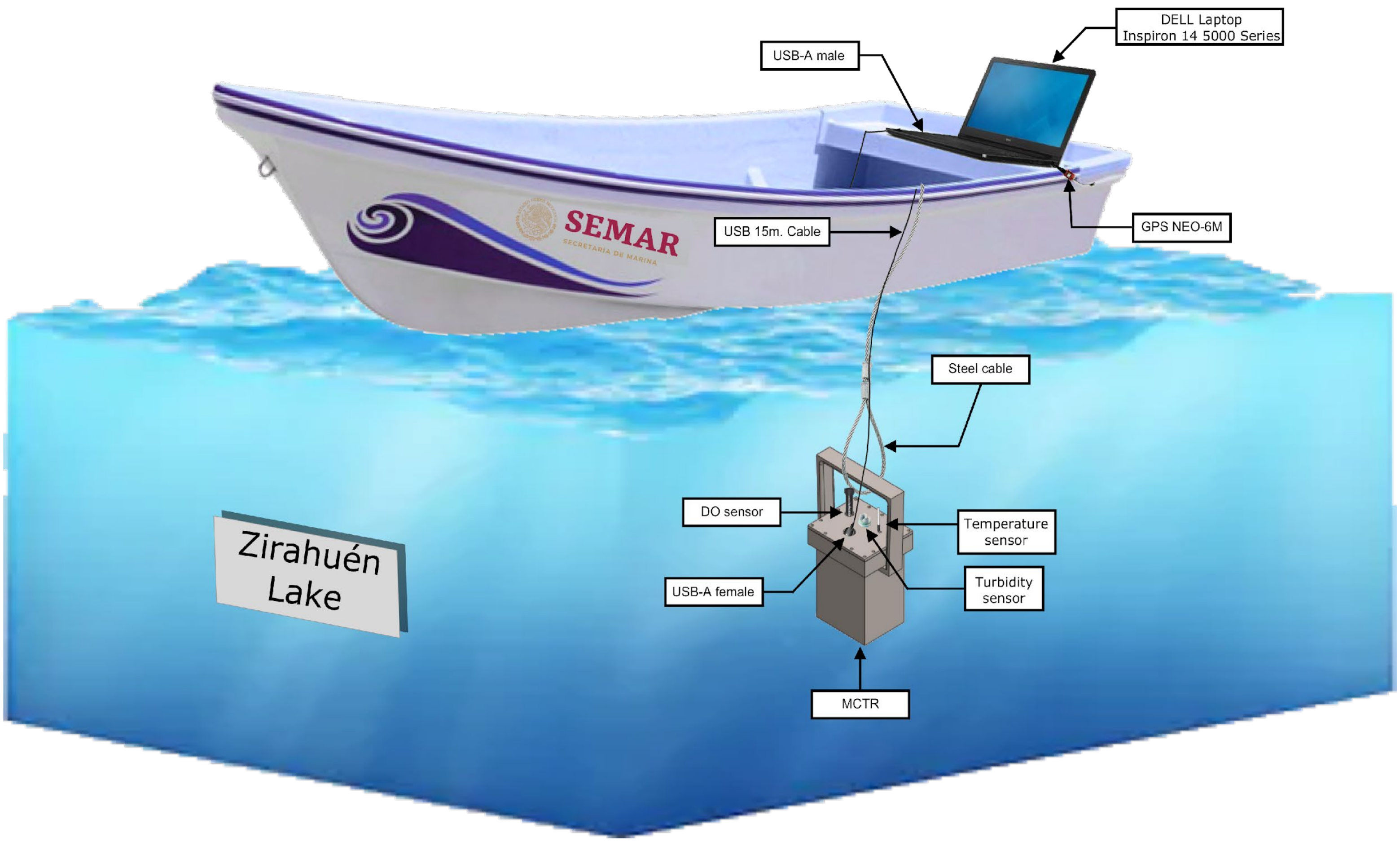

Figure 10. A demonstrative illustration regarding the acquiring samples process at the study site. Source: own elaboration with the help of sketch software.

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Environmental analysis

In Zirahuén Lake, the water quality estimated evaluation results using the methodologies and equipment developed, can be perceived in Table 4. In this one, the values obtained from different sampled points according to wQI_{NSF} are shown.

Table 4. Physicochemical parameter results obtained from the 8 geographical duly labeled sampled points at different depths of Zirahuén Lake, including measurement times, as well as absolute pressure, dissolved oxygen saturation percentage and water quality value according to wQI_{NSF}.

