Dispersion Curves of Water Quality Parameters in the Fuerte River and Huites Dam, Mexico: Assessment of Aquatic Fauna Survival

Dra. **Maritza ARGANIS[1,*]**, M.Eng. **Margarita PRECIADO[2,*]**, M.Eng. **Cecilia GONZALEZ[2]**, M.I.D. **Helena RIVAS-LÓPEZ[2]**

[1] National Autonomous University of Mexico UNAM, Institute of Engineering, Av. Universidad 3000. Ciudad Universitaria, Coyoacán, CDMX, C.P. 0451

[2] Mexican Institute of Water Technology IMTA, Paseo Cuauhnáhuac 8232 Progreso, Morelos, C.P. 62550

* MArganisJ@iingen.unam.mx; preciado@tlaloc.imta.mx

Abstract: *The water quality parameters profile of a river and a reservoir in the Fuerte River, Sinaloa, Mexico, was analyzed to identify the survival conditions of the Tilapia fish species inhabiting this area. Dissolved Oxygen (DO) was identified as the most critical parameter affecting their survival. Field data reported in publicly accessible databases was used; genetic programming was applied to approximate the model of the average DO concentration profile against the length, resulting in a logarithmic model used for forecasting in a section near the last sampling point. The model also indicated dissolved oxygen conditions below 5 mg/l, implying a survival risk for Tilapia. A heat map (risk) of DO concentration behavior over time and across different sampling sections was obtained, which helped identify dates with higher survival risks for Tilapia. The application of differential equations to hydraulics and environmental engineering topics was evidenced in this practical case.*

Keywords: *Diffusion equation, Concentration, Dissolved Oxygen, Río Fuerte, Huites Dam, Tilapia*

1. Introduction

Surface freshwater found on Earth (rivers, lagoons, lakes, human-made reservoirs) supports the development and life of diverse aquatic species (flora and fauna). Anthropogenic activities cause changes in water quality parameters since often, discharges into receiving bodies are made without prior treatment as established by a country's current regulations. Sampling of water parameters helps infer the survival scenarios of organisms [1]. In Mexico, many rivers suffer from a lack of thorough monitoring of water quality parameter concentrations [2]; although efforts have been made to carry out these identifications [3], it is important to have models that not only diagnose but also forecast the behavior of these quality parameters along the river's course, to better document their self-purification capacities.

Mexico's great diversity of environments and species is largely due to its territory being included between two biogeographic regions, the Nearctic and the Neotropical. It is estimated that 57% (289) of the 507 freshwater species living in Mexico are endemic, highlighting the importance of species exclusivity by basin. The basins and regions with the highest percentages of endemic species are: Lerma-Santiago River 66%, Usumacinta-Grijalva 36%, Pánuco 40%, Balsas 35%, Ameca 32%, Papaloapan 21%, Coatzacoalcos 13%, Conchos 21%, Tunal 62%, Cuatro Ciénegas pools 50%, Chichancanab lagoon 85%, and the Media Luna lagoon 65% [4].

Genetic programming [5-8] was applied to approximate the model of the average DO concentration profile against the length. Minimum, maximum, and optimal survival conditions for the Tilapia fish species (Oreochromis niloticus), characteristic of the studied area, were added to the previous data to draw conclusions regarding its survival based on the considered parameters. Additionally, the diffusion equation was numerically solved to determine the temporal and spatial behavior of DO concentration in various sections of the river and the analyzed reservoir. This allowed for the identification of sections and time periods posing risks to the survival of aquatic fauna. The study area for this paper is located in the El Fuerte River basin.

CONAGUA, through the National Water Quality Measurement Network (RENAMECA) [3], conducts systematic and permanent water quality monitoring of the main water bodies in the country. Water quality measurement includes the analysis of physicochemical and microbiological parameters, established according to the type of water body being characterized. The water quality monitoring stations from RENAMECA were selected, as shown in Figure 1.

