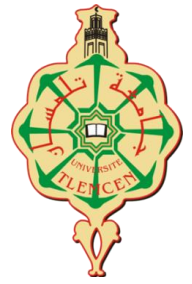




Institute for Water
and Energy Sciences
(incl. Climate Change)



PAN-AFRICAN UNIVERSITY
INSTITUTE FOR WATER AND ENERGY SCIENCES
(including **CLIMATE CHANGE**)

Master Dissertation

Submitted in partial fulfillment of the requirements for the Master degree in
WATER ENGINEERING

Presented by

Mohammed Ayoub Rebahi

**Modelling and Simulation of Wastewater Treatment Plants:
Exploring Scenarios with GPS-X Simulator**

Defended on 17/04/2025 Before the Following Committee:

Chair	Umaru Garba Wali	Prof	School of Engineering, College of Science and Technology, University of Rwanda
Supervisor	Cherifa Abdelbaki	Prof	University of Tlemcen, Algeria
Co-supervisor	Sidi Mohammed Tiar	Dr	University of Tlemcen, Algeria
External Examiner	Chicgoua Noubactep	Prof	University of Goettingen, Germany
Internal Examiner	Boumediene Maamar	Dr	University of Tlemcen, Algeria

Statement of the Author

I, Mohammed Ayoub Rebahi, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here have been fully cited and referenced in accordance with the academic rules and ethics

Dedication

I dedicate this work to my beloved family, whose unwavering support, encouragement, and sacrifices have been the foundation of my journey. To my parents, who instilled in me the values of perseverance and curiosity, and to professors, whose guidance has shaped my academic and professional growth.

Also dedicate this work to all researchers and professionals striving to address water challenges in arid and semi-arid regions, working towards a sustainable future in the face of climate change.

Acknowledgment

I would like to express my deepest gratitude to my academic advisors and professors, whose guidance, expertise, and continuous encouragement have been invaluable throughout this research. Their insights and constructive feedback have helped shape my understanding and strengthened the quality of this work.

My sincere appreciation goes to the Pan African University Institute for Water and Energy Sciences (PAUWES) for providing an excellent academic environment and resources that have greatly contributed to my learning experience. I am also grateful to all faculty members and staff for their support during my studies.

I extend my heartfelt thanks to my family for their unwavering support, patience, and belief in my abilities. Their encouragement has been my greatest motivation in pursuing this academic endeavor.

Special thanks to my colleagues and friends, whose discussions, collaboration, and shared experiences have enriched my academic journey. Their companionship has made this experience both rewarding and inspiring.

Finally, I acknowledge all institutions, organizations, and individuals who contributed directly or indirectly to this research, particularly those involved in water resource management and climate change adaptation. Their work continues to inspire me in my pursuit of sustainable solutions for water-related challenges.

Mohammed Ayoub Rebahi

Abbreviations and Acronyms

- **ANAMMOX:** Anaerobic Ammonium Oxidation
- **ARIMA:** Autoregressive Integrated Moving Average
- **ASM:** Activated Sludge Model
- **BAF:** Biological Aerated Filter
- **BOD:** Biochemical Oxygen Demand
- **COD:** Chemical Oxygen Demand
- **DO:** Dissolved Oxygen
- **EPA:** Environmental Protection Agency
- **EWMA:** Exponentially Weighted Moving Average
- **GPS-X:** General Purpose Simulator for Wastewater Treatment Processes
- **HRT:** Hydraulic Retention Time
- **ISO:** International Organization for Standardization
- **LOWESS:** Locally Weighted Scatterplot Smoothing
- **MANTIS2:** Model for Advanced Nutrient and Treatment Integrated Simulation
- **MBBR:** Moving Bed Biofilm Reactor
- **MBR:** Membrane Bioreactor
- **MLSS:** Mixed Liquor Suspended Solids
- **NH₄-N:** Ammonium Nitrogen
- **NO₂-N:** Nitrite Nitrogen
- **NO₃-N:** Nitrate Nitrogen
- **PO₄-P:** Phosphate Phosphorus
- **RAS:** Return Activated Sludge
- **RMSE:** Root Mean Square Error
- **SBR:** Sequencing Batch Reactor
- **SG Filter:** Savitzky-Golay Filter

- **SRT**: Sludge Retention Time
- **STEP** : Station de Traitement des Eaux Polluées (French for WWTP)
- **TSS**: Total Suspended Solids
- **UASB**: Upflow Anaerobic Sludge Blanket
- **WAS**: Waste Activated Sludge
- **WHO** : World Health Organization
- **WWTP**: Wastewater Treatment Plant

TABLE OF CONTENT

Statement of the Author.....	i
Dedication	ii
Acknowledgment	iii
Abbreviations and Acronyms	iv
Abstract	xii
Resumé	xiii
CHAPTER 1. GENERAL INTRODUCTION	1
1.1- Background.....	1
1.2- Problem Statement and Research Gap in WWTP Optimization in Algeria	2
1.3- Research Objectives	4
1.4- Significance of the Study.....	5
1.4-1. Environmental Impact.....	5
1.4-2. Technological Advancement.....	5
1.4-3. Economic and Operational Benefits.....	5
1.4-4. Relevance to Algeria’s Water Management Goals	5
1.5- Scope of the Study.....	5
1.6- Outline of the Thesis.....	6
Chapter 2. LITERATURE REVIEW	7
2.1- Conventional Wastewater Treatment: Processes, Importance, and Future Challenges ..	7
2.2- Challenges and Solutions for Wastewater Treatment in Arid and Semi-Arid Regions ..	9
2.3- Wastewater Treatment Process Modeling: Steps, Importance, Evolution, and Future Directions	14
2.4- Comparison of WWTP Modeling Software: GPS-X, SIMBA, And Alternatives	17
2.5- MANTIS2: An Advanced Whole-Plant Wastewater Treatment Model	18
Chapter 3. Methodology.....	20

3.1-	Study Area.....	20
3.2-	Description of El Kerma WWTP	21
3.2-1.	Station Power	22
3.2-2.	Pretreatment	22
3.2-3.	Primary Sedimentation.....	23
3.2-4.	Secondary (biological) treatment	23
3.2-5.	Secondary Sedimentation.....	24
3.2-6.	Disinfection.....	25
3.2-7.	Sludge Recirculation and Treatment.....	25
3.3-	Monitored Parameters and Analytical Methods.....	26
3.4-	Descriptive Data Analysis of Monitored Parameters	27
3.5-	Application of Mantis2 model in WWTP el kerma	28
3.6-	Graphical Construction of WWTP Layout.....	29
3.7-	Selection of the library	30
3.8-	Selection of the Model for Each Process Unit	30
3.9-	Correction of Data	31
3.10-	Model Calibration.....	35
3.10-	The scenarios	41
Chapter 4.	Result and discussion.....	44
4.1 -	Data correction	44
5.1 -	Calibration result	47
4.2-	Validation result	51
4.2-	Scenario	52
4.2-	Conclusion :.....	62
Chapter 5:	Summary, Conclusions & Perspectives	64
5.1-	Summary	64

5.2- Conclusions	65
5.3- Perspectives	66
References	67

List of Tables

Table 2. 1:Case Studies on WWTP Performance in Algeria	13
Table 2. 2:Tool comparison	17
Table 3. 1: Characteristic of WWTP el karma.....	21
Table 3. 2: Influent and Effluent characteristics.....	27
Table 3. 3: Kinetic. stoichiometric and operational parameter.....	37
Table 4. 1:The RMSE for Data correction method	45
Table 4. 2:The kinetic, stoichiometric and operational calibrated parameter.....	49

List of Figures

Figure 2. 1: Typical wastewater treatment.....	9
Figure 2. 2: Wastewater reuse	10
Figure 2. 3: Health effect of pollution.....	11
Figure 3. 1: Situation of Oran wastewater treatment plant	20
Figure 3.2: El kerma Wastewater treatment Plant	21
Figure 3.3: EL kerma WWTP process.....	22
Figure 3. 4: The primary decanteur	23
Figure 3. 5: The Aeration tank (Activated sludge).....	24
Figure 3. 6: The secondary clarifier	24
Figure 3. 7: Disinfection Basin	25
Figure 3. 8: Anaerobic digester	26
Figure 3. 9: The Layout.....	29
Figure 3. 10: Data File Tool with Values (COD & Flow rate).	39
Figure 3. 11: Optimizer Settings	40
Figure 3. 12: Optimization Approach.....	41
Figure 4. 1: The COD influent real and corrected data	45
Figure 4. 2: The COD effluent real and corrected data	46
Figure 4. 3: The Flow t real and corrected data.....	47
Figure 4. 4: Dynamic calibration for COD effluent	50
Figure 4. 5: Linear Regression test (measured COD/simulated COD).	50
Figure 4. 6: Dynamic Validation results for the effluent COD.....	51
Figure 4. 7: Linear Regression test (measured COD/simulated COD).	52
Figure 4. 8: COD effluent after increased load of 10%.....	53
Figure 4. 9: COD effluent after increased load of 30%.....	54

Figure 4. 10: COD effluent after increased load of 50%.....	56
Figure 4. 10: The baseline designed system.....	57
Figure 4. 11: The COD effluent with the baseline system after increasing the flow	58
Figure 4. 12: Upgraded Configuration	58
Figure 4. 13: The COD effluent after upgrading the system.....	59
Figure 4. 14: Full-Capacity system	60
Figure 4. 15: The COD effluent for the Full-Capacity system.....	61
Figure 4. 16: The COD effluent for the designed flowrate	62

Abstract

Wastewater treatment establishes critical functions to safeguard the environment together with water conservation especially within arid and semi-arid regions experiencing water scarcity. The research examines El Kerma Wastewater Treatment Plant (WWTP) in Oran Algeria through Mantis2 model implementation in GPS-X simulation platform for optimization modeling. The research evaluates treatment performance while developing operational strategies that identify potential improvements for pollutant removal efficiency. A complete review of wastewater treatment processes together with modeling methodologies and advanced simulation software applications was performed. Research activities included data acquisition followed by preprocessing and model development through calibration of influent and effluent parameters and followed by dynamic simulations under conditions such as growing organic loads and rising population numbers and maximum plant capacity usage. The model benefit from sensitivity analysis together with optimization techniques which helped to enhance predictive accuracy by providing improved parameter values. The El Kerma WWTP successfully reaches high organic matter elimination levels by achieving COD removal beyond 90% of COD. Model scenarios indicated potential compliance issues when dealing with higher hydraulic and organic loads so process adjustments became necessary to maintain regulatory adherence. Research findings support wastewater treatment modeling growth by delivering strategic guidance to policymakers and engineers who need to optimize wastewater management throughout Algeria and similar areas.

Keywords

COD and BOD reduction, Computational simulation, Dynamic simulation, El Kerma WWTP, GPS-X software, Mantis2 model, Model calibration and validation, Organic pollutant removal, Scenario-based analysis, Wastewater process modeling, Wastewater treatment, Wastewater treatment plant (WWTP)

Resumé

Le traitement des eaux usées établit des fonctions essentielles pour protéger l'environnement ainsi que la conservation de l'eau, en particulier dans les régions arides et semi-arides qui connaissent une pénurie d'eau. La recherche examine l'usine de traitement des eaux usées (STEP) d'El Kerma à Oran en Algérie par le biais de la mise en œuvre du modèle Mantis2 dans la plateforme de simulation GPS-X pour la modélisation d'optimisation. La recherche évalue le rendement du traitement tout en élaborant des stratégies opérationnelles qui permettent d'identifier les améliorations possibles pour l'efficacité de l'élimination des polluants. Un examen complet des processus de traitement des eaux usées ainsi que des méthodologies de modélisation et des applications logicielles de simulation avancées a été effectué. Les activités de recherche comprenaient l'acquisition de données suivie du prétraitement et de la mise au point de modèles par étalonnage des paramètres d'influent et d'effluent, ainsi que des simulations dynamiques dans des conditions telles que des charges organiques croissantes et un nombre croissant de populations et de plantes maximales utilisation de la capacité. Le modèle bénéficie de l'analyse de sensibilité ainsi que des techniques d'optimisation qui ont contribué à améliorer la précision prédictive en fournissant des valeurs de paramètres améliorées. La STEP d'El Kerma atteint avec succès des niveaux élevés d'élimination de matière organique en éliminant plus de 90 % de DCO. Les scénarios de modèle indiquaient des problèmes potentiels de conformité lorsqu'il s'agissait de traiter des charges hydrauliques et organiques plus élevées, de sorte que des ajustements du processus sont devenus nécessaires pour maintenir le respect de la réglementation. Les résultats de la recherche appuient la modélisation de la croissance du traitement des eaux usées en fournissant une orientation stratégique aux décideurs et aux ingénieurs qui doivent optimiser la gestion des eaux usées dans l'ensemble de l'Algérie et des régions similaires.

Mots-clés

Traitement des eaux usées, modélisation des processus d'eaux usées, simulation informatique, logiciel GPS-X, modèle Mantis2, station d'épuration (STEP), SEEU d'El Kerma, élimination de polluants organiques, réduction de la DCO et de la DBO, étalonnage et validation du modèle, simulation dynamique, scénario-analyse basée.