Geographical Point	Hour	Depth *(m)*	Dissolved oxygen *(mg/L)*	Temperature *(°C)*	Turbidity *(NTU)*	Absolute pressure *(ATM)*	DO Saturation (%)	wQI_{NSF}
P0 Latitude 19.4422758 Longitude -101.7493304	12:03 p. m.	0	11.71	21.25	34.68	1.00	131.6	77
	12:04 p. m.	4	10.99	20.56	36.15	1.39	87.4	81
	12:04 p. m.	5	10.19	20.5	36.15	1.49	75.6	76
	12:04 p. m.	6	9.70	20.5	36.15	1.58	67.5	71
	12:05 p. m.	8	9.58	20.44	36.88	1.78	59.2	63
	12:05 p. m.	10	8.95	20.06	36.88	1.92	50.7	58
P1 Latitude 19.4404291 Longitude -101.7526956	12:13 p. m.	0	10.35	20.94	39.07	1.00	115.6	79
	12:14 p. m.	2	9.98	20.87	39.07	1.20	93.0	81
	12:14 p. m.	4	9.85	20.69	39.07	1.39	78.5	76
	12:14 p. m.	5	9.45	20.56	39.07	1.49	70.1	71
	12:14 p. m.	6	9.36	20.56	39.07	1.58	65.2	66
	12:15 p. m.	8	8.87	20.37	38.34	1.78	54.8	59
	12:15 p. m.	10	8.42	19.69	38.34	1.97	46.2	57
	12:16 p. m.	13	6.24	18.56	38.34	2.26	29.2	43
P2 Latitude 19.4386634 Longitude -101.7541212	12:25 p. m.	0	9.77	21.06	37.60	1.00	109.4	81
	12:25 p. m.	5	9.60	20.62	38.34	1.49	71.3	72
	12:26 p. m.	10	8.64	19.75	38.34	1.97	47.5	54
	12:26 p. m.	13	6.60	18.69	38.34	2.26	30.9	43

Geographical Point	Hour	Depth (m)	Dissolved oxygen (mg/L)	Temperature (°C)	Turbidity (NTU)	Absolute pressure (ATM)	DO Saturation (%)	wQI_{NSF}
P3 Latitude 19.427665 Longitude -101.753215	12:49 p. m.	0	10.86	21.44	39.80	1.00	122.5	78
	12:49 p. m.	2	10.69	21.12	39.07	1.20	100.1	84
	12:50 p. m.	4	10.52	20.87	40.54	1.39	84.1	79
	12:50 p. m.	5	10.33	20.75	39.80	1.49	77.0	76
	12:50 p. m.	6	10.06	20.69	40.54	1.58	70.2	72
	12:50 p. m.	8	9.79	20.44	39.80	1.78	60.5	64
	12:51 p. m.	10	8.62	20.31	39.07	1.97	50.4	57
P4 Latitude 19.428859 Longitude -101.751466	12:59 p. m.	0	9.47	21.25	39.80	1.00	106.4	81
	12:59 p. m.	2	9.44	20.94	39.80	1.20	88.0	78
	01:00 p. m.	4	9.38	20.69	39.80	1.39	74.7	72
	01:00 p. m.	5	9.26	20.62	39.80	1.49	68.8	69
	01:00 p. m.	6	9.21	20.56	40.54	1.58	64.1	64
	01:00 p. m.	8	9.30	20.44	40.54	1.78	57.5	59
	01:01 p. m.	10	8.74	20.31	39.80	1.97	48.5	54
	01:01 p. m.	13	5.64	18.25	39.80	2.26	26.2	41
P5 Latitude 19.43173 Longitude -101.749156	01:09 p. m.	0	9.56	21.25	41.27	1.00	107.4	80
	01:10 p. m.	2	9.50	20.87	40.54	1.20	88.5	79
	01:10 p. m.	4	10.02	20.56	40.54	1.39	79.6	76
	01:10 p. m.	5	10.54	20.5	41.27	1.49	78.1	74
	01:10 p. m.	6	9.59	20.37	41.27	1.58	66.5	67
	01:10 p. m.	8	9.45	20.31	41.27	1.78	58.3	60
	01:11 p. m.	10	9.86	20.25	41.27	1.97	54.7	57
	01:11 p. m.	13	6.82	18.62	39.80	2.26	31.9	43
P6 Latitude 19.437235 Longitude -101.746635	01:25 p. m.	0	9.33	21.5	40.54	1.00	105.4	81
	01:25 p. m.	5	10.66	20.69	42.00	1.49	79.3	75
	01:25 p. m.	10	8.32	20.25	42.74	1.97	46.2	51
	01:26 p. m.	13	6.95	18.5	41.27	2.26	32.4	43
P7 Latitude 19.44543 Longitude -101.744907	01:46 p. m.	0	10.58	22	36.88	1.00	120.6	76
	01:46 p. m.	5	10.64	20.94	38.34	1.49	79.6	74
	01:46 p. m.	10	10.51	20.06	38.34	1.97	58.1	59
	01:47 p. m.	13	5.02	18.37	38.34	2.26	23.4	39