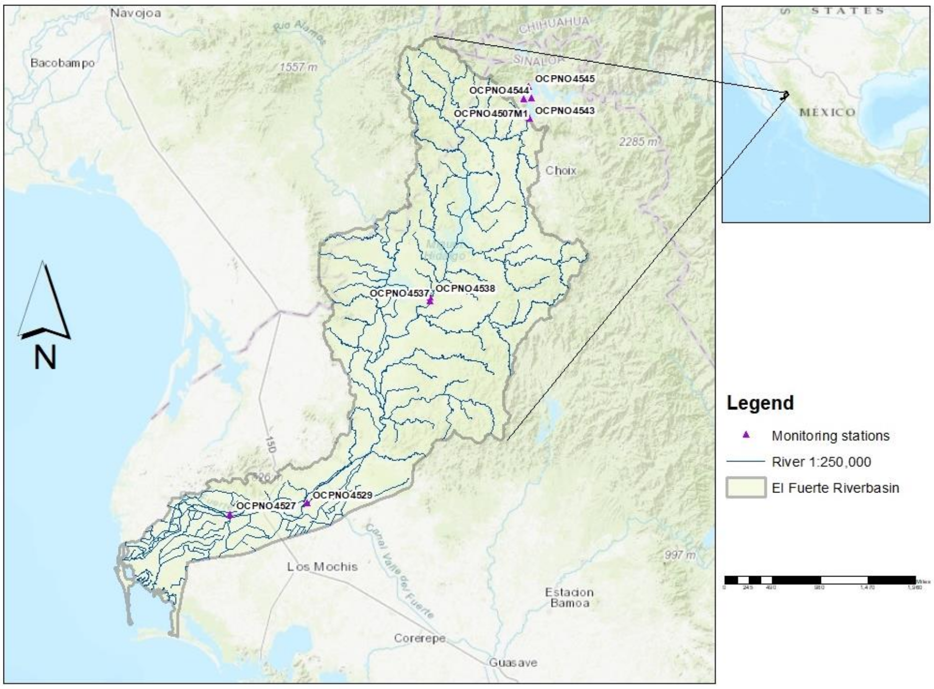

Fig. 1. Monitoring stations. Fuerte River, Sin., Mexico

2. Methodology

2.1 Genetic Programming (GP)

Genetic Programming (GP) [5] is revolutionary in many fields, owing to its ability to evolve programs that solve complex problems. It mirrors natural evolution by using concepts like mutation, crossover, and selection to find solutions that traditional methods may miss. GP can address a wide range of problems in engineering, bioinformatics, economics, and more. It automates solution creation, saving time and reducing the need for extensive human intervention. GP often discovers novel solutions that human designers might not consider, leading to significant breakthroughs. GP is used for predictive modeling and data mining, aiding in the understanding of vast data sets. In engineering, it helps optimize design and operations, enhancing efficiency and performance. GP is crucial in the evolution of AI and machine learning models, pushing the boundaries of what's possible.

Genetic programming harnesses the power of evolution to solve some of the toughest problems out there. Furthermore, GP originated from the need to design computer programs, modifying simple genetic algorithms. Individuals in GP are operators or branches with operators that reproduce, exchange, or mutate to create new operations, resulting in mathematical models or actual code. The traditional Genetic Programming block diagram is shown in Figure 2 [5].

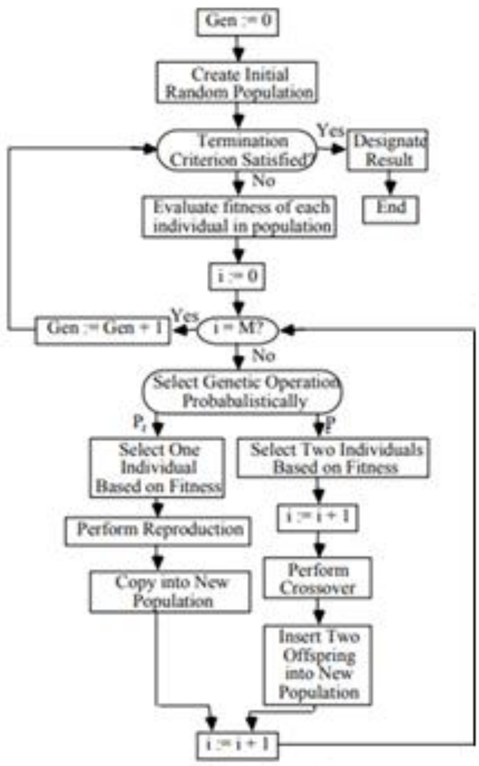

Fig. 2. Genetic programming flowchart Source:[5]