CHAPTER 1. GENERAL INTRODUCTION

1.1- Background

Algeria, a country heavily impacted by water scarcity, faces mounting pressure to ensure sustainable water management as per capita water availability is projected to drop to 220 m³ by 2050 (Frank Water, 2019). Rapid population growth, urbanization, and industrial expansion, including the development of 57 new industrial zones, have intensified the demand for water resources, further straining already limited supplies (Frank Water, 2019). Additionally, climate change has exacerbated the crisis, with rainfall in western Algeria decreasing by approximately 40% since 1900, accelerating dam sedimentation and depleting groundwater reserves (Sabry Zaki, 2022). The country's aging water infrastructure presents another challenge, with losses of up to 25% of stored dam water annually due to inefficiencies, while irrigation demands exceed current capacity by a ratio of 3:1 (Frank Water, 2019; Sabry Zaki, 2022)

To combat these issues, Algeria has implemented a dual strategy that combines wastewater treatment and desalination to enhance water security. Under the National Water Plan and Sustainable Development Goal 6 (SDG6), wastewater recycling has been prioritized, leading to the operation of 200 wastewater treatment plants (WWTPs) treating approximately 480 hm³ of wastewater per year, with 6% of the treated effluent reused for irrigating 7,900 hectares of agricultural land (Aroua-Berkat & Aroua, 2022). Notable projects, such as the Laghouat WWTP, which operates with a 26,700 m³/day capacity using activated sludge treatment, have provided water for arid regions since 2008. To ensure safe reuse, the government has established regulatory frameworks such as Executive Decree 07-149, which mandates 100-meter buffer zones around wastewater reuse sites to mitigate contamination risks (Aroua-Berkat & Aroua, 2022). However, assessments indicate variable compliance across treatment plants. For instance, the Ain Sefra WWTP meets nitrate discharge limits for irrigation but struggles with ammonia concentrations, exceeding standards by 30–40% (Moussaoui et al., 2023). Moreover, national averages show that biological oxygen demand (BOD₅) levels in treated effluent reach 42.56 mg/L, surpassing the regulatory limit of 30 mg/L, highlighting the challenge of high organic loads in treated wastewater (Aroua-Berkat & Aroua, 2022).

Alongside wastewater reuse, Algeria has made significant investments in desalination as part of a \$5.4 billion program to construct seven new plants between 2025 and 2030, with the goal of increasing desalination capacity to 5.8 million m³/day, ultimately meeting 60% of the

country's drinking water needs by 2030 (Goosen, 2025). Additionally, some WWTPs have been optimized to integrate energy production with wastewater treatment. For example, the Beni Messous WWTP has doubled its treatment capacity while simultaneously generating biogas to support energy efficiency in operations (Aroua-Berkat & Aroua, 2022). In agriculture, treated wastewater has been increasingly used to irrigate drought-resistant crops such as olives and barley, helping to conserve freshwater resources while sustaining food production (Aroua-Berkat & Aroua, 2022; Moussaoui et al., 2023).

Despite these advancements, Algeria still faces persistent challenges in achieving comprehensive water security. There are notable regional disparities, as desalinated water supplies 18% of drinking water in the northern regions, whereas southern areas remain heavily reliant on groundwater (Fanack Water, 2019; Goosen, 2025). Operational inefficiencies also persist, with only 53% of wastewater undergoing treatment despite a reported 91% sewerage network coverage, indicating systemic gaps in collection and processing (Aroua-Berkat & Aroua, 2022). Additionally, climate variability poses a significant risk to treatment plant operations, as fluctuating temperatures between 9.75°C and 23.85°C in northern Algeria affect the efficiency of biological wastewater treatment processes (Aroua-Berkat & Aroua, 2022; Moussaoui et al., 2023).

Going forward, Algeria's long-term water security depends on integrating its \$3 billion desalination investment with enhanced wastewater reuse policies. While the country aims to increase wastewater treatment capacity to 925 million m³ annually by 2030, success will require addressing technical inefficiencies, optimizing plant operations, and fostering public-private partnerships to strengthen investment and infrastructure resilience (Fanack Water, 2019; Aroua-Berkat & Aroua, 2022). The balance between large-scale infrastructure expansion and precision management will be critical in ensuring a sustainable and climate-resilient water future.

1.2- Problem Statement and Research Gap in WWTP Optimization in Algeria

1.2.1. Lack of Advanced Modeling Applications

Many wastewater treatment plants (WWTPs) in Algeria rely heavily on empirical methods and manual process control, leading to suboptimal performance and inefficiencies. Traditional monitoring techniques often involve laboratory testing of effluent parameters (BOD, COD, nitrates, ammonia, etc.), which provides valuable insights but lacks real-time adaptability.

Key Issues

- **Limited Use of Computational Models:** Advanced wastewater treatment modeling software, such as GPS-X, BioWin, or WEST, is not widely used in Algeria, restricting the ability to simulate and predict plant performance under different conditions.
- **Reactive vs. Predictive Control:** Current WWTP operations often rely on a reactive approach (adjustments made after observing poor treatment efficiency), whereas predictive simulation models could allow for proactive interventions.
- **Lack of Digital Twin Implementation:** Digital twins virtual replicas of WWTPs using real-time sensor data and AI are used in modern wastewater management but are absent in most Algerian facilities.

1.2.2. Insufficient Scenario-Based Analysis for Fluctuating Loads

WWTPs are subject to high variability in influent characteristics, including seasonal variations in flow rate, sudden increases in organic matter from industrial discharges, and climate-induced changes in water temperature and pH. However, few studies have systematically modeled these dynamic scenarios to optimize treatment efficiency.

Key Issues :

- **Seasonal and Hydraulic Variability:** Many Algerian WWTPs experience fluctuations in organic load due to rainfall patterns, industrial waste discharges, and changes in population density. However, limited research has assessed how these variations impact treatment efficiency.
- **High Organic and Hydraulic Loads:** Most plants were designed based on historical flow rates, but due to population growth and industrial expansion, many WWTPs now receive higher loads than originally intended.
- **Lack of Sensitivity Analysis:** Few studies have performed sensitivity analysis (using models like ASM1, ASM2) to predict the critical factors affecting effluent quality under different operational conditions.

1.2.3. Need for Performance Enhancement Strategies

Many existing Algerian WWTPs struggle with compliance under increased organic and hydraulic loading, leading to violations of effluent standards. There is an urgent need for data-driven strategies to enhance plant efficiency.

Key Issues :

- **High BOD₅ and COD Levels in Treated Effluent:** Studies have reported BOD₅ concentrations **above** 42.56 mg/L, exceeding the regulatory limit of 30 mg/L, indicating poor organic matter removal efficiency (Larhyss Journal, 2023).
- **Energy Inefficiencies in Aeration Systems:** Aeration is the most energy-intensive process in activated sludge treatment. Many WWTPs lack real-time oxygen control (e.g., using DO probes with adaptive control algorithms), leading to over-aeration and high energy costs.
- **Lack of Resource Recovery Integration:** Few plants implement sludge-to-biogas conversion or phosphorus recovery technologies (e.g., struvite crystallization), missing opportunities for circular economy approaches.
- **Operational Training Gaps:** Many WWTP operators **lack training in advanced treatment optimization techniques**, leading to reliance on manual adjustments rather than data-driven process control.

1.3- Research Objectives

The primary objective of this study is to develop a comprehensive model of the Oran WWTP using the Mantis2 model within GPS-X and evaluate its performance under various operational scenarios. The specific objectives include:

1. **Assessing the efficiency** of the Oran WWTP in organic matter removal, nutrient elimination, and overall effluent quality under existing operational conditions.
2. **Simulating various treatment scenarios** using GPS-X to analyze the impact of different influent characteristics and process modifications on treatment efficiency.
3. **Optimizing operational strategies**, such as aeration rates, sludge retention times, and denitrification configurations, to enhance treatment performance and reduce environmental impact.
4. **Evaluating the applicability of the Mantis2 model** for whole-plant simulation and its potential role in improving wastewater treatment processes in Algeria.
5. **Providing recommendations** for improving the efficiency, sustainability, and regulatory compliance of wastewater treatment plants in Algeria.

1.4- Significance of the Study

This research is significant for several reasons:

1.4-1. Environmental Impact

Improved wastewater treatment processes reduce pollutant discharge into natural water bodies, protecting aquatic ecosystems and public health. By optimizing treatment performance, this study contributes to reducing the carbon footprint and energy consumption of wastewater treatment operations.

1.4-2. Technological Advancement

By integrating the Mantis2 model within GPS-X, this study contributes to the advancement of wastewater treatment modeling, providing valuable insights into the efficiency of biological nutrient removal processes. The findings will help engineers, policymakers, and wastewater treatment operators adopt data-driven approaches to decision-making and plant management.

1.4-3. Economic and Operational Benefits

Optimization of wastewater treatment processes can lead to significant cost savings by reducing energy consumption, improving sludge management, and minimizing chemical usage. This study will propose cost-effective solutions for plant operators, enhancing the overall sustainability of wastewater treatment systems.

1.4-4. Relevance to Algeria's Water Management Goals

Algeria faces challenges related to water scarcity and pollution control. By assessing and optimizing the performance of a major wastewater treatment plant, this study aligns with Algeria's national water management strategies, supporting efforts to enhance water reuse and conservation.

1.5- Scope of the Study

The study focuses on El Kerma WWTP in Oran, Algeria, analyzing its operational performance using MANTIS2 modeling in GPS-X software. The research includes:

- **Data Collection:** Historical influent and effluent water quality data for key parameters (COD, BOD, TSS, NH₄-N, etc.).
- **Model Development:** Calibration and validation of the MANTIS2 model to simulate plant performance.

- **Scenario Analysis:** Evaluating plant performance under different loading conditions, including increased organic loads and hydraulic variations.
- **Optimization Strategies:** Identifying process adjustments to enhance pollutant removal efficiency and maintain regulatory compliance.

1.6- Outline of the Thesis

The thesis is structured as follows:

Chapter 1: Introduction

- Provides the background, motivation, research objectives, significance, and structure of the study.

Chapter 2: Literature Review

- Reviews wastewater treatment technologies, modeling approaches, and the application of GPS-X and Mantis2 in wastewater treatment plant simulations.

Chapter 3: Methodology

- Describes the case study site (Oran WWTP), data collection procedures, model setup, calibration, validation, and simulation scenarios.

Chapter 4: Results and Discussion

- Presents the simulation results, analyzes the efficiency of different treatment scenarios, and discusses the implications for wastewater treatment plant optimization.

Chapter 5: Conclusion and Future Work

- Summarizes key findings, highlights contributions to the field, discusses study limitations, and suggests future research directions.

Chapter 2. LITERATURE REVIEW

2.1- Conventional Wastewater Treatment: Processes, Importance, and Future Challenges

The conventional wastewater treatment systems use organized physical, chemical and biological operations to extract pollutants from wastewater before releasing it for reuse. The fundamental wastewater management procedures serve both environmental compliance expectations and risk reduction requirements for wastewater effluent. The treatment process begins with preliminary treatment that eliminate large solid particles to safeguard future equipment until the process reaches maximum operational potential. Wastewater treatment starts with initial barrier processes to filter out big solids which also incorporates grit separation after possibly using comminution to fragment larger materials. The operation of grit chambers through water velocity control or air applications prevents organic matter settlement as a standard preliminary treatment stage (Cambi, 2021; Fao, 1992)

The primary treatment process follows preliminary treatment by employing sedimentation methods together with skimming to remove floating along with settleable solids. Sedimentation basins and primary clarifiers serve to enable natural sedimentation of suspended particles in this process stage. This process removes 65% of oil and grease materials together with 50–70% of total suspended solids (TSS) and 25–50% of biochemical oxygen demand (BOD). Traditional primary treatment utilizes two techniques: sedimentation basins and clarifiers yet modern implementations integrate state-of-the-art solutions such as dissolved air flotation and lamella separators (Cambi, 2021)The improved technologies enhance operational performance mainly in facilities with confinement issues or stringent wastewater discharging standards.

The essential function of secondary treatment or biological treatment consists in removing dissolved and colloidal organic matter. Aerobic biological processes enable microorganisms to break down organic pollutants with the presence of oxygen during this stage. The activated sludge process together with trickling filters MBBR and MBR represent the main approaches for secondary treatment. Three primary systems used with biological treatment facilities are Aeration tanks and Secondary clarifiers along with Sequencing batch reactors (SBRs). The achievement of environmental discharge standards depends heavily on secondary treatment efficiency because such methods significantly decrease organic content while enhancing water quality (Fao, 1992).

Advanced treatment methods known as tertiary treatment remove remaining pollutants together with pathogens until the treated effluent reaches both regulatory standards and reuse requirements. During this stage the facility uses ozonation alongside chlorination and ultraviolet (UV) irradiation for disinfection to eliminate harmful pathogens from wastewater. The removal of fine particles in the water depends on the use of filtration systems that combine sand filters alongside membrane filters. The implementation of tertiary treatment becomes essential when treated wastewater needs reuse for agricultural and industrial purposes and water supply because it provides the highest possible water quality (Cambi, 2021; FAO, 1992).