Source: own elaboration.

The results show that the water quality according to wQI_{NSF} estimation in most geographical points is good from the surface to 5 meters depth; media over 5 and up to 10 meters evaluated, and poor when reaching 13 meters. This quality evaluation estimation is directly related to the variation of dissolved oxygen saturation percentage from one point to another since the temperature and depth variation remain almost constant.

Table 5 shows the behavior of dissolved oxygen levels, DO saturation, temperature, turbidity, and water quality obtained from the average number of samples acquired at different depths and with their respective standard deviation. Indistinct to its variation, the estimation of the water quality index remains within the desired ranges without changing its evaluation. Also, an expected decrease in DO level, temperature, and water quality can be observed. Turbidity is the parameter that persists almost stable.

Table 5. Dissolved oxygen levels, temperature, turbidity, and water quality behaviors obtained from the averaging of the measurements sampled at different depths in Zirahuén Lake with their respective standard deviation.

Depth (m)	**Dissolved Oxygen (mg/l)**		**DO_{SAT} (%)**		**Temperature (°C)**		**Turbidity (NTU)**		wQI_{NSF} **(units)**	
0	10.2	± 0.772	114.87	± 8.796	21.34	± 0.303	38.70	± 2.039	79	± 1.853
2	9.9	± 0.501	92.39	± 4.826	20.95	± 0.102	39.62	± 0.608	81	± 2.118
4	10.2	± 0.555	80.87	± 4.411	20.67	± 0.114	39.22	± 1.630	77	± 3.070
5	10.1	± 0.529	74.98	± 4.011	20.65	± 0.137	39.35	± 1.715	73	± 2.477
6	9.6	± 0.293	66.71	± 2.096	20.54	± 0.104	39.51	± 1.829	68	± 2.844
8	9.4	± 0.309	58.05	± 1.932	20.40	± 0.053	39.37	± 1.577	61	± 2.053
10	9.0	± 0.721	50.28	± 3.957	20.09	± 0.231	39.35	± 1.754	56	± 2.546
13	6.2	± 0.685	29.00	± 3.255	18.50	± 0.149	39.32	± 1.091	42	± 1.479

Source: own elaboration.

Figure 11 highlights the trend lines in the graphs that describe Zirahuén Lake parameters behavior. Using a curve adjustment algorithm, the equations that describe the behavior of each parameter were obtained, allowing to have an estimated calculation according to the desired depth. For dissolved oxygen saturation:

$$f_{DO} = e^{\frac{47439 - 1000\,p}{9888}} \tag{10}$$

where p is the depth. In the same way for temperature:

$$f_{temp} = e^{\frac{5(5551-20\,p)}{9009}} \tag{11}$$

In the case of turbidity, the equation of the curve is expressed as follows:

$$f_{turb} = \frac{20(50\,p-48831)}{24601} \tag{12}$$

Finally, for the estimation of water quality, the corresponding equation is described below:

$$f_{WQI} = e^{\frac{8221-100\,p}{1821}} \tag{13}$$

On the other hand, each graph has the coefficient of determination (R^2), which means that a coefficient close to 1 would fit perfectly to the measured data; in the present work there are adjustment values very close to the unit, which is indicative of a low error level (RMSE).