In this paper, arithmetic and transcendent operators (+, -, *, /, ln, sin, cos), constant terms and an independent variable (distance d) and a dependent variable the concentration of the analyzed parameter were considered. The parameters used by GP are shown in Table 1.

Table 1: GP parameters considered

Parameter	Value
population size	200,
generations	1000,
tournament size	20,
stopping criteria	0.01,
const_range	(-1.0,1.0),
p_crossover	0.7,
p_subtree_mutation	0.1,
p_hoist_mutation	0.05,
p_point_mutation	0.1,
max_samples	0.9,
verbose	1,
parsimony_coefficient	0.01,
random_state	42,

The objective function considered to obtain the mathematical model to approximate the mean concentration of a water quality parameter as a function of distance x was the minimization of the mean square error. A Python code program generated with the support of an AI [9] and executed in Anaconda's Jupyter notebook [10] was used.

2.2 Data set

Dissolved Oxygen (DO), Water Temperature (Tw) and Hydrogen Potential (PH) data recorded on various dates between 2012 and 2022 were considered (Figure 3 shows the distance of each section from section 0).

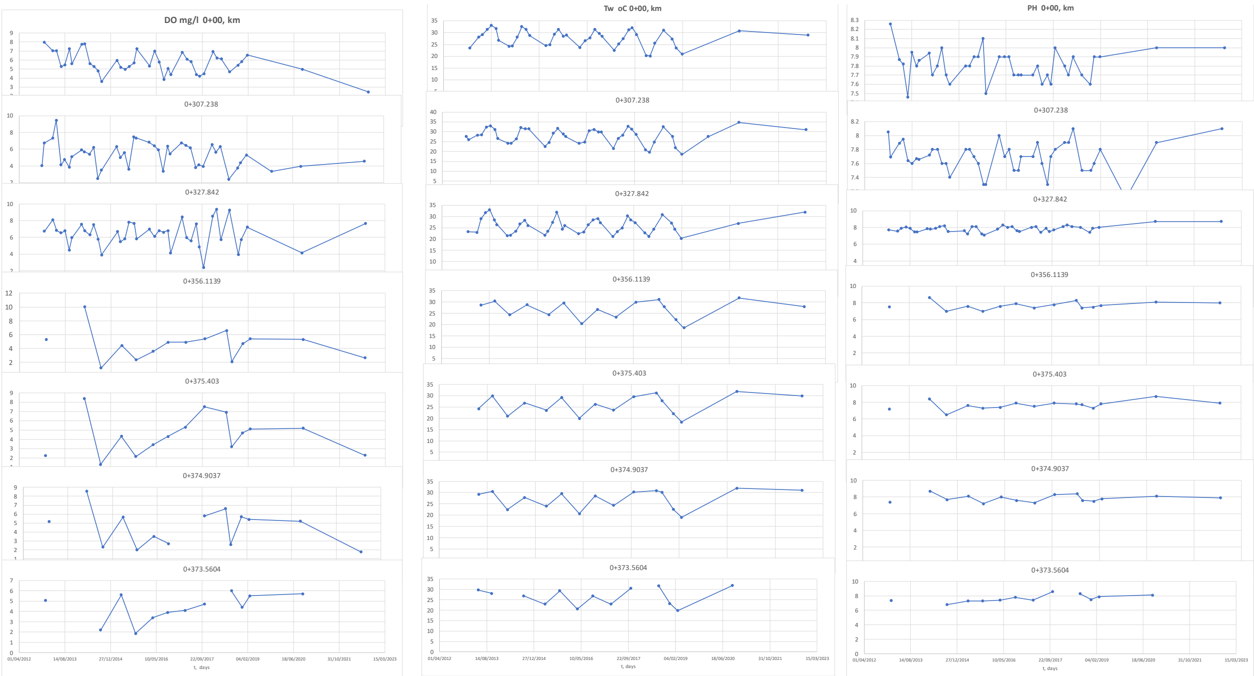

Fig. 3. DO, Ta, PH Measured data in different sections of the Fuerte River and Huites Dam, Sin.,Mexico