The essential operation of wastewater treatment requires sludge management to handle and minimize the amounts of sludge that forms throughout treatment. The treatment of sludge consists of three main processes that start with thickening followed by dewatering and continuing with stabilization through anaerobic digestion. Treatment facilities gain sustainability through energy source enhancements because anaerobic digestion processes organic matter in sludge while creating biogas from the breakdown (FAO, 1992); Sludge management operations need to be effective for controlling both environmental risks and maximizing useful resources from waste.

Wastewater treatment through traditional methods continues as the universal base for wastewater facilities since it provides affordability and dependable service. Various hurdles remain that need solution to enhance both efficiency and sustainability of current practices. Bio-treatment performs significant energy consumption because of its aeration and pumping activities which requires substantial power use. Installation of modern control systems together with energy-efficient technologies minimizes operational expenditures for these processes. Modern wastewater treatment operators focus on resource recovery because they extract phosphorus and nitrogen from wastewater to use in agriculture while creating energy from biogas produced from wastewater. The adoption of membrane bioreactors together with innovative biological treatment processes via advanced technologies presents strong potential to enhance treatment outcomes while minimizing environmental influence (Cambi 2021; FAO 1992). Sustainable water management depends heavily on the continuous development of wastewater treatment technologies because rising global water needs and evolving environmental standards.

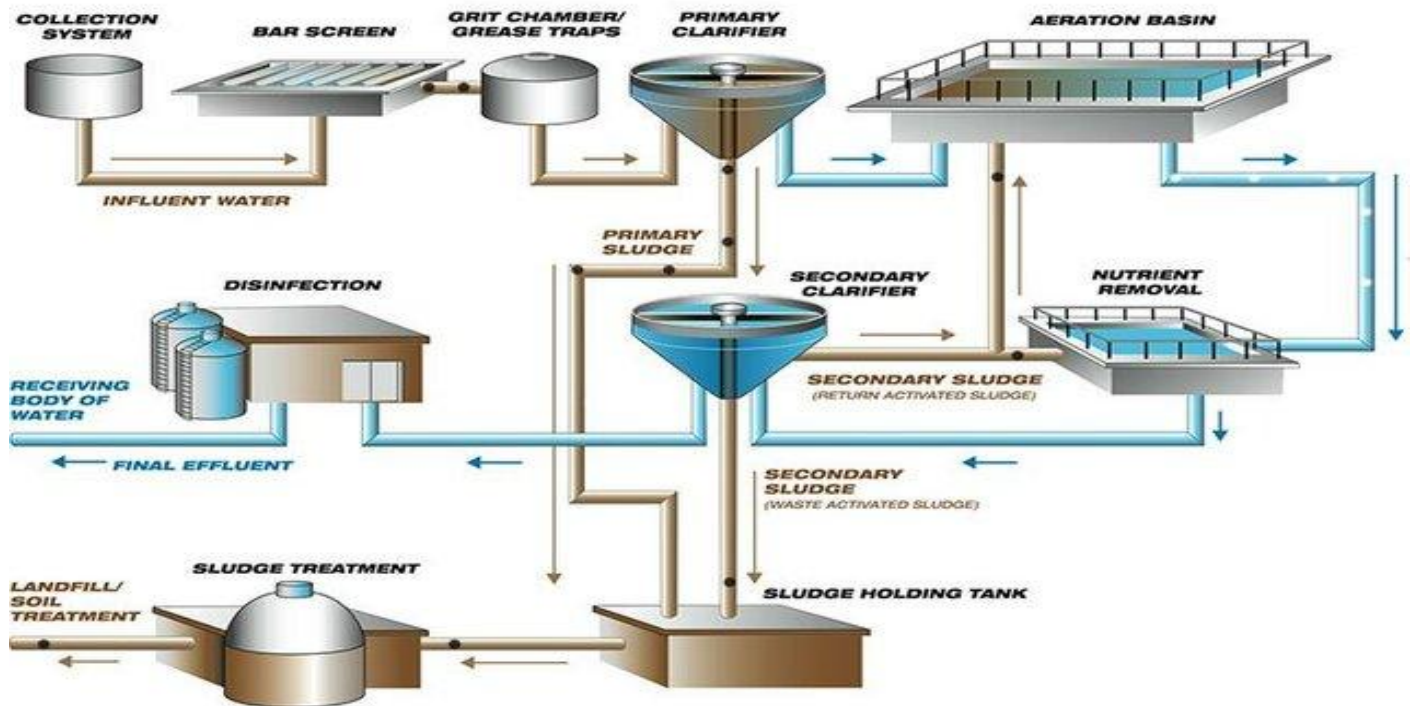


Figure 2. 1: Typical wastewater treatment (Mallik et al., 2018)

2.2- Challenges and Solutions for Wastewater Treatment in Arid and Semi-Arid Regions

Wastewater treatment in dry areas along with semi-arid regions faces distinct problems because of severe water shortages and environmental boundaries as well as economic conditions. These areas experience powerful drinking water needs together with minimal accessible freshwater supply and minimal infrastructure so wastewater reuse becomes essential for sustainability in water management. The severity of water scarcity is worsened because agriculture requires up to 80% of accessible freshwater resources. Megalithic groundwater extraction causes additional salt accumulation and degrades local environments which ultimately decreases the quantity of water that humans can use. Recovery of treated wastewater has become essential for both irrigation activities and groundwater recharge programs. Wastewater collection reaches only 50% of total wastewater generation from MENA countries and an additional 57% of collected wastewater remains untreated which obstructs safe and efficient reuse opportunities (Fanack Water, 2017).



Figure 2. 2:Wastewater reuse

Wastewater treatment deployment becomes more difficult because of insufficient infrastructure and technical obstacles. Standards wastewater treatment systems experience difficulty handling both high salinity water conditions and industrial waste pollutants that include heavy metallic materials from textile and manufacturing facilities. The implementation of composting waste toilets and vacuum-flush systems proves suitable for arid regions provided that site needs along with climatic conditions meet appropriate standards. The high energy needs coupled with high implementation costs of membrane filtration systems and desalination make these advanced wastewater treatment technologies unsuitable for impoverished regions. The scarcity of both cost-effective energy solutions and renewable power sources in dry regions reduces their ability to install wastewater treatment systems due to their high energy costs (Ahmed Abou-Shady, 2022; Frank Water, 2017)

Risk to human health together with environmental hazards represent major issues of concern. Spilling wastewater through reuse without suitable treatment permits the introduction of hazardous materials including salts that infect both soil and water bodies together with disease-causing agents and heavy metals into ecosystems. Soil and water pollution from this procedure creates dangers to farming output together with health risks for people. The irrigation standards of treated wastewater in Jordan are met by 85% however extended wastewater agricultural usage exposes soil to potential degradation from salt and chemical residue accumulation. Water stress and reduced natural pollutant dilution capacity in water bodies become worse because of climate change effects on temperature rise and unpredictable rainfall patterns (Breulmann et al., 2022; Radaideh, 2022).

Health effects of pollution

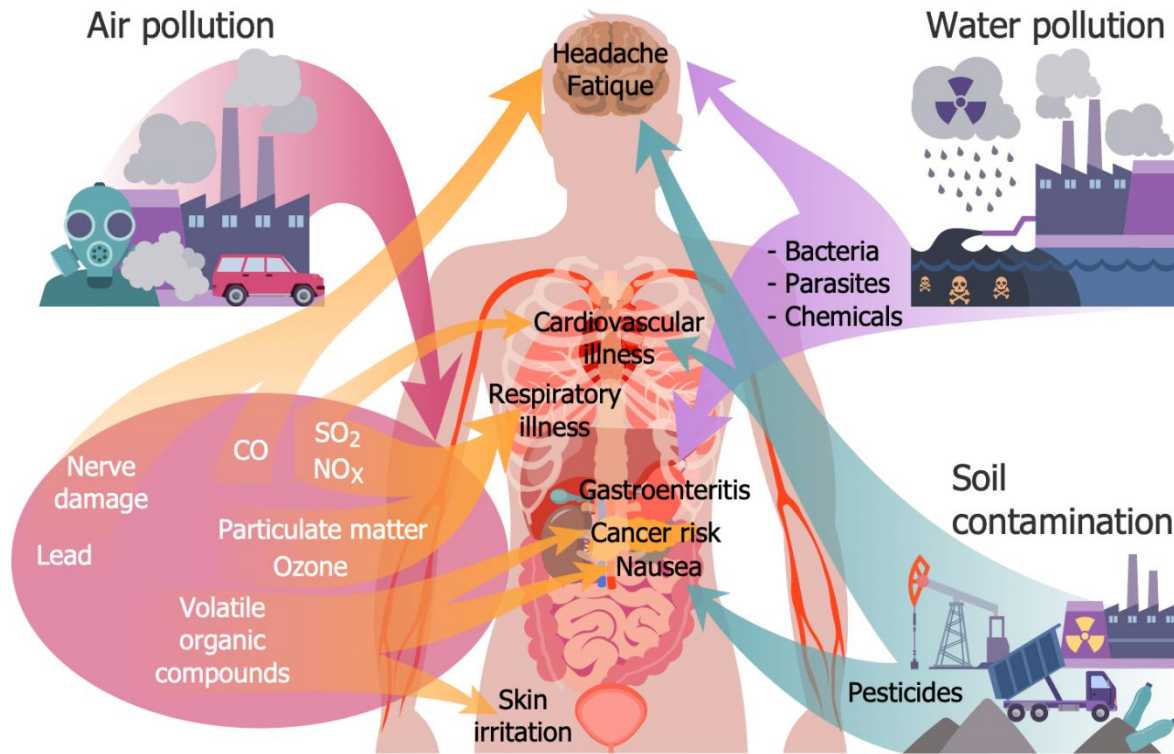


Figure 2. 3: health effect of pollution (ConceptDraw,)

Several system impediments including economic limitations and governmental oversight challenges make it more complicated to treat wastewater along with its subsequent reuse. People typically oppose new technologies including composting toilets because they lack accurate knowledge about these systems and their traditional customs differ. National water management strategies face obstacles to successful wastewater treatment integration because of weak regulatory frameworks alongside fragmented policies. Approval-based wastewater reuse by unregulated facilities creates substantial health dangers and causes problems with infrastructure operation. The expansion of decentralized treatment projects faces delays due to financial shortage combined with limited technical expertise. The initiative of decentralized wastewater treatment plant establishment in countries like Egypt and Morocco remains locally limited due to financial constraints and operational implementation obstacles (FundsforNGOs, 2022).

The identified challenges require various innovative solutions and policy recommendations for resolution. Hybrid water reuse systems that mix treated wastewater with brackish water present opportunities to maintain agricultural irrigation without significant environmental

consequences. Biological treatment methods joined with membrane bioreactors provide better ways to clean textile wastewater and municipal wastewater respectively. Government policies must include wastewater management within national water frameworks as Jordan now implements 36 wastewater facilities through its national funding approach (Radaideh, 2022; Marc Breulmann et.al , 2022).

The improvement of wastewater treatment in arid and semi-arid territories requires decentralized low-energy management systems which local communities can operate independently. Proper capacity building requires adequate training for local system technicians who must monitor water quality while performing maintenance of the systems to prevent failures and deficiencies. The promotion of sustainable practices will occur when safe wastewater reuse regulations become stronger and recycling programs start offering incentives for agricultural uses. The achievement of secure water management in water-affected areas requires an extensive approach connecting technological advancements with community relationships and governmental framework activities according to FundsforNGOs (2022) and Fanack Water (2022).

The case of Algeria exemplifies these challenges while also highlighting the progress made in wastewater treatment and reuse. As one of the most water-stressed countries in North Africa, Algeria has invested in wastewater treatment plants (WWTPs) to mitigate freshwater shortages and promote sustainable water management. However, despite improvements, many plants still face operational inefficiencies, water quality issues, and barriers to reuse. The Ain Sefra WWTP effectively removes nitrates and organic matter, yet high ammonia concentrations limit its irrigation potential (Moussaoui et al., 2023). Similarly, the Baraki WWTP in Algiers meets most physicochemical standards but struggles with bacteriological contamination, requiring additional disinfection before agricultural reuse(Chirane et al., 2024). The El Oued-Kounine WWTP has demonstrated strong pollutant removal capabilities but requires continuous monitoring to maintain compliance with environmental regulations(Khechekhouche & Bouchemal, 2020)Dynamic modeling studies in Sedrata and Souk-Ahras WWTPs reveal that while some plants can accommodate increased wastewater volumes, others require sludge management optimization to improve operational efficiency(Sabri et al., 2017). Moreover, assessments such as the Fuzzy Analytic Hierarchy Process (FAHP) applied to Ain El Houtz WWTP underscore the need for systematic evaluation frameworks to enhance plant performance and management (Abdelmoumene et al., 2024)

The Algerian case studies illustrate that while wastewater treatment facilities are operational,

key barriers persist, including underutilization of treated wastewater, inconsistent disinfection processes, and high ammonia levels. These challenges are not unique to Algeria but reflect broader trends in arid and semi-arid regions where wastewater treatment remains underdeveloped due to governance issues, technical limitations, and financial constraints. Addressing these challenges requires enhanced monitoring mechanisms, improved treatment processes, and robust policies to promote wastewater reuse, particularly in agriculture, where demand for non-conventional water resources is high. Countries like Jordan have successfully incorporated treated wastewater into their national water strategies, operating over 36 wastewater facilities with a focus on agricultural reuse (Radaideh, 2022). Algeria and other MENA countries could benefit from similar approaches, integrating advanced treatment technologies, decentralized systems, and regulatory reforms to optimize wastewater management.