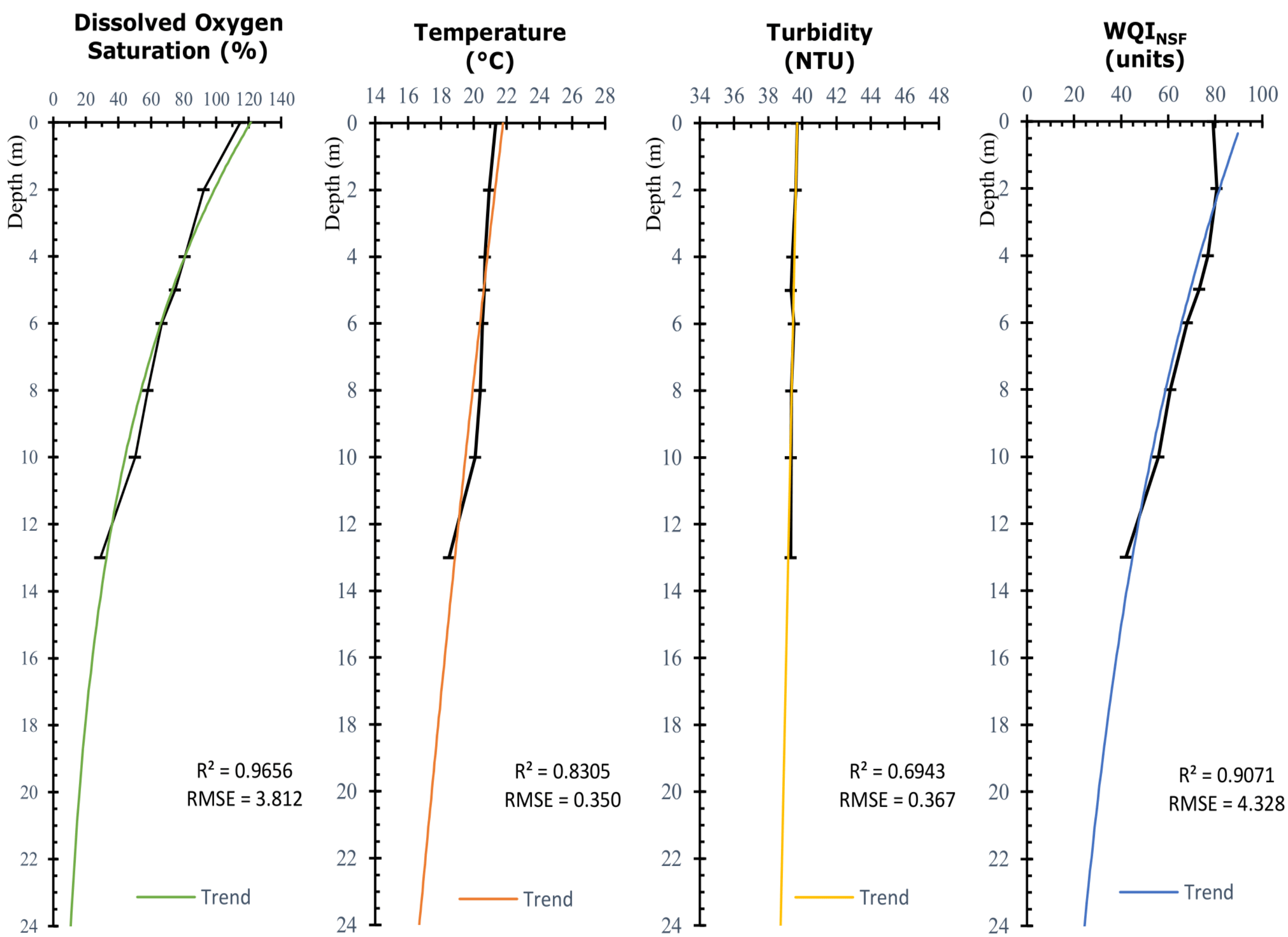

Figure 11. Temperature, dissolved oxygen saturation, turbidity, and water quality behavior at different depths. The graphs demonstrate the characteristic behavior of an oligotrophic lake. Source: own elaboration.

According to Mendoza *et al*. (2015) at a sampling point called "CNVG" conducted on 11 May 2014 at a 7-hour interval, it shows poor water quality when performing dissolved oxygen saturation measurements; mentions that the average depth from which the samples were obtained was 22 m deep, it should be mentioned that in May, agree with the nature of the lake, it is completely stratified, so taking as reference the estimation model of Equation (13) according to sampling, performed in only 2 minutes, due to the standard absolute pressure, the temperature at that point and dissolved oxygen levels, is part of the behavior of the lake the dissolved oxygen saturation result, it means 20.43 %; if evaluating the depth sampled using Equation (10), at that depth, it is 16.87% ±4.16, indicates a very poor water quality at that point, regarding Equation (13) with an index score of 21.9 units.