2.2 Average Concentration Profile

Statistical measures including the mean, standard deviation, and skewness coefficient were obtained for each parameter and section analyzed. The mean value was used to construct the concentration profile along the river and the reservoir. Additionally, survival conditions for typical fish species found in Mexico were included [11, 12], along with the minimum values and optimal survival ranges for Tilapia inhabiting the surface waters of the study area.

2.3 Diffusion Equation for Heat Map (Risk)

The diffusion equation of the concentration (C) in mg/l of a substance, considering the independent variables time (t) in s, and distance (x) in cm, with diffusion coefficient D in cm^2/s, can be expressed as follows [13]:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{1}$$

Selecting derivation schemes of Newtonian advance polynomials of the first and second degree, pivot in xi [14]:

$$\frac{C_i^{n+1} - C_i^n}{\Delta t} = D\frac{C_{i+1}^n - 2C_i^n + C_{i-1}^n}{(\Delta x)^2} \tag{2}$$

Clearing C_i^{n+1}: yields an explicit finite difference scheme:

$$C_i^{n+1} = C_i^n + \frac{D\Delta t}{(\Delta x)^2}(C_{i+1}^n - 2C_i^n + C_{i-1}^n) \tag{3}$$

To ensure the stability of the scheme, the Courant-Friedrichs-Lewy (CFL) stability condition [15] is satisfied:

$$\frac{D\Delta t}{(\Delta x)^2} \leq 0.5 \tag{4}$$

To give an example of the case of DO:

Considering a typical value of the diffusion coefficient D for the DO:

$D=2.1\times10^{-5}cm^2/s$

The following values of the increments in time and length are proposed and the stability condition is verified: Δt=7,776,000 s (3 months)

Δx=2,493,333.333 cm (24.93 km)

$$\frac{2.1 \times 10^{-5} \times 7{,}776{,}000}{(2{,}493{,}333.333)^2} \leq 0.5$$

$2.626 \times 10^{-8} \leq 0.5$, cumple estabilidad

Substituting data:

$$C_i^{n+1} = C_i^n + 2.626 \times 10^{-8}(C_{i+1}^n - 2C_i^n + C_{i-1}^n) \tag{5}$$

Finally, the explicit finite difference scheme results:

$$C_i^{n+1} = C_i^n(1 - 5.252 \times 10^{-8}) + 2.626 \times 10^{-8}C_{i+1}^n + 2.626 \times 10^{-8}C_{i-1}^n \tag{6}$$

For the calculation, the DO data were linearly interpolated for quarterly values of time in the initial (0+00 km) and final (0+374 km) sections taken as boundary conditions; the DO data were interpolated in the different sections, to take into account initial conditions at t0=0; the scheme was applied in finite differences and a color scale was used, assigning a green color to the data with the highest DO value and a red color to the data with the lowest DO value, thus building a heat map (risk).

3. Results

3.1 Average concentration value profiles

Average profiles values of DO, Tw and Ph are shown in Figures 4 to 6.