Table 2. 1: Case Studies on WWTP Performance in Algeria

WWTP Name	Location	Key Findings	Challenges Identified	Reference
Ain Sefra	Algeria (South-East)	Efficient in nitrate and organic matter removal	High ammonia concentration limits reuse	Moussaoui et al., 2023
Baraki	Algiers	Meets physicochemical standards	Bacteriological contamination requires extra disinfection	(Chirane et al., 2024)
El-oued- Kounine	Algeria	Strong pollutant removal	Requires continuous monitoring for compliance	Khechekhouch e et al., 2022
Sedrata	North-East Algeria	Capacity expansion from 4,000 to 40,000 m ³ /day	Sludge extraction need optimization	Sabri et al., 2017

Ultimately, the sustainable development of wastewater treatment in arid and semi-arid regions depends on a multi-faceted approach combining technological innovation, policy reforms, and infrastructure investments to enhance treatment efficiency and maximize water reuse. Hybrid water reuse systems, which mix treated wastewater with brackish water, present a promising solution to sustain agricultural irrigation while mitigating environmental risks. Moreover,

energy-efficient biological treatment systems, such as MBRs and constructed wetlands, can improve water quality while reducing operational costs. Strengthening local capacity through technical training programs will also be essential to ensure the successful implementation of decentralized wastewater treatment plants, particularly in rural areas where centralized infrastructure is less feasible (Marc Breulmann et al., 2022). By adopting a holistic, integrated water management approach, countries in arid regions can maximize the benefits of wastewater treatment while addressing the pressing challenges posed by water scarcity and climate change.

2.3- Wastewater Treatment Process Modeling: Steps, Importance, Evolution, and Future Directions

Modern water management requires process modeling as a crucial method which engineers use for designing treatment systems while optimizing their operation and management. Process modeling establishes an ordered method for modeling treatments during operational changes so engineers can refine system designs through optimized choices of reactor placements alongside air distribution decisions and waste management systems. The Activated Sludge Models (ASM1–ASM3) function dynamically to help engineers predict changes in SBR performance and performance improvement of other advanced treatment methods by showing different influent flow conditions (Deepak & Rustum, 2023).

Process modeling helps achieve regulatory compliance together with being a critical component. The strict environmental regulations concerning wastewater effluent quality require treatment plants to use process models that predict removal efficiency of pollutants and facilitate operational adjustments needed to comply with standards. The modeling technique known as mechanistic simulation helps maintain operational efficiency by ensuring regulatory compliance within nitrogen and phosphorus removal processes (Duarte et al., 2024). These prediction tools enable decision-makers to select affordable options that also advance environmental sustainability.

Process models decrease wasteful experimentation costs by enabling economic and energy efficiency optimization in wastewater treatment operations. Engineers can decrease capital as well as operational expenditures by utilizing scenario simulations to optimize operational strategies. Modelling has brought significant benefits to energy consumption optimization by focusing on aeration systems because these systems absorb most treatment facility energy. Predictive control models with advanced capabilities allow operators to adjust aeration levels

immediately which minimizes power consumption and improves process performance (Duarte et al, 2024).

Wastewater treatment modeling incorporated modern technologies including hybrid models and digital twins due to recent advancements. Hybrid models unite mechanistic models with data-driven techniques to make advanced predictive control systems by merging empirical and physical knowledge together with machine learning systems which create more precise adaptable systems. Through this method organizations can obtain improved real-time operational control. Real-time simulations as well as anomaly detection through digital twin technology helps wastewater treatment plant operators perform proactive maintenance before equipment malfunctions occur (Duarte et al., 2024; Wei, 2013).

Throughout the years process modeling techniques have been progressively developed through various approaches. Wastewater modeling underwent a significant advancement when ASM1 was introduced during the late 1980s and 1990s since it delivered dynamic simulations for carbon and nitrogen removal. The initial models demonstrated restricted capabilities to replicate treatment system processes effectively. Proficiency in phosphorus removal became possible with ASM2 and ASM3 along with added hydraulic components and settling behavior enhancements in the models during the 2000s. The improved modeling accuracy required more powerful computing systems and specialized staff knowledge as well as additional computing power to operate the programs (Malini Deepak, 2023). Hybrid modeling strategies emerged recently to enhance traditional models through mechanical methods that integrate machine learning capabilities. Various new modeling strategies meet difficulties from flawed source data and black-box properties of selected machine learning techniques that diminish understanding and interpretation potential (Duarte et al., 2024)

Process modeling needs to overcome various barriers even when considering contemporary advancements. The challenge of model calibration persists because specific site situations need regular modifications to preserve model accuracy. The operating proficiency of wastewater treatment operators and engineers depends on their ability to understand data-driven models since uninterpretable systems lack their acceptance. The field of wastewater treatment modeling shows increasing interest in resource recovery because experts develop models for enhancing energy and nutrient extraction processes from wastewater sludge (Duarte et al., 2024; Wei, 2013). Process modeling stands indispensable in sustainable wastewater treatment as technology advances since it creates links between theoretical work and practical needs and innovative solutions.

Having established that advanced process modeling is essential for optimizing wastewater treatment systems, ensuring regulatory compliance, and reducing operational costs on a global scale, it is instructive to examine how these modeling techniques have been implemented in real-world applications. In Algeria, innovative simulation approaches have been applied across various regions to tackle specific operational challenges and enhance treatment performance. The following case studies from Northeastern and Western to Northern and Northwestern Algeria demonstrate how models such as ASM1, combined with dynamic simulation tools, not only validate these theoretical advancements but also provide practical solutions that drive sustainable water management.

Studies conducted on Souk-Ahras and Sedrata WWTPs in Northeastern Algeria utilized the ASM1 model and GPS-X simulator to predict treatment performance under varying inflow rates and sludge extraction scenarios. The Sedrata WWTP demonstrated the potential to expand its capacity from 4,000 m³/day to 40,000 m³/day, while optimization of sludge extraction at the Souk-Ahras WWTP led to a 37% reduction in sludge production by increasing discharge from 710 to 900 m³/day (Sabri et al., 2017). Additionally, energy optimization models assessed oxygen transfer efficiency in aeration basins, which account for 50–80% of total energy expenditure in WWTPs (Dairi et al., 2011).

In Western Algeria, Mascara WWTP employed a multivariate statistical approach to identify the key process variables affecting treatment efficiency. This model optimized BOD₅ removal efficiency, achieving a 96% reduction, while also identifying correlations between process parameters that contributed to reduced energy consumption in the plant (Benstaali et al., 2024).

Similarly, Ain El Houtz WWTP in Northern Algeria applied a nutrient removal model to enhance nitrogen and phosphorus elimination, achieving 86% nitrogen removal and 85% phosphorus removal under dynamic conditions. The Monte Carlo simulation method was further applied to calibrate seasonal variations, improving predictive accuracy for treatment performance across different environmental conditions (Aliyu et al., 2025).

In Northwestern Algeria, the Maghnia WWTP study provides a compelling illustration of advanced process modeling, complementing other regional case studies. Here, steady-state simulations using the ASM1-based model yielded robust long-term performance predictions, with effluent COD, TSS, and NH₄-N achieving RMSE values of approximately 3.7%, 17%, and 37%, respectively. In contrast, dynamic simulations designed to capture transient conditions

such as seasonal variations in inflow and pollutant loads exhibited higher deviations, with RMSE values rising to around 23% for COD, 67% for TSS, and 56% for NH₄-N. These results highlight both the strengths and challenges of the modeling approach: while steady-state simulations offer excellent accuracy under stable conditions, dynamic simulations reveal the complexity of predicting variable behaviors under fluctuating operational scenarios. Overall, the dual simulation approach not only enhances understanding of process performance but also supports strategic decision-making to improve operational efficiency and resilience in wastewater treatment (Tiar et al., 2024).

These case studies illustrate that while wastewater treatment plants in Algeria are increasingly leveraging process modeling tools, key operational challenges such as high ammonia levels, sludge management inefficiencies, and bacteriological contamination remain significant concerns. Nonetheless, integrating dynamic simulations and optimization frameworks has provided valuable insights for enhancing plant performance and decision-making.

2.4- Comparison of WWTP Modeling Software: GPS-X, SIMBA, And Alternatives

Several software tools are widely used for wastewater treatment plant (WWTP) modeling, each offering distinct advantages based on specific objectives. BioWin is well-suited for biological nutrient removal (BNR) calibration and cost optimization, demonstrating strong predictive accuracy for COD and BOD removal. WEST excels in real-time control and uncertainty analysis, making it ideal for dynamic plant optimization. GPS-X is particularly effective for dynamic parameter estimation, ensuring precise biogas yield predictions. The table below summarizes the strengths and validation metrics of each software tool, aiding in the selection of the most appropriate tool for different modeling needs.

Table 2. 2:Tool comparison

Software	Strength	Validation Metrics	Reference
BioWin	BNR calibration, cost optimization	$R^2 > 0.95$ for COD/BOD	(Xu et al., 2020)
West	Real-time control, uncertainty analysis	Confidence intervals for μH	(Vangheluwe et al., n.d.)
GPS-X	Dynamic parameter estimation	$\pm 3\%$ biogas yield accuracy	(Hydromantis, 2023)

2.5- MANTIS2: An Advanced Whole-Plant Wastewater Treatment Model

MANTIS2 represents a state-of-the-art wastewater treatment model that Hydromantis created for implementation on GPS-X simulation software. MANTIS2 represents a complete modeling system that enables comprehensive simulation of biological along with chemical and physical wastewater processes against the rising complexity of contemporary treatment facilities. MANTIS2 utilizes advanced modeling methodologies that enable officials and engineering teams to maximize plant functions while maximizing resource utilization and maintaining environmental regulations (Hydromantis, 2023).

MANTIS2 boasts a critical strength from its complete integration of processes that permits simulation of multiple wastewater treatment procedures. The model successfully represents biological sequences that involve BOD carbonaceous oxygen demand degradation with nitrogen and phosphorus elimination and side-stream deammonification through anaerobic ammonium oxidation process (ANAMMOX) according to (Beres, 2015). Through MANTIS2 users can recover resources by creating biogas through anaerobic digestion while removing selenium oxyanions during wastewater treatment operations focused on mining and textile industries (Abou-Elela et al., 2016; Beres, 2015)). Through chemical reaction simulation the model includes vital precipitation reactions of calcium carbonate (CaCO_3) as well as iron phosphate (FePO_4) and struvite formation to support phosphorus recovery and prevent scaling in treatment facilities (Hydromantis, 2023)

The modeling structure in MANTIS2 implements 48 state variables which follow 21 soluble substances and 27 particulate compounds to track essential wastewater components including organic matter and nutrients and microbial biomass. MANTIS2 adopts a model structure that unifies 56 various reaction sequences between biological growth and chemical equilibria in addition to gas-liquid exchanges (such as CO_2 and CH_4 emissions) (Beres, 2015). MANTIS2 combines features of conventional modeling with a plant-wide model structure by integrating activated sludge treatment and both anaerobic digestion and tertiary filtration processes. The comprehensive modeling approach of MANTIS2 generates a precise simulation output of treatment plants across multiple operational environments so it becomes extremely useful for both real-time optimization and simulation functions (GPS-X Technical Reference - v8.0, 2019)

One crucial capability of MANTIS2 allows dynamic calibration and validation procedures. The model demonstrates excellent predictive power in determining chemical oxygen demand (COD) and BOD_5 and total suspended solids (TSS). It shows results falling within the range of

experimental measurements by 5–10%. MANTIS2 demonstrated effective simulation of hybrid anaerobic-aerobic treatment system effluent characteristics at different hydraulic and organic loading rates through its application in laboratory studies (S. I. Abou-Elela, 2016; Moradvandi, 2024). Scenario testing with MANTIS2 lets users modify hydraulic loading rates (HLR) organic loading rates (OLR) and media surface area of attached-growth systems to predict system performance across different operational conditions (Pereira, 2014)

Tests conducted with MANTIS2 in multiple applications show its wide applicability for municipal wastewater facilities and industrial plants. Municipal wastewater treatment plant (WWTP) in Pennsylvania utilized MANTIS2 capabilities for high-purity oxygen activated sludge system dynamic calibration to meet official discharge requirements (Hydromantis, 2023). The model demonstrated successful performance through simulating selenium extraction applications from coal-mining drainage and textile wastewater which minimized environmental risks from heavy metal pollutants according to Beres (2015). MANTIS2 proved useful for validating pilot-scale UASB (Upflow Anaerobic Sludge Blanket) alongside BAF (Biological Aerated Filter) system operations at different flow rates between 7 and 28 m³/day for decentralized treatment applications (Abou-Elela et al., 2016).