In Zirahuén Lake sampling work carried out in May 2014 by Mendoza *et al*. (2015), a supersaturation of dissolved oxygen present in the lake is mentioned that can be harmful to the species; However, it does not mention the depth at which this item is sampled. Within the results shown in Table 4, in the surface area of the lake, that is, before 50 cm of depth, we obtain supersaturation at all points sampled due to the high-temperature values on the surface. This is referring to almost zero non-standard absolute pressure, equivalent to the atmospheric pressure of the geographical area and dissolved oxygen levels presented on the surface. It should be mentioned that it is difficult to find endemic species less than 1 meter deep in Zirahuén Lake (Conabio, 2005; Conabio, 2012a; Conabio, 2012b; Conabio, 2013a; Conabio, 2013b), and in relation to the nature of the species to be located from 7 to 12 meters deep, the water quality for the endemic species of the lake is considered good to medium. Despite these considerations, the evaluation of water quality in the lake, in accordance with Mexican Official Standard NOM-127-SSA1-1994 (Salud, 2000), is not considered suitable for human consumption since it exceeds approximately by 33 NTUs of quality.

Scarce limnological information is available for most smaller bodies of water, but even for the best-characterized lakes, the results are often difficult to compare since the studies are carried out following different methodologies and/or only show results on some specific Physico-chemical characteristics (Sigala *et al*., 2017). However, the present work makes a comparison of Zirahuén Lake analyzed values by different authors in 3 sample points of relevance, which can be appreciated in Table 6.

Table 6. Comparative measurements of 3 similar geographical points were analyzed by different authors in different years, but at the same time of year with their respective ones.

Reference point		**P7**			**P2**				**P6**				
Date		04-may-18	11-may-14	jul-98	04-may-18	11-may-14	01-jul-05	2000-2001	04-may-18	11-may-14	Mar-09	2009	jul-98
Depth	***m***	5	-	-	5	-	5	-	13	22	40	42	28
DO_{SAT}	**%**	79.6	72.58	86.59	71.3	71.67	83.5	87.2	32.4	20.43	5.71	5.45	15.43
Temperature	***°C***	22	22	22.5	20.6	21.3	20	20.2	18.5	17.7	19.5	17	16.1
Turbidity	***NTU***	36.8	2.4	-	38.3	2.6	0.5	-	41.27	3.1	-	-	1.5
wQI_{NSF}	***u.***	74	85	92	72	84	88	89	43	48	30	29	35
Asociated word		*good*	*good*	*excellent*	*good*	*good*	*good*	*good*	*bad*	*bad*	*bad*	*bad*	*bad*
Reference		Table 4	Mendoza *et al*., 2015	Bernal-Brooks *et al*., 2002	Table 4	Mendoza *et al*., 2015	Rendón, Chacón, Vergara y Rosas, 2009	Martínez y Tavera, 2005	Table 4	Mendoza, *et al*., 2015	Vergara *et al*., s.f.	Rendón *et al*., 2009	Bernal-Brooks *et al*., 2002

Source: own elaboration.

The values obtained from these sites were used to calculate dissolved oxygen saturation so that the wQI_{NSF} evaluation could be estimated. The degradation of the lake can be seen over the years since in 1998, the studies carried out on the surface, an assessment of water quality as excellent with a value of 92 units is appreciated; a contiguous study, in 2014, changed the water quality to good with an assessment of 85 units, while the analysis carried out by the present work, evaluates point P7 as good water quality with an evaluation of 9 units below the evaluation of the year 2014; the same behavior can be reflected in point P2 going from 89 units in the year 2000 to 72 units in the year 2018; however, the water quality evaluated by the authors mentioned in Table 6, is considered good.

Point P6 shows that the deeper is, the lower the water quality assessment. All authors agreed that, as stated to the maximum depth reached in their measurements, the water quality is considered as bad where the saturation of dissolved oxygen is low. It is important to mention that the measured values regarding the water turbidity differ greatly from one study to another; however, it does not have a significant impact on the water quality indicator since it is still within the acceptable parameters.