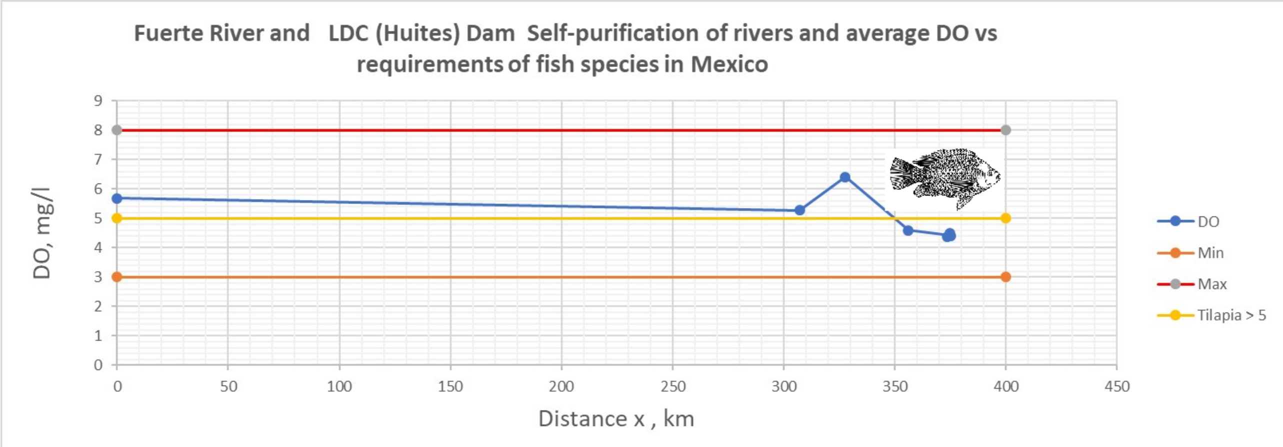

Fig. 4. Average value profile for concentration of DO and survival values of Tilapia fish