MANTIS2 presents various benefits when compared to conventional wastewater methods. Through integration of three well-established models - ASM2d (Activated Sludge Model No. 2d) and UCTADM1 (University of Cape Town Anaerobic Digestion Model No. 1) and ANAMMOX - users can simulate aerobic and anaerobic treatment systems under one unified platform (Beres, 2015; Pereira, 2014). MANTIS2 includes sustainability tools with capabilities to measure carbon footprint (Scopes 1–3 emissions) and evaluate biogas production potential which reduces energy needs (Beres, 2015). Through MANTIS2 users can evaluate complex treatment setups involving membrane bioreactors together with sidestream phosphorus removal methods and chemical technologies for optimal nutrient performance (Ali MORADVANDI, 2024; Pereira, 2014)

MANTIS2 offers several advantageous capabilities but users face obstacles when using this model. The model requires skilled professionals to perform the calibration of 48 state variables while requiring advanced expertise to analyze simulation outcomes due to its complexity (Beres, 2015; Ali MORADVANDI, 2024). The computational requirements are significant since high-resolution simulations need powerful hardware to maintain operational efficiency (Beres, 2015).

Chapter 3. Methodology

3.1- Study Area

The study focuses on the El Kerma Wastewater Treatment Plant (WWTP), located in the commune of El Karma, south of the Wilaya of Oran, Algeria (latitude: 35.6983° N, longitude: -0.6346° E). As the largest sewage treatment facility in Algeria this plant serves to process domestic wastewater from the Wilaya of Oran population that amounts to 1,526,000 inhabitants.

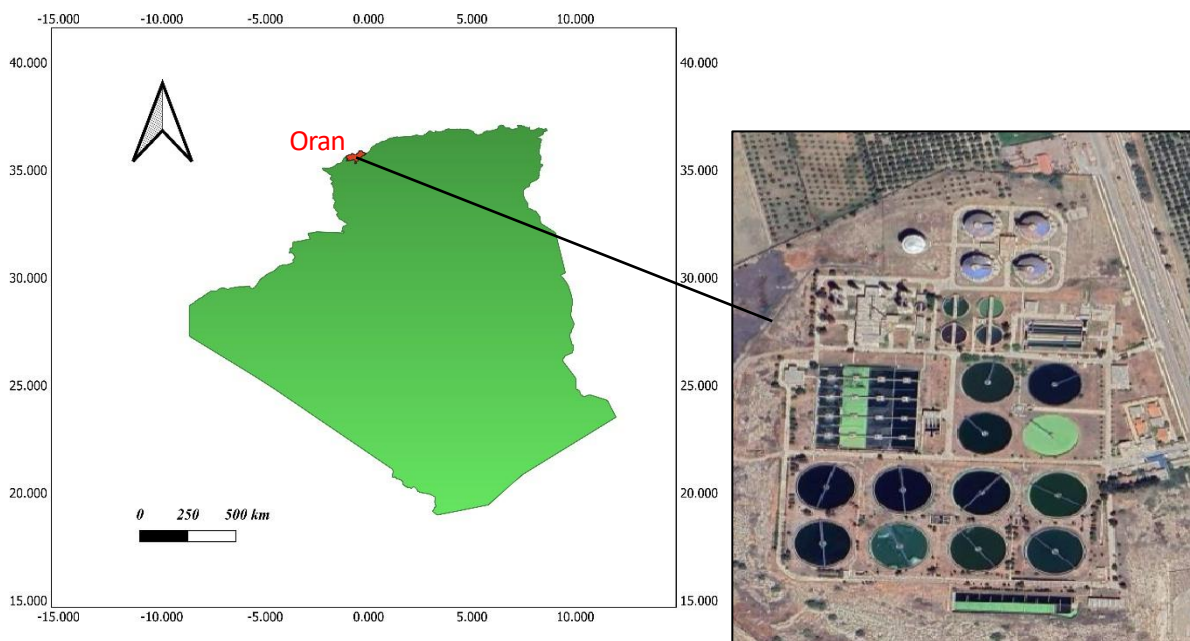


Figure 3. 1: Situation of Oran wastewater treatment plant

The treated wastewater outlet releases effluent into the Great Sebkhia of Oran where it impacts an essential saline wetland that exists under threat from pollution sources. The habitat of different wildlife species together with environmental protection benefits are supported by this wetland system. The area deals with multiple environmental problems which include increasing salt levels in addition to eutrophication and unprocessed waste water pollution

Constructed over 30 months by WABAC from March 2006 to May 2009, the El Kerma WWTP has been operational since 2009 and was transferred to SEOR for management in May 2011. It integrates advanced technologies to meet growing demands for wastewater treatment and environmental protection.

Table 3. 1: Characteristic of WWTP el karma

Population Equivalent	1,526,000 inhabitants (270 100m³)
BOD5 at the entrance to the STEP	91 560 kg/d
COD at the entrance to the STEP	228 910 kg/d
Mass load of MES at the entrance to the STEP	96 860 kg/d
Average daily flow	270 096m³

3.2- Description of El Kerma WWTP

The WWTP operates in a semi-arid zone which receives less than 500mm of annual rainfall (between 300 to 400) mainly concentrated in winter season so effective wastewater treatment combined with reuse becomes essential for dealing with water shortage. The research optimizes plant management processes to establish operational standards that similar facilities in Algeria and arid areas across the world can utilize.

The El Kerma Wastewater Treatment Plant (WWTP), located south of Oran, Algeria, is the largest facility of its kind in the country. It is designed to process 270,100 m³/day of domestic wastewater, serving a population equivalent of 1.53 million. This facility plays a critical role in safeguarding the environment and addressing water scarcity in the region.



Figure 3.2: El kerma Wastewater treatment Plant

3.2-1. Station Power

The city of Oran is equipped with a sewage system connected to a pumping station (small lake) capable of handling 4 m³/s through a discharge line. This station pumps wastewater to the El Kerma WWTP, after which the water is transported by a gravity channel to the treatment plant. The treatment chain is divided into two main lines: a water line and a sludge line.

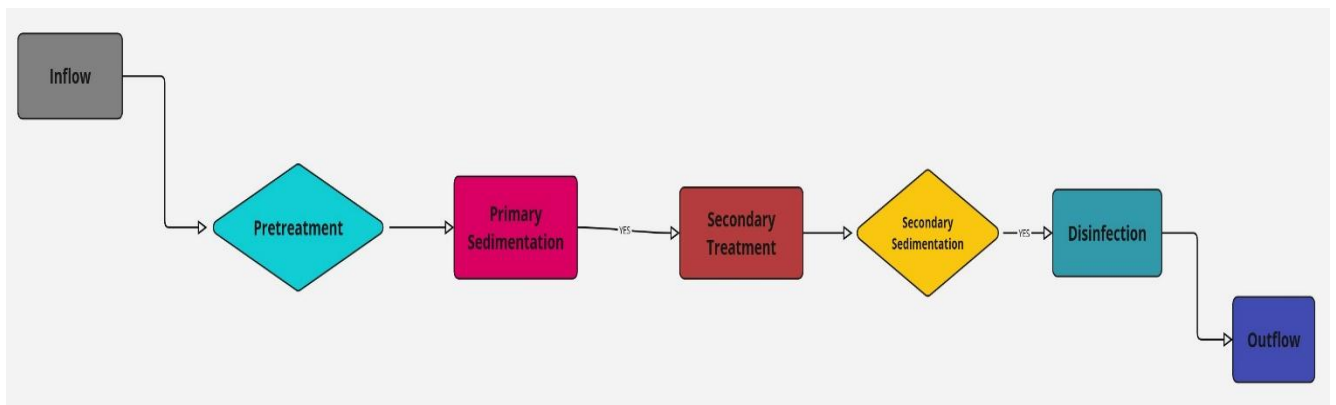


Figure 3.3: EL Kerma WWTP process

3.2-2. Pretreatment

The pretreatment stage involves initial processes to prepare the wastewater for subsequent treatment. Screening, using two units with four channels each, is designed to remove large debris. Fine screens with a 10 mm bar spacing are inclined at 75° to maximize passage area. The screens are cleaned mechanically with rigid rakes to maintain efficiency. Key features include mechanical isolation for maintenance, the ability to handle peak flows during heavy rains with redundancy (three operational screens while one remains on standby), and proper disposal of washed and bagged refuse.

Following the screening, sand and oil removal is conducted in four sand-blasting channels. Overfill blades regulate upstream water levels, ensuring consistent flow distribution. The sand removal zone is 4.8 m wide, and the oil removal zone is 2 m wide. Settled sands are extracted via an air-lift system and transported to a central collection pit. Each de-sanding unit measures 50 m in length and is constructed from reinforced concrete. This stage achieves approximately 95% efficiency in removing particles larger than 150 micrometers.

3.2-3. Primary Sedimentation

The primary sedimentation phase includes four sedimentation tanks equipped with scraper bridges. These tanks operate at a hydraulic loading rate of 1.5–2.5 m/h. Each tank has a diameter of 48.9 m and an average depth of 2.56 m. The removal efficiencies in this stage are approximately 33% for BOD₅, 29% for COD, and 63% for suspended solids. Effluent from the sedimentation tanks is directed to common pits for further processing.



Figure 3. 4: The primary clarifier

3.2-4. Secondary (biological) treatment

The secondary treatment process utilizes a medium-load activated sludge system, forming the core of the biological treatment stage. This system effectively reduces nitrogen pollution, particularly during summer, through nitrification facilitated by bacterial metabolism. The process occurs in four aeration basins constructed from reinforced concrete, each with a volume of 10,584 m³. Surface aerators, equipped with variable speed controls and adjustable immersion depths via overflow weirs, ensure efficient oxygen supply and homogeneous mixing of sludge to prevent deposition of suspended matter and erosion of structural surfaces. Each basin measures 89.80 m in length, 22.45 m in width, and 5.25 m in water depth and includes a degassing compartment for foam removal, which is transferred to sludge dewatering facilities. A concrete supply pipe directs influent to a distribution channel upstream of the basins. In case one basin is out of service, flow can be redistributed among the remaining three basins. Additionally, two pumps are available for basin drainage when required, ensuring operational flexibility and reliability.



Figure 3. 5: the Aeration tank (Activated sludge)

3.2-5. Secondary Sedimentation

The secondary sedimentation process ensures the separation of biomass from treated water and provides initial thickening of settled biological sludge. After biological treatment, the mixed liquor flows from the aeration tanks into the center of eight secondary clarifiers via a distribution structure. Each clarifier, with a diameter of 56.5 m and a height of 3.4 m (two-thirds of the diameter), operates similarly to primary clarifiers, utilizing a scraper that completes one rotation every 35 minutes. Suspended solids settle at the bottom of the basins, forming active secondary sludge. This sludge is either returned to the aeration tanks as return activated sludge or directed to sludge treatment facilities for further processing. Clarified water overflows at the periphery into double recovery gutters and is discharged by gravity to the treatment plant outlet, ensuring efficient and reliable separation.

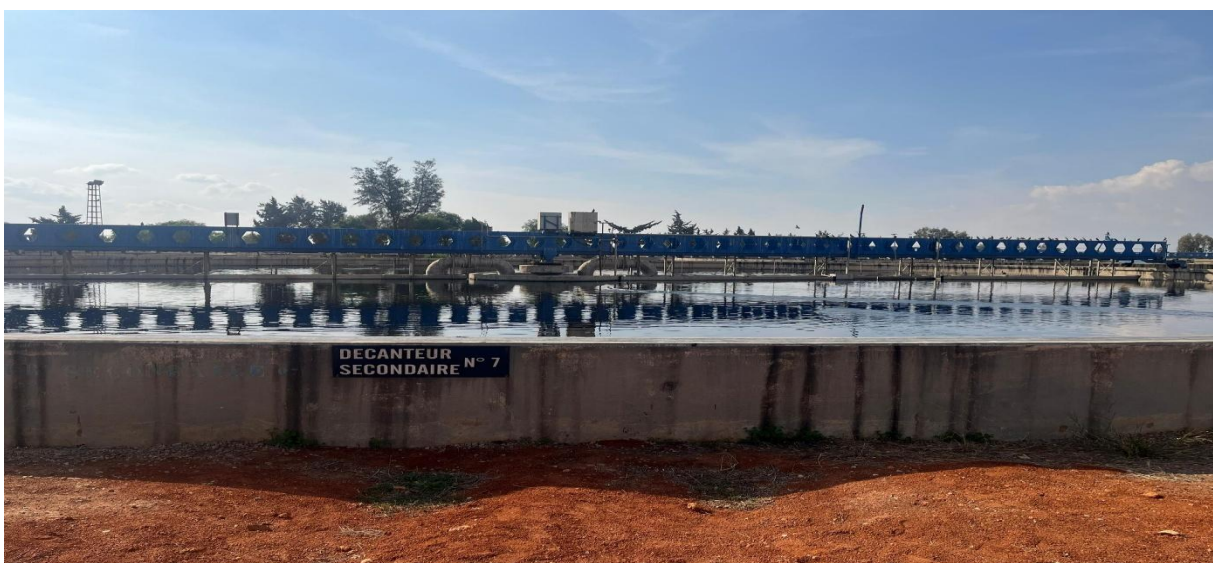


Figure 3. 6: The secondary clarifier

3.2-6. Disinfection

The disinfection stage aims to enhance the bacteriological quality of treated effluent to protect the receiving water body, the Great Sebkhia of Oran. After secondary sedimentation, the effluent flows into two contact basins where chlorine is injected as the final treatment. The basins, designed with baffles to optimize mixing and contact time, each measure 100 m in length, 10 m in width, and 4.05 m in water depth, providing a total useful volume of 7,700 m³. Based on a 30-minute retention time at peak flow during rain, the system ensures effective disinfection before the treated water is discharged into the Great Sebkhia, safeguarding the surrounding environment.