The SAM device performs parameter measurements and water quality estimates in less than 2 minutes per point sampled, reflecting a great advantage over those methodologies that make use of devices such as Garmin GPS, GARMIN GPSMAP 62 stc, multiparameter HACH, probe YSI model55, Horiba ES-14, Horiba ES-1, oximeter YSI 51B, Hydrolab

Quanta G and VanDorn bottles (Mendoza *et al*., 2015; Bernal-Brooks & MacCrimmon, 2000; Rendón, Chacón, Vergara, & Rosas, 2009; Vergara *et al*., s.f.; Martínez-Almeida & Tavera, 2005; Sigala *et al*., 2017). In these devices, the measurements are obtained independently by parameter, recorded, and subsequently reported by data handling and analysis, once its laboratory analysis was completed as indicated by the monitoring cycle for water quality assessment (UNECE, 1996) over a long period. Some of the devices mentioned above are made up of high-cost, very precise, and well-calibrated sensors and even more capable of evaluating other parameters. However, they only perform measurements of each parameter and even, cannot estimate failure or missing measurements because the device cannot be accessed or is limited to perform it. They also cannot relate measured parameters when estimating water quality instantly.

The present work estimates the wQI_{NSF} only by relating three measured parameters, as suggested by the NSF, in a short period with the intention to provide sampling operators with analysis of each parameter, automating the sampling process. The system also allows separate analysis of dissolved oxygen, turbidity, and temperature parameters, estimation models are used to enable faster analysis than conventional studies by automating the parameters characterization behavior involved in large water bodies.

Because of conducting a field study complexity, measurements at all sampling sites are not always possible. As a result, mathematical models of parameter estimation were created considering the situation that the system was not able to access a zone, or a sensor presented some failure. In this way, it is possible to know the value of a specific parameter and even of the water quality at a certain depth without measurement by monitoring its defined characteristic equation.

This system is proposed as a technological tool to support, by maintaining the reduction of costs, sacrificing the precision of the sensors since they are commercial use sensors. However, the system allows the integration of sensors for industrial use and more sensors for pH measurement, total solids, among others, representing a greater investment since the cost of production would rise, although such integration is not ruled out as future work.

Conclusions

This work has been developed acknowledge to the motivation of creating technological tools for lake areas study in Michoacán, Mexico. The main characteristic is the ability to perform measurements in a short time, since the analysis in situ, avoids the need to carry a sample to the laboratory or even contaminate the samples by conventional methods, allowing to reduce and accelerate the limnological work in this type of studies. This project can be scalable, since new sensors such as pH and light intensity can be coupled and integrated, among others of greater interest to the limnologist, and stored in a digital logbook in the same automatic way as was done in the present work. In future work, it is expected to conduct studies at greater depth and a greater number of test sites, hoping to fully characterize this lake and, additionally, expand these studies to larger lakes such as Pátzcuaro and Cuitzeo Lakes. Zirahuén shows signs of deterioration, so it is urgent to take the necessary measures for its conservation. The lack of technological resources that provide efficient methods of analysis in the ecosystem is a constant affecting biodiversity research in the lake, so this work was developed to be a specialized tool in the evaluation and analysis of lake areas at a reduced cost in a short period.