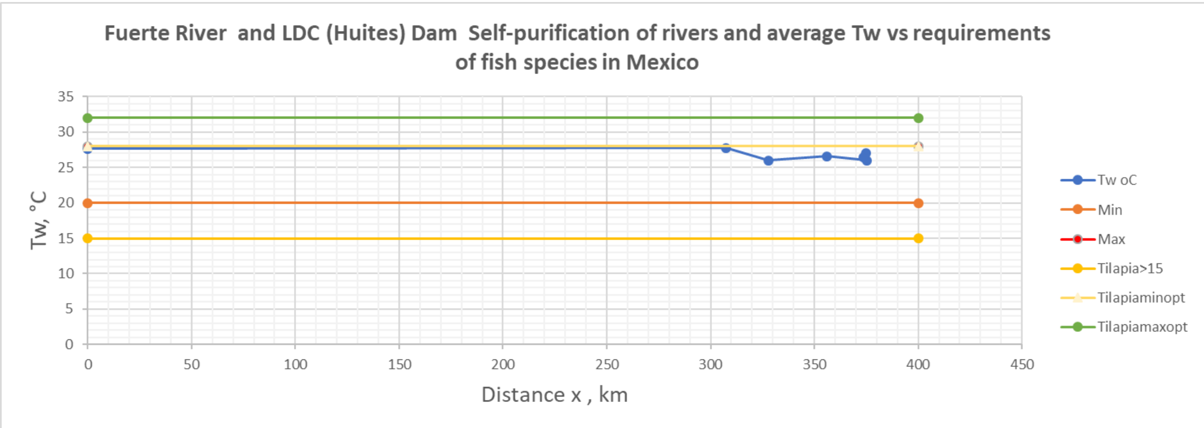

Fig. 5. Average value profile for concentration and survival values Tilapia fish

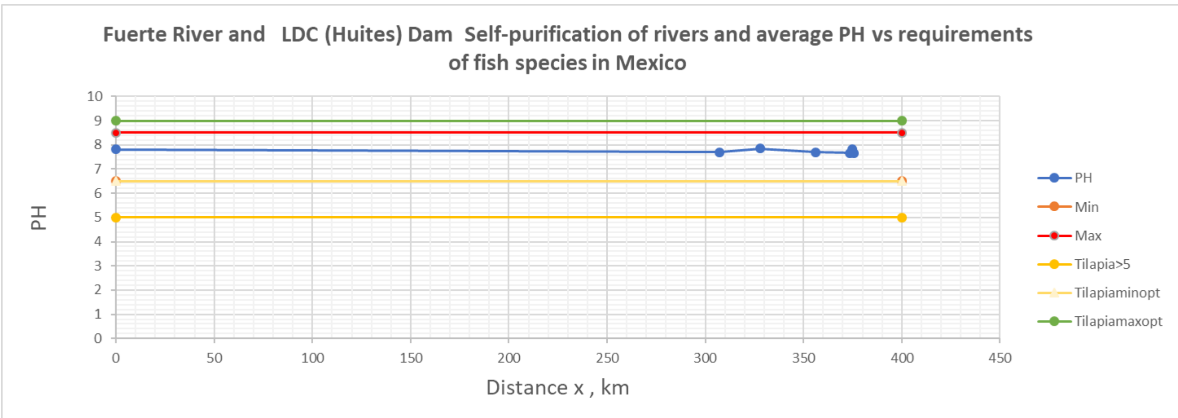

Fig. 6. Average value profile for PH concentration and survival values of Tilapia fish

From figures 3 and 4, it can be seen that the parameter with the highest risk of survival of Tilapia is the DO, since the average values in some sections fall to values below 5 mg/l, already in the sections within the reservoir.

3.2 GP Model

With GP, 75% of the measured data of the DO was used to obtain a mathematical model and validation was done with 25% of them; The mean square errors (MSE) and the coefficients of determination R^2 obtained in the measured and validated data obtained by the Python program developed by an AI reports the following results: MSE (training): 0.8616, R^2 (training): -0.4134, MSE (test): 16.6448, R^2 (test): -408.48823527524695. Figure 7 shows the comparison of the measured data vs. the calculated data of the mean concentration profile of the DO and with respect to an identity function.

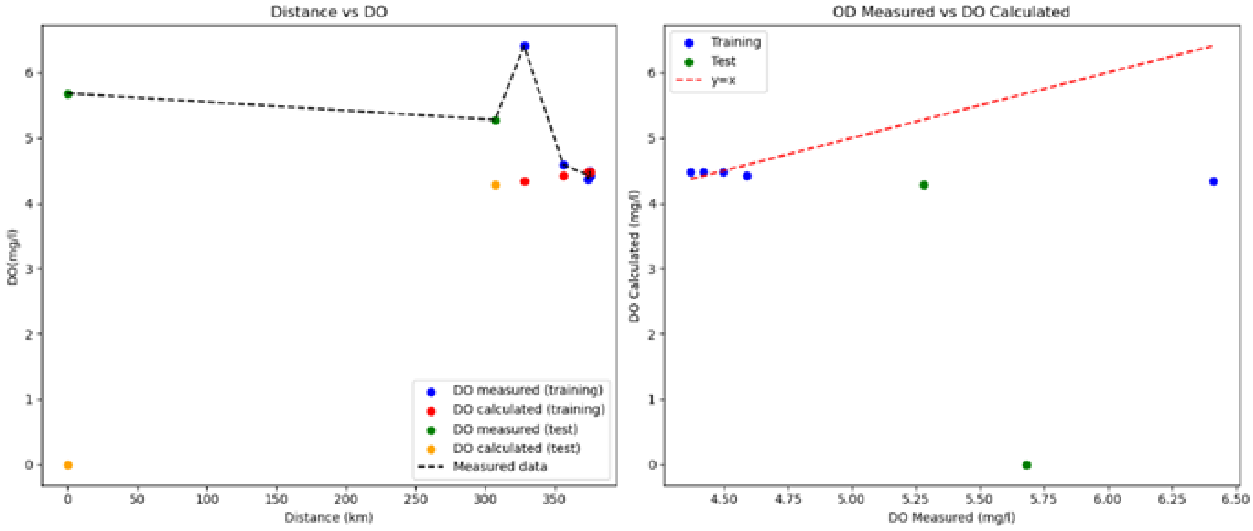

Fig. 7. PG algorithm behavior during training and validation, as well as with respect to measured and computed data vs. an identity function