Figure 3. 7: Disinfection Basin

3.2-7. Sludge Recirculation and Treatment

The sludge recirculation and excess sludge management processes are essential to maintaining a stable mixed liquor suspended solids (MES) concentration in the aeration basin, ensuring effective biological treatment. Settled sludge is pumped to two dedicated pits for recirculation and excess sludge. A portion of the sludge extracted from the secondary decanter is recirculated back to the inlet of the aeration basin, referred to as return or recirculation sludge. Four Archimedes screw pumps are used for the return of sludge, which is then gravitated to activated sludge ponds. These pumps are driven by motors housed in protective boxes, and a bearing beam is installed above the motors for ease of assembly and disassembly. A wall valve on the inlet line isolates the pumping station when necessary.

Excess sludge is regularly removed to maintain a stable MES concentration, as biomass increases with the pollution treated. The volume of excess sludge directed to thickening is measured using an electromagnetic flowmeter, with real-time data transmitted to the station

management system for monitoring and recording purposes. Three submersible pumps are installed in the return sludge pumping station, with two pumps in operation and one as a backup.

The sludge treatment process includes the management of primary and excess activated sludge. Primary sludge, collected several times a day from sedimentation tanks, undergoes thickening, reaching a solids concentration of 3% to 5%. This thickened sludge is homogenized before being directed to digestion. Excess activated sludge is thickened using polymer flocculants and transported to homogenization tanks. Both types of sludge are then mixed in the homogenization basin to create a homogeneous slurry. The sludge is then digested at a temperature of 37°C, releasing gases that are collected and stored or used for digester boilers, with excess gas being burned. After digestion, the sludge undergoes final thickening and is stored in silos before being mixed with lime for stabilization and final disposal.



Figure 3. 8: anaerobic digester

3.3- Monitored Parameters and Analytical Methods

The laboratory at EL KERMA- WWTP conducted analyses to derive the physicochemical parameters. A total of 1011 samples. These samples were collected for both influent and effluent waters, aligning with daily monitoring data, to capture the temporal variations in their qualities. Samples were collected from 10 cm below the surface using a Silicon/Teflon water pump. Twelve water quality parameters were measured: temperature, potential of hydrogen (PH), TSS, DO, biochemical oxygen demand (BOD5), COD, NH4-N, Nitrates (NO3-N), Nitrites (NO2-

N), Phosphate (PO₄-P), turbidity, and chloride. Temperature and pH. Standard methods for water and wastewater analysis were employed for all the applied analytical procedures

3.4- Descriptive Data Analysis of Monitored Parameters

The descriptive statistics for the El Kerma WWTP influent and effluent parameters provide an in-depth understanding of the load variability and the efficiency of the treatment process.

Table 3. 2: Influent and Effluent characteristics

Parameter	Median	Mean	STD	Min	Max
Influent Characterization					
TSS mg/l	247.5	264	130.05	25	1656
BOD ₅ mg/l	270	268	95.94	15	888
COD mg/l	510.34	515	179.63	82	1584
Flow m ³ /j	68818	65175	25890.5	157	145173
PH	7.6	7.6	0.31	4.5	9.6
Temperature	21.2	20.7	5.26	5	31.4
Effluent characterization					
TSS mg/l	13	21	28.45	2	385
BOD ₅ mg/l	12	23.06275	37.19	1	280
COD mg/l	54.085	72.14468	73.65	2	660
PH	7.73	7.715095	0.35	6.1	8.9
Temperature	19.15	19.32595	5.91	4.7	31.3

For the influent. Total Suspended Solids (TSS) have a median value of 247.5 mg/l with a mean of 264 mg/l. and a standard deviation (STD) of 130 mg/l. This range, from as low as 25 mg/l to a maximum of 1656 mg/l, indicates significant variability in the incoming solid loads. which could be influenced by factors such as diurnal flow patterns or episodic events (e.g., heavy rainfall). Similarly. Biochemical Oxygen Demand (BOD₅) exhibits a median of 270 mg/l and a mean close to 268 mg/l. with a standard deviation of approximately 96 mg/l and a range of 15 to 888 mg/l.

These figures confirm a consistently high organic load in the influent. which is critical for understanding the stress imposed on the biological treatment processes. Moreover. Chemical Oxygen Demand (COD) values median around 510 mg/l and mean about 515 mg/l. with a STD of 180 mg/l and a range from 82 to 1584 mg/l. further underscore the substantial organic burden that the plant must treat. Additionally. the influent flow rates. with a median of 68.818 m³/day and a high standard deviation of about 25.890 m³/day. reveal considerable variability in daily

volumes, which can affect hydraulic retention times and overall process performance. The pH and temperature data, with median values of 7.6 and 21.2°C respectively, indicate a relatively neutral and moderately warm influent environment, conducive to efficient microbial activity.

Turning to the effluent, the treatment process demonstrates significant pollutant removal. The median TSS drops dramatically to 13 mg/l (mean 21 mg/l), reflecting a high removal efficiency that is essential for meeting regulatory discharge limits. BOD₅ values are similarly reduced, with a median of 12 mg/l (mean ~23 mg/l), indicating that the biological processes are effectively degrading the organic matter. COD values in the effluent have a median of approximately 54 mg/l (mean around 72 mg/l), suggesting an impressive reduction in organic content compared to the influent. The pH in the effluent remains stable at around 7.73, and the temperature is slightly lower (median 19.15°C) than the influent, which may be attributed to cooling effects within the treatment process.

Overall, these statistics reveal that the El Kerma WWTP is achieving high removal efficiencies. TSS and BOD₅ are reduced by over 90% and COD by nearly 90% when comparing median values, despite the inherent variability in influent quality and flow. However, the broad ranges and high standard deviations in certain parameters highlight the dynamic nature of the wastewater entering the plant, emphasizing the importance of continuous monitoring and adaptive control strategies to maintain optimal treatment performance.

3.5- Application of Mantis2 model in WWTP el kerma

The Mantis2 model, integrated within the GPS-X simulation platform, offers a comprehensive biochemical framework for modeling wastewater treatment processes. This model facilitates the analysis of various treatment configurations, including biological removal of Biochemical Oxygen Demand (BOD), nitrogen, and phosphorus, as well as resource recovery processes like biogas production and struvite precipitation. By encompassing both mainstream and side stream treatment processes, Mantis2 enables a holistic evaluation of wastewater treatment plant (WWTP) performance.

The selection of Mantis2 is further justified by its ability to simulate complex biochemical interactions within WWTPs. Its detailed representation of microbial processes and nutrient cycles aligns with the intricate dynamics observed in real-world treatment facilities. This alignment enhances the accuracy of simulations and supports the development of effective operational strategies.

3.6- Graphical Construction of WWTP Layout

Influent is the raw wastewater entering the treatment plant, carrying a diverse mix of organic matter, suspended solids, nutrients (like nitrogen and phosphorus), and various pollutants. This mixture often exhibits significant fluctuations in flow rate and composition, making it critical to accurately characterize the influent as it sets the foundation for effective treatment. Once the influent is introduced into the system, it flows directly into the completely mixed tank—a reactor designed to ensure uniform blending of the wastewater. In this tank, mechanical or hydraulic mixing prevents stratification, ensuring that all contaminants are evenly distributed; this uniformity is essential for optimizing biochemical reactions and ensuring that subsequent treatment processes receive a consistent feed. The homogenized wastewater then moves seamlessly into the secondary clarifier, where gravitational forces allow the suspended solids to settle out from the liquid. In the clarifier, design parameters such as hydraulic retention time and surface loading rate are optimized to promote efficient settling, so that the heavier sludge collects at the bottom while the clearer water rises to the surface. Finally, the treated water, now referred to as the effluent, is discharged from the system or directed toward further polishing steps if required to meet strict regulatory standards. This interconnected process, from influent to completely mixed tank to secondary clarifier and finally to effluent, ensures that the treatment system operates efficiently, with each unit supporting the next to achieve a high level of water quality and process stability.

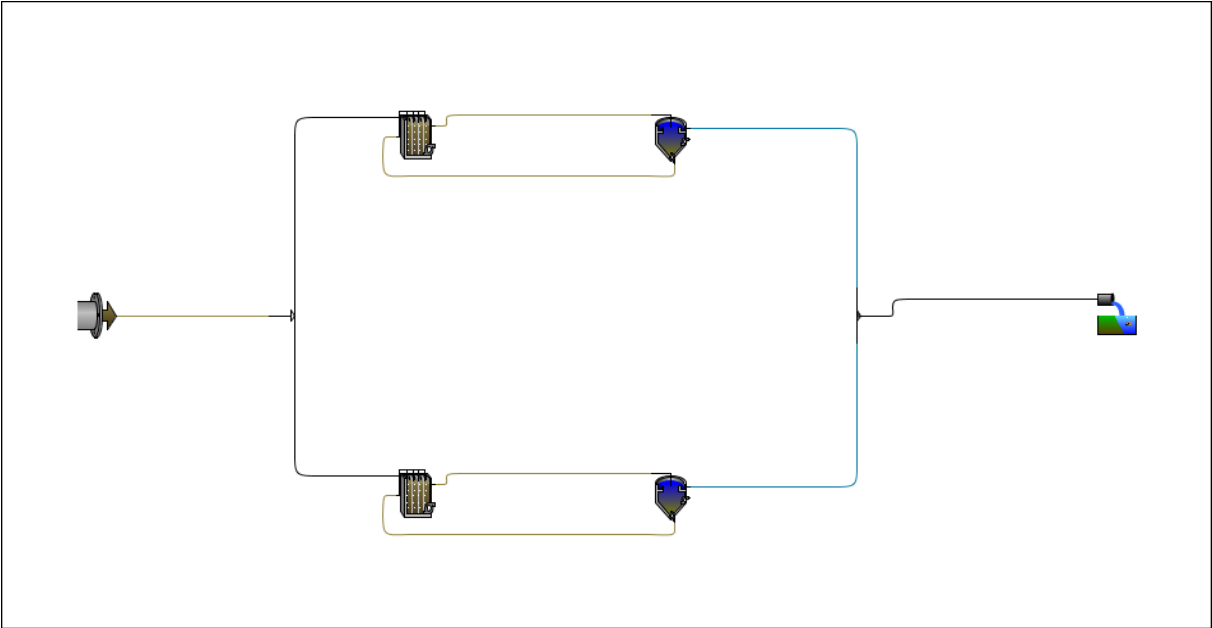


Figure 3. 9: The Layout

The graphical construction capabilities of GPS-X enable the visualization of process flows and interactions between different treatment units. This visual representation aids in identifying potential bottlenecks, optimizing process sequences, and enhancing overall plant performance.

3.7- Selection of the library

Before beginning the assessment of individual treatment units, it is essential to choose a modeling library that best represents the intricate processes within the wastewater treatment plant. In the GPS-X environment, libraries serve as repositories of predefined components and state variables that are critical for accurate simulation of biological and chemical phenomena. This study focuses on the advanced capabilities of the Mantis2 model. Therefore, the Mantis2lib library was selected. This library is specifically designed to capture the detailed biochemical interactions and nutrient removal processes that characterize modern wastewater treatment, making it ideally suited for simulating the dynamic behavior of the Oran WWTP.

3.8- Selection of the Model for Each Process Unit

For each process unit within the WWTP, GPS-X offers a range of models designed to accurately capture the physical and biochemical phenomena occurring in that unit. In our study, the influent wastewater characterization is critical, as the quality of the incoming load significantly influences the overall plant behavior. To this end, the CODstat model was chosen for influent characterization. This model estimates the various fractions of COD such as readily biodegradable substrate (SS), slowly biodegradable substrate (XS), soluble inert matter (SI), and particulate inert matter (XI) based on the total COD concentration, using default percentages provided by the software. Users can modify these values to better reflect local conditions and improve model accuracy.

For the clarifier, where the key process is the separation of biomass from treated water, the simple1d model was selected. This model is designed to simulate settling behavior and sludge thickening in a straightforward yet robust manner, ensuring that the critical separation dynamics are accurately captured. Finally, the overall simulation is underpinned by the Mantis2LIB library, which integrates advanced biochemical kinetics and stoichiometry. This library supports the enhanced representation of microbial growth, nutrient transformations, and resource recovery processes, thereby enabling a comprehensive and realistic simulation of the activated sludge process throughout the WWTP.

3.9- Correction of Data

The calibration of the wastewater treatment plant (WWTP) model required an initial correction of the input data to ensure consistency and reliability in the simulation results. The raw dataset exhibited fluctuations and potential anomalies, which could arise due to measurement errors, operational disturbances, or extreme variations in influent and effluent conditions. To address these issues, statistical smoothing techniques were applied using **R software** to enhance data quality before model calibration.