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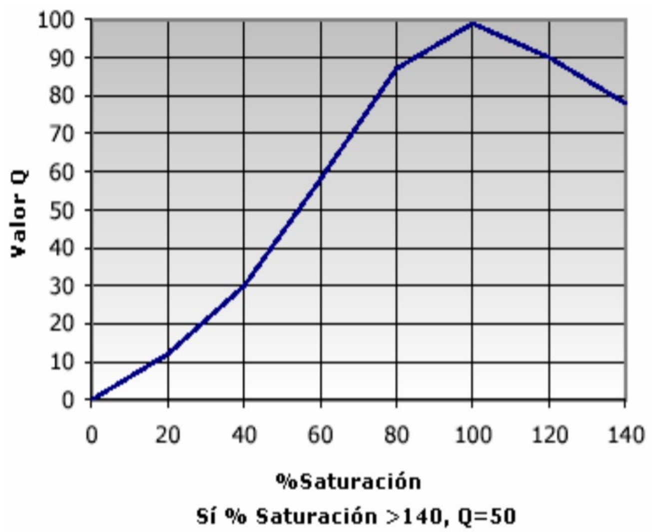
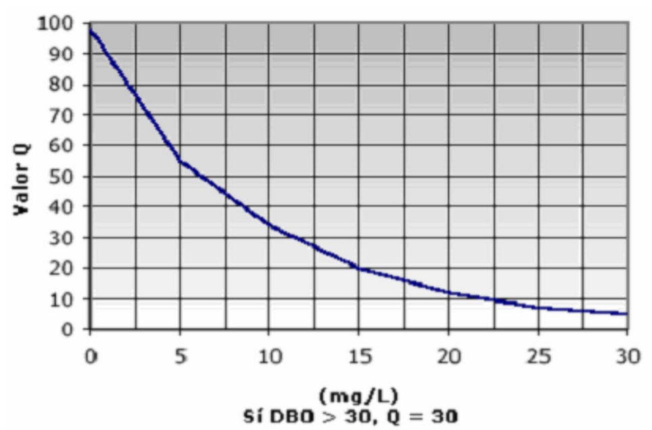
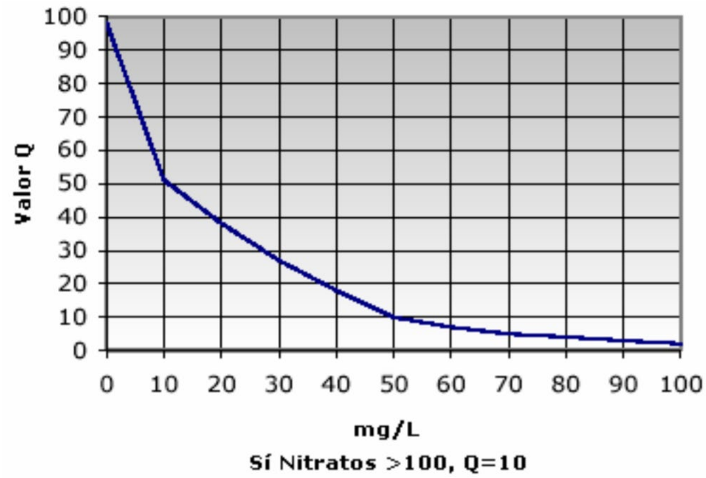
Annex I

Function curves graphs for each parameter involved in water quality the calculation by the U.S. National Sanitation Foundation (Universidad de Pamplona, s.f.).



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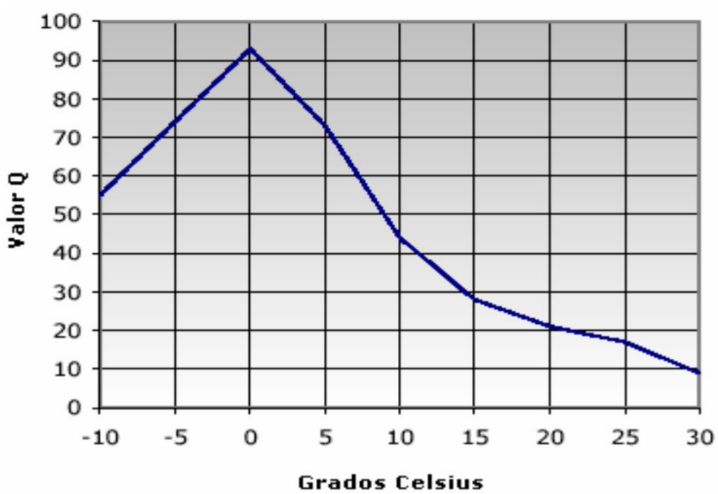
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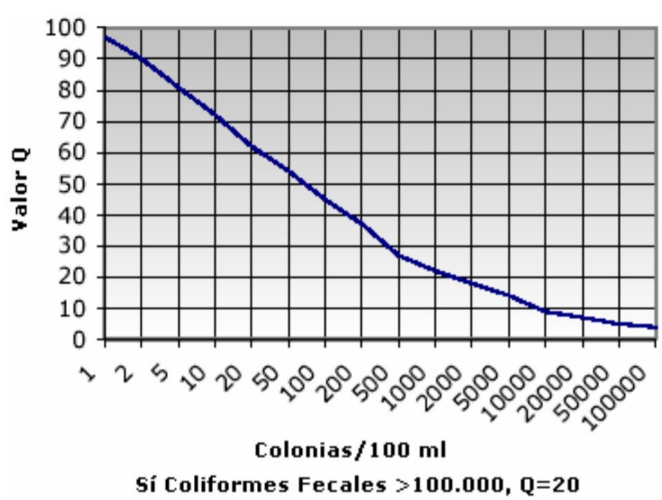
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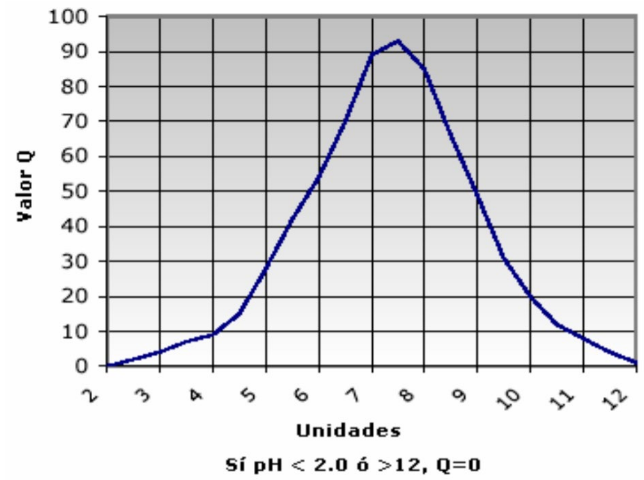
Colonias/100 ml
Sí Coliformes Fecales >100.000, Q=20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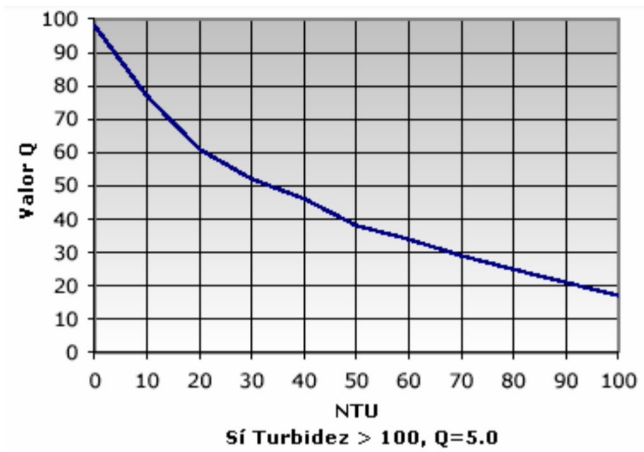
Unidades
Sí pH < 2.0 ó >12, Q=0