The equation obtained with GP of the average concentration of DO in mg/l vs distance x in km took the form (the negative sign in the natural logarithm that GP originally reported is not considered):

$$DO = ln\,(0.235x) \tag{7}$$

To investigate the survival condition of the Tilapia fish beyond the last section considered, for example, at x= 400 km the dissolved oxygen reported by the model is: 4,543 mg/l, i.e. the model would predict survival risk even at 400 km

3.3 Heat Map (risk)

To account for the variation in the critical DO parameter over time and across different sections, it was proposed to numerically solve the diffusion differential equation, resulting in the tabular function of dissolved oxygen. By assigning a color scale where green represents the highest DO value and red the lowest, information appears highlighted with a bold border on dates with the highest risks to the survival of aquatic species (Figure 8). For instance, Tilapia survives with suggested DO values greater than 5 mg/l; below these values, their survival is at risk.

t día/ d km	0	24.93	49.87	74.80	99.73	124.67	149.60	174.53	199.47	224.40	249.33	274.27	299.20	324.13	349.07	374
						OD mg/l										
30/12/2012	7.99	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.07
30/03/2013	7.07	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	4.64
28/06/2013	5.45	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	4.21
26/09/2013	7.05	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	3.78
25/12/2013	6.74	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	3.35
25/03/2014	7.56	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	2.92
23/06/2014	5.33	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	2.49
21/09/2014	3.64	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	2.64
20/12/2014	4.9	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	3.99
20/03/2015	5.7	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.34
18/06/2015	5.08	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	3.89
16/09/2015	6.15	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	1.9
15/12/2015	6.31	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	2.64
14/03/2016	5.89	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	3.38
12/06/2016	5.66	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	3.67
10/09/2016	4.94	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	3.91
09/12/2016	5.49	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	4.01
09/03/2017	6.56	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	4.11
07/06/2017	5.48	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	4.37
05/09/2017	4.27	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	4.62
04/12/2017	5.83	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	4.98
04/03/2018	6.23	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.37
02/06/2018	5.43	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.77
31/08/2018	5.03	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.49
29/11/2018	5.84	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	4.52
27/02/2019	6.46	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.51
28/05/2019	6.23	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.54
26/08/2019	5.99	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.57
24/11/2019	5.76	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.6
22/02/2020	5.53	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.63
22/05/2020	5.29	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.66
20/08/2020	5.06	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.69
18/11/2020	4.77	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.72
16/02/2021	4.46	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.75
17/05/2021	4.14	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.79
15/08/2021	3.83	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.82
13/11/2021	3.51	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.85
11/02/2022	3.2	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.88
12/05/2022	2.88	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.91
10/08/2022	2.57	7.89	7.79	7.69	7.58	7.48	7.38	7.28	7.18	7.08	6.98	6.87	6.77	6.73	5.65	5.94

Fig. 8. Dissolved oxygen DO (mg/l) behavior as a function of time t (months) and length d (km) and critical values for the survival of Tilapia (historical conditions)

4. Conclusions

The water quality parameters study on the Fuerte River and Huites Dam demonstrates a critical need for continuous monitoring to ensure the survival of aquatic species like Tilapia. Dissolved Oxygen (DO) emerged as the most influential factor affecting aquatic life, with values consistently below the threshold of 5 mg/l in several sections, posing a high risk to fish survival. The implementation of genetic programming and the diffusion equation provided valuable tools for the behaviour modelling of DO and predicting areas of risk. This study also provides a forward-looking perspective on improving water management in Mexico. This analysis underscores the importance of integrated water resource management, where continuous monitoring, innovative modelling techniques, and the application of advanced technologies such as artificial intelligence can optimize the prediction and mitigation of environmental risks. As Mexico grapples with increasing challenges in water quality due to anthropogenic activities, strengthening regulatory frameworks and expanding the scope of research and development in water treatment and distribution systems is essential.

Key recommendations include an enhanced Monitoring by expanding the coverage of the National Water Quality Measurement Network (RENAMECA) to include more detailed, real-time data collection; also a technological Integration, with an invest in AI-driven models for predictive analysis and risk assessment of water quality, ensuring timely interventions in high-risk areas. Finally to promote the adoption of environmentally sustainable practices in agriculture and industry to reduce contamination of water bodies.