Five different methods were tested to refine the dataset, each with unique advantages in handling noise and fluctuations. The selection of the final smoothing technique was determined based on the minimization of Root Mean Square Error (RMSE), ensuring that the processed data maintained its key characteristics while reducing unnecessary variability.

a. Moving Average Filter

The use of moving average filters in wastewater treatment plant (WWTP) modeling serves primarily to smooth fluctuations in process data, reducing noise and variability, and thereby improving model accuracy and stability. Given the inherent variability in influent quality and flow rates due to factors such as rainfall infiltration, industrial discharges, and operational inconsistencies, data preprocessing is crucial for obtaining reliable simulations. Moving average filters help stabilize input datasets such as influent flow rates, chemical oxygen demand (COD), biochemical oxygen demand (BOD), pH, and temperature, ensuring consistency for use in Activated Sludge Models (ASM) and WWTP simulation tools like GPS-X, BioWin, WEST, and SIMBA (Duarte et al., 2024; Nesmerak & Blazkova, 2014)

A key advantage of moving average filters is their ability to improve model accuracy by minimizing the impact of outliers and measurement errors. Additionally, they contribute to enhanced model stability, preventing abrupt variations in input data that could otherwise lead to unstable simulation outputs. The filtering process also enables simplified trend analysis, making it easier to detect long-term operational patterns and identify anomalies in effluent quality. (Wang et al., 2021) In a study on industrial wastewater treatment, researchers successfully applied a moving average filter to influent COD data, allowing for improved analysis of microbial activity and better prediction of effluent quality. (Golubović, 2016)

Despite these advantages, moving average filters have limitations, particularly in handling

datasets with significant short-term fluctuations. The filter tends to smooth out rapid variations, potentially masking critical process disturbances. Alternative methods such as exponential weighted moving averages (EWMA) provide greater sensitivity to recent data, making them more effective for real-time monitoring (Alex, 2024). Similarly, advanced machine learning models like ARIMA and Support Vector Machines (SVM) can capture complex temporal dependencies, offering improved forecasting capabilities for influent characteristics and effluent quality predictions (Chaoui et al., 2023)

b. Savitzky-Golay (SG) Filter

The Savitzky-Golay (SG) filter is a valuable tool for smoothing noisy data in wastewater treatment plant (WWTP) modeling, helping improve the accuracy and stability of predictive models. Its primary function is to reduce noise in key process data, such as influent flow rates, chemical composition, and water quality parameters (e.g., COD, BOD, NH₃-N). By smoothing fluctuations while preserving the shape of the data, the SG filter enhances trend identification, model calibration, and operational decision-making.

Compared to traditional smoothing techniques like moving averages or Kalman filters, the SG filter is more effective in maintaining data features, making it particularly useful for datasets with significant variability. It has also been applied in wastewater surveillance for SARS-CoV-2, where it was effective in filtering viral signals (Arabzadeh et al., 2021). Furthermore, integrating the SG filter with machine learning models, such as Extreme Learning Machine (ELM) or Partial Least Squares Regression (PLSR), can further improve predictive accuracy (Xing et al., 2019).

c. Exponential Smoothing

The exponential smoothing method is a widely used technique in time series forecasting, allowing for the prediction of future values based on historical data trends. Although its direct application in wastewater treatment plant (WWTP) modeling is not extensively documented, it holds significant potential for forecasting influent parameters, which are crucial for optimizing treatment processes. Influent characteristics such as flow rates, chemical composition, COD, BOD, and NH₃-N can vary significantly over time due to environmental and operational factors. By applying exponential smoothing, WWTPs can generate more accurate short-term forecasts, enabling proactive adjustments to treatment processes, chemical dosing, and energy

consumption, ultimately improving effluent quality and operational efficiency.(Simplilearn, 2025)

At its core, exponential smoothing assigns exponentially decreasing weights to past observations, prioritizing recent data while gradually reducing the influence of older values. This characteristic makes it particularly effective for short-term forecasting, as it can quickly adapt to gradual changes in trends and patterns(Rob J Hyndman and George Athanasopoulos, 2018);

One of the key advantages of exponential smoothing is its ability to give greater weight to more recent data points, making it well-suited for capturing recent trends in influent fluctuations. This characteristic sets it apart from other traditional smoothing methods such as moving averages and the Savitzky-Golay filter, which treat all data points more equally or focus on local polynomial approximations, respectively. Additionally, while machine learning models like ARIMA, LSTM, and CNN-LSTM can provide more sophisticated forecasting capabilities, they typically require large datasets, extensive training, and high computational resources. Exponential smoothing, on the other hand, offers a simpler and more computationally efficient alternative for WWTP applications, particularly when rapid, real-time predictions are required.

Although there is limited research on the direct application of exponential smoothing in WWTP modeling, similar approaches have been successfully used in water demand forecasting. For instance, studies have demonstrated its effectiveness in predicting daily variations in water consumption, which can be adapted for influent forecasting in WWTPs (Cieżak & Kutylowska, 2023).By leveraging its ability to smooth fluctuations and detect trends, WWTP operators can make more informed decisions about process adjustments, reducing operational costs and improving compliance with environmental regulations.

d. LOWESS (Locally Weighted Scatterplot Smoothing)

LOWESS (Locally Weighted Scatterplot Smoothing) is a non-parametric regression technique that can enhance data analysis and predictive modeling in wastewater treatment plants (WWTPs). Although its direct application in WWTPs is not extensively documented, its ability to smooth noisy data and identify patterns presents significant potential benefits in this field. In WWTPs, influent and effluent parameters such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), and nutrient concentrations often exhibit fluctuations due to seasonal variations, industrial discharges, and demographic changes(Ngila et al., 2020). By

filtering short-term variations while preserving long-term trends, LOWESS can improve data reliability, which is crucial for accurate model calibration and validation (Bodaka et al., 2023)

Beyond data smoothing, LOWESS can facilitate pattern recognition in wastewater datasets, helping operators detect hidden trends and assess the effectiveness of treatment processes (Simon Judd, 2025). This capability is particularly valuable for optimizing operational strategies, such as adjusting chemical dosing, aeration, and sludge management to enhance treatment efficiency and effluent quality (Behrendt, 2025). Compared to other smoothing techniques, LOWESS offers greater flexibility in handling non-linear trends and non-uniformly spaced data, making it preferable to exponential smoothing, which is better suited for gradual trends, or the Savitzky-Golay filter, which struggles with irregularly spaced datasets (An et al., 2024). However, despite its advantages, LOWESS has higher computational demands, which may limit its real-time applicability unless optimized for efficiency (Silva, 2023)

Although specific case studies on LOWESS in WWTP modeling are limited, its successful application in environmental monitoring highlights its potential in wastewater analysis. For instance, LOWESS has been effectively used to smooth viral signal fluctuations in wastewater surveillance for SARS-CoV-2, demonstrating its ability to handle irregular datasets and extract meaningful trends (Rauch et al., 2020). By leveraging this technique, wastewater treatment facilities could improve data-driven decision-making, enhance process optimization, and ultimately contribute to more sustainable and efficient wastewater management. However, further research is needed to explore its full potential and address computational challenges associated with real-time implementation.

e. Spline Interpolation

Spline interpolation is an essential mathematical technique used to generate smooth curves through a set of data points, offering significant advantages in wastewater treatment plant (WWTP) modeling. One key application of spline interpolation in WWTPs is **data augmentation**, where it helps enrich datasets by generating synthetic values between observed data points. This is particularly useful in time-series predictions, where missing or sparse data can affect the accuracy of machine learning models used for energy consumption forecasting and process optimization (Harrou et al., 2023). By applying cubic spline interpolation, WWTP operators can improve the resolution of their datasets, leading to more accurate modeling of influent flow rates, energy consumption, and pollutant loads.

Another critical application of spline interpolation in WWTPs is in optimizing water distribution calculations. Studies have shown that cubic spline interpolation provides a more accurate representation of flow distribution compared to other interpolation methods, such as Lagrange interpolation or polynomial fitting. This is particularly relevant in cases where flow rates or pollutant concentrations vary spatially or temporally, such as in aeration tanks or sedimentation basins. Research in irrigation systems has demonstrated that cubic spline interpolation can enhance the accuracy of water distribution modeling, achieving deviations of less than 10% from measured values (Ge et al., 2018). These findings suggest that similar benefits could be realized in WWTP applications, where accurate flow distribution modeling is essential for optimizing energy efficiency and chemical dosing.

In addition to data smoothing and augmentation, spline interpolation has been applied in environmental modeling to reconstruct missing data in climate-related studies. For instance, research on rainfall modeling demonstrated that cubic splines effectively interpolate missing precipitation data, providing insights into long-term climate trends and their impact on agricultural production (Yasmin et al., 2024). This capability can be directly applied to WWTPs, where variations in influent composition due to seasonal changes or industrial discharges need to be accurately modeled to maintain regulatory compliance and operational efficiency.

These techniques ensured that extreme values did not disproportionately impact the calibration process. The selection of the final smoothing method was based on RMSE values

3.10- Model Calibration

This study focuses on analyzing the dynamics of Chemical Oxygen Demand (COD) effluent quality as a key indicator of wastewater treatment plant performance. The MANTIS framework was employed to simulate and optimize the treatment process, considering its capability to represent complex biochemical interactions in activated sludge systems. Previous research highlights the critical role of COD in assessing plant efficiency, reinforcing the importance of accurate modeling in this study.

A sensitivity analysis approach guided the application of the MANTIS model, addressing longstanding challenges in process control and system identification within wastewater treatment research. One of the key influencing factors in biological treatment processes is temperature, as it directly impacts microbial activity, biochemical reaction rates, and overall

treatment efficiency. Within the MANTIS framework, temperature variations affect reaction kinetics, biomass growth, and the removal efficiency of organic matter, including COD. Therefore, temperature consistency was analyzed over consecutive months to ensure accurate model calibration and validation.

a) Kinetic, Stoichiometric, and Operational Parameter Adjustments

The calibration of the MANTIS model involves adjusting both biological and operational parameters to enhance the accuracy of predictions, particularly for COD effluent under dynamic conditions. The process includes refining kinetic and stoichiometric parameters such as the maximum specific growth rate of heterotrophic biomass ($\mu_{\max,H}$), which influences microbial growth and substrate utilization (Sabri et al., 2017). Additionally, the heterotrophic yield coefficient (Y_H) determines the efficiency of organic matter conversion into biomass, directly affecting the degradation process (Faris et al., 2022). Another key factor is the decay coefficient of heterotrophic biomass (b_H), which reflects the rate at which microbial populations decline over time, influencing the system's ability to maintain stability (Hvala et al., 2017). These parameters are first established through steady-state calibration and later refined dynamically to improve model performance.

Operational parameters such as underflow rate and pumped flow play crucial roles in the calibration and operation of wastewater treatment plants, particularly those utilizing activated sludge processes. The underflow rate controls the amount of sludge returned to the biological reactor from the secondary clarifier, directly influencing sludge retention time (SRT). Adjusting the underflow rate is essential for maintaining optimal microbial conditions, as SRT determines the balance of microorganisms, their growth rates, and their capacity to remove pollutants (Lilley & Pybus, 1997; Von Sperling & Chernicharo, 2005). A well-regulated SRT ensures that the microbial community remains balanced and effective in degrading organic matter and nutrients. If SRT is too short, beneficial microorganisms may be washed out, reducing treatment efficiency. Conversely, excessively long SRTs can lead to the overgrowth of filamentous bacteria, negatively affecting sludge settleability (Von Sperling & Chernicharo, 2005; Weik, 2000)

Similarly, pumped flow refers to the rate at which sludge is recycled back into the biological reactor, a critical factor in maintaining a high concentration of active biomass for efficient organic matter and nutrient removal (Lilley & Pybus, 1997; Von Sperling & Chernicharo, 2005)

Effective sludge recycling helps sustain microbial activity, enhancing pollutant degradation and ensuring stable treatment performance. Moreover, regulating pumped flow plays a key role in effluent quality control, as it influences the concentration of suspended solids, biochemical oxygen demand (BOD), and nutrients such as nitrogen and phosphorus in the final effluent (Roche et al., 2022; Simon-Várhelyi et al., 2020). By carefully adjusting these operational parameters, wastewater treatment plants can optimize sludge retention time, maintain microbial stability, and enhance overall plant performance, ensuring that effluent quality meets regulatory standards.

Proper calibration of these parameters allows for a more accurate representation of settling behavior and sludge management, balancing sludge retention and effluent discharge. The calibration process begins with steady-state calibration, where kinetic and stoichiometric parameters are set using stable data. This is followed by *dynamic calibration*, in which parameters like ($\mu_{\max, H}$, Y_H and b_H) are fine-tuned to reflect dynamic conditions more accurately. Finally, operational parameters such as underflow rate and pumped flow are adjusted to optimize sludge management and maintain effluent quality.