Valor Q
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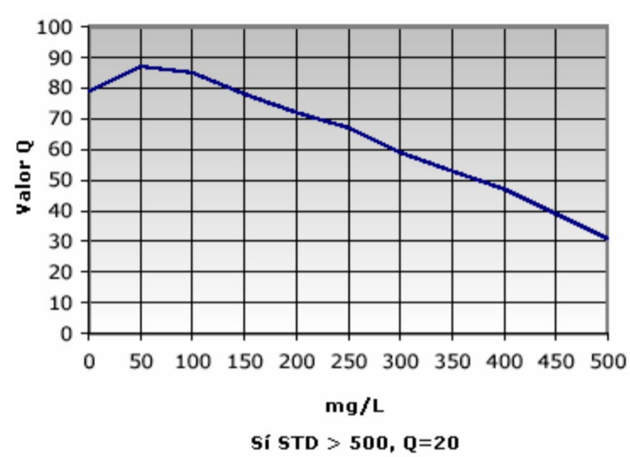
Sí Turbidez > 100, Q=5.0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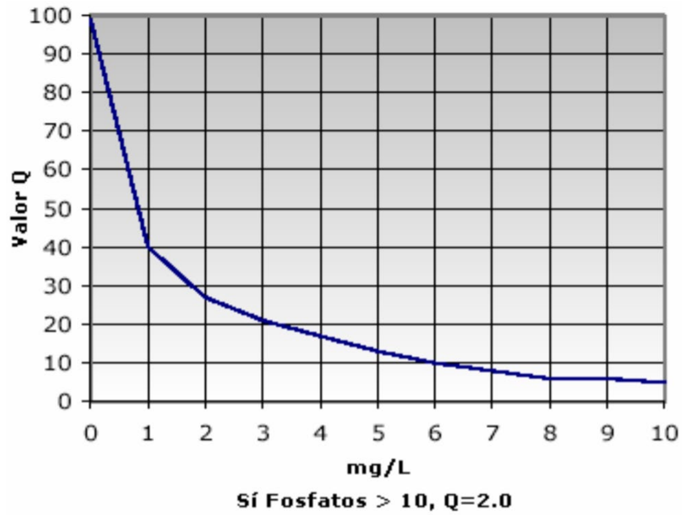
500
mg/L
Sí STD > 500, Q=20



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