In conclusion, addressing the challenges of water quality in the Fuerte River and other Mexican water bodies requires a multidisciplinary approach, combining scientific research, technological innovation, and robust policy-making to protect aquatic ecosystems and ensure water resource sustainability for future generations.

References

[1] Official Journal of the Federation / Diario Oficial de la Federación (DOF). *NORMA Oficial Mexicana NOM-001-SEMARNAT-2021*. Accessed October 17, 2024.

https://www.dof.gob.mx/nota_detalle.php?codigo=5645374&fecha=11/03/2022#gsc.tab=01.
[2] Agua. *Pollution in Mexico / Contaminación en México*. Accessed 2024. https://agua.org.mx/agua-contaminacion-en-mexico/.
[3] National Network for Water Quality Measurement / Red Nacional de Medición de Calidad del Agua (RENAMECA). Accessed 2024. https://www.gob.mx/conagua/articulos/resultados-de-la-red-nacional-de-medicion-de-calidad-del-agua-renameca?idiom=es.
[4] Espinoza Pérez, Héctor. "Biodiversidad de peces en México (Fish Biodiversity in Mexico)." *Revista Mexicana de Biodiversidad*, Supl. 85 (2014): S450-S459. https://doi.org/10.7550/rmb.32264.
[5] Koza, J.R. *Genetic Programming: On the Programming of Computers by Means of Natural Selection*. Cambridge, The MIT Press, 1992.
[6] Medupe, Medupe, and Moatlhodi Wise Letshwenyo. "Investigation of Self-Purification and Water Quality Index During Dry and Rainy Seasons in the Khurumela Stream (Botswana)." *Journal of Ecohydraulics*, (June 2024): 1-18. https://doi.org/10.1080/24705357.2024.2363755.
[7] Bozorg-Haddad, Omid, Shima Soleimani, and Hugo A. Loáiciga. "Modeling Water-Quality Parameters Using Genetic Algorithm–Least Squares Support Vector Regression and Genetic Programming." *Journal of Environmental Engineering* 143, no. 9 (2017): 04017061.
[8] Elsayed, Ahmed, Maysara Ghaith, Ahmed Yosri, Zhong Li, and Wael El-Dakhakhni. "Genetic Programming Expressions for Effluent Quality Prediction: Towards AI-Driven Monitoring and Management of Wastewater Treatment Plants." *Journal of Environmental Management* 356 (2024): 120510. https://doi.org/10.1016/j.jenvman.2024.120510.
[9] Copilot. Accessed 2024. https://copilot.cloud.microsoft/?fromcode=cmc&redirectid=C0E05F6C48714F4EAC209E64FE37D0F3&auth=2.
[10] Anaconda. Accessed 2024. https://anaconda.org/.
[11] Proain. "Producción de peces (Pisciculture) en México / Fish Production in Mexico", October 8, 2020. Accessed October, 22, 2024. https://proain.com/blogs/notas-tecnicas/produccion-de-peces-piscicultura-en-mexico?srsltid=AfmBOooiAujXCLhJAGkZXot7inGQSEMGrsXlUYvGOld0ZBe8hZ8A6VHl.
[12] Hendrickson, Dean A., and Alejandro Varela Romero. "Fishes of the Río Fuerte Drainage." In Libro Jubilar en Honor al Dr. Salvador Contreras Balderas, edited by Ma. de Lourdes Lozano-Vilano, 171-195. Monterrey, Universidad Autónoma de Nuevo León, 2002.
[13] Millán, J. "Simulación numérica. Ecuación de difusión / Numerical Simulation. Diffusion Equation)." *Revista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingeniería* 15, no. 2 (2011): 29-38.
[14] Gerald, Curtis F. *Numerical Analysis / Análisis numérico*. 2nd ed. Alfaomega, 1997.
[15] Laney, Culbert B. *Computational Gasdynamics*. Cambridge, Cambridge University Press, 1998.