Table 3. 3: kinetic. stoichiometric and operational parameter

Parameters	Symbol	Unit	Default Value	Calibrated
Stoichiometric Parameters				
Yield for Autotrophic	Y_A	g COD/g COD	0.66	0.4
volatile suspended solids/total suspended	VSS/TSS	g VSS/g TSS	0.70	0.83
Kinetic Parameters				
Maximum specific growth rate for heterotrophic biomass	$\mu_{\max H}$	d^{-1}	3.2	4.00
Heterotrophic decay Coefficient	b_H	d^{-1}	0.62	1.22
Operational parameter for the secondair clarifier				
Underflow rate	RAS	m^3/d	6000	4000
Pumped flow	WAS	m^3/d	104	445

b) Sensitivity Analysis Optimizer (dynamic simulation)

The sensitivity analysis optimizer in GPS-X is a powerful tool designed to optimize model parameters by minimizing a user-defined objective function. It employs the Nelder-Mead simplex algorithm, a widely used direct search method for unconstrained optimization problems. This algorithm iteratively generates a sequence of simplices geometric figures with $n+1$ vertices in n -dimensional space to approximate the optimal point of the objective function (Lagarias et al., 1998). One of the key advantages of the Nelder-Mead algorithm is that it is a direct search method, meaning it does not require derivatives of the objective function. This makes it particularly useful for complex models where derivatives may be difficult to compute or entirely unknown (Gao & Han, 2012). Additionally, it is well-suited for multi-dimensional optimization, allowing it to navigate complex surfaces efficiently to find a local minimum, which is essential when optimizing multiple parameters simultaneously (Hydromantis, 2023).

In GPS-X, the algorithm has been modified to accommodate variable boundaries, enhancing its flexibility and ensuring that optimized parameters remain within feasible or physically meaningful ranges (Hydromantis, 2023). The primary objective is to minimize the difference between simulated results and actual data. In wastewater modeling, for instance, parameters such as the heterotrophic maximum specific growth rate are optimized to better align the simulation with experimental data (Mehta & Dasgupta, 2012). The Nelder-Mead algorithm is widely recognized for its robustness, as it can handle noisy or irregular objective functions, which are common in real-world applications (Lagarias et al., 1998). It is also relatively easy to implement compared to more complex optimization methods, making it accessible to a broad range of users (Gao & Han, 2012). Moreover, the ability to handle variable boundaries enables more realistic optimization scenarios, particularly in cases where parameters must adhere to physical or operational constraints (Fang et al., 2005).

However, despite its advantages, the Nelder-Mead algorithm has some limitations. One of the main drawbacks is its susceptibility to converging to local minima rather than the global minimum, especially in complex optimization landscapes (Lagarias et al., 1998). This can sometimes be mitigated by using multiple initial guesses or combining the algorithm with other optimization techniques. Additionally, while generally efficient, its performance can be affected by the dimensionality of the problem and the complexity of the objective function (Gao & Han, 2012). Nonetheless, the sensitivity analysis optimizer in GPS-X, powered by the Nelder-Mead simplex algorithm, remains a flexible and effective tool for optimizing model

parameters within specified boundaries, making it a valuable asset in modeling and simulation applications.

To achieve an optimal match between simulated and observed COD effluent concentrations, a Controller Data File was generated in GPS-X. This file contained influent COD concentrations along with corresponding flow rates allowing for dynamic process simulations for the months of September and October.

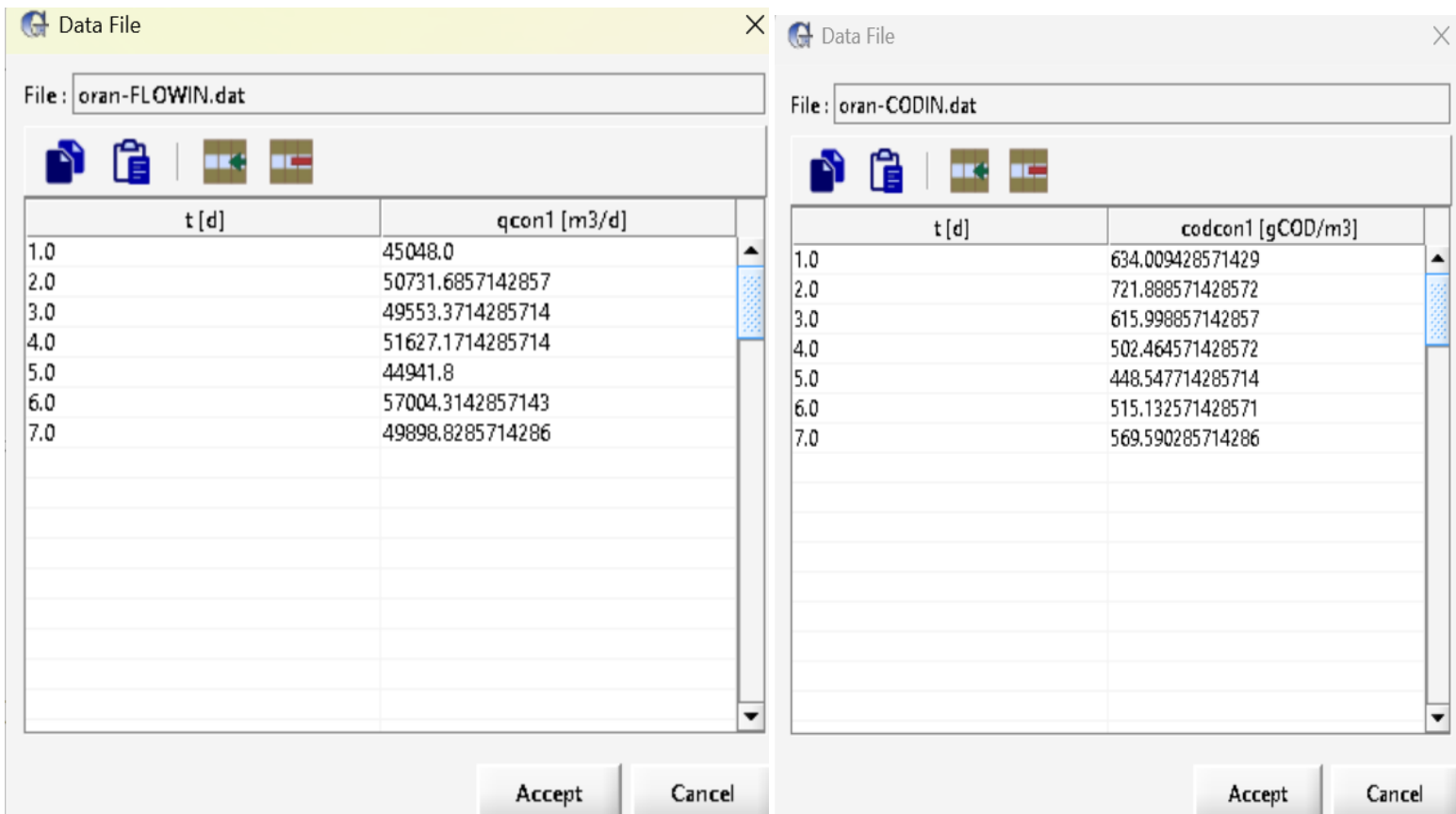


Figure 3. 10:Data File Tool with Values (COD & Flow rate).

Following this, the configuration of the GPS-X optimizer module begins by selecting the target variable, which in this case is the COD effluent output. The next step involves identifying the sensitive parameters that require adjustment to achieve the best fit between simulated and observed values. Once these parameters are defined, the optimizer settings are specified to guide the calibration process

In the final step, the optimization approach is determined by selecting appropriate objective functions. For this study, we utilized the Fit to Data, Time Series, and relative difference methods. The Relative Difference method plays a crucial role in quantifying the deviation

between simulated and observed COD values by calculating the percentage difference at each time step. This approach enhances model calibration by ensuring that both absolute and proportional discrepancies are minimized, leading to improved predictive accuracy. It is important to note that the initial parameter values used in the optimization process were set to their default values, allowing the sensitivity analysis to systematically adjust them for improved calibration results. These methods ensure a comprehensive assessment of the model's predictive accuracy by minimizing the difference between simulated and measured COD effluent concentrations.

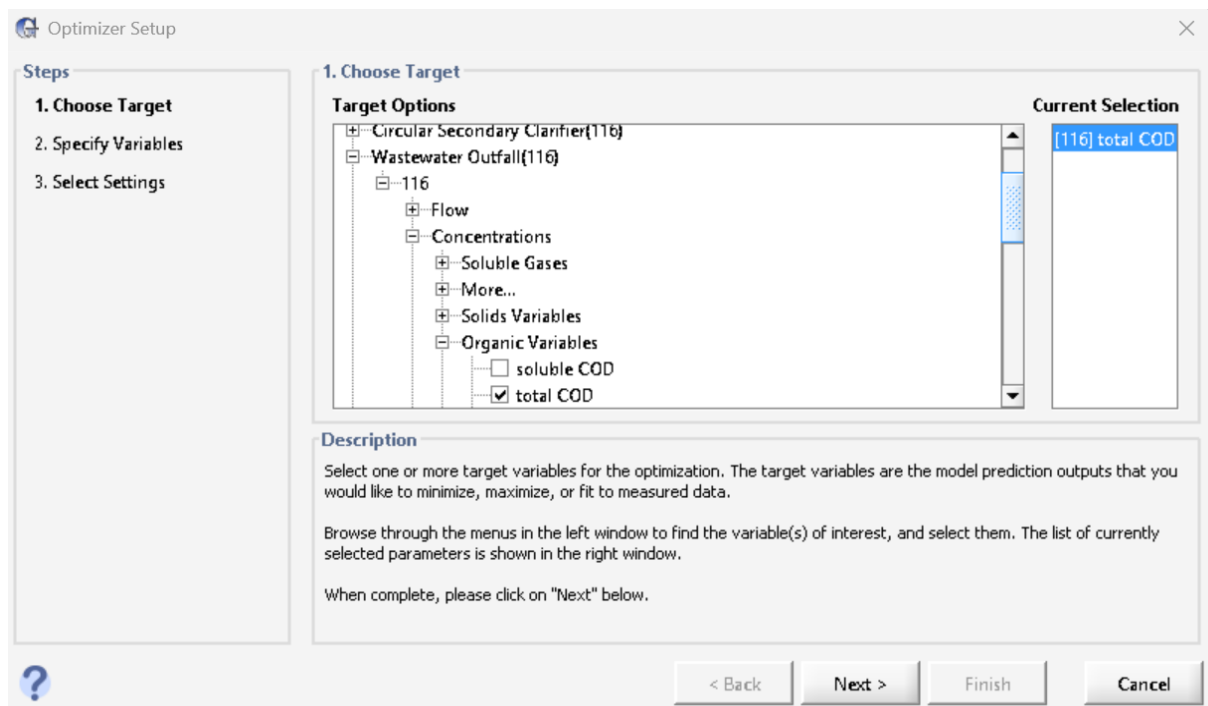


Figure 3. 11: Optimizer Settings

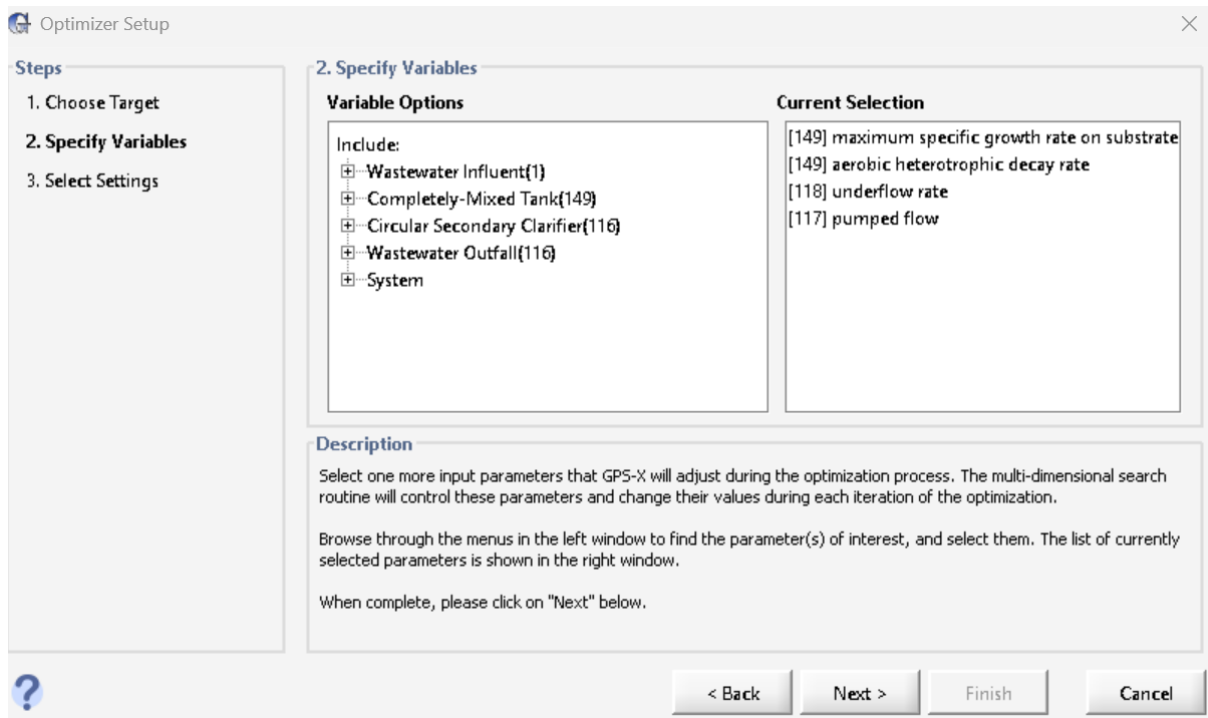


Figure 3. 12: Optimization Approach.

3.10- The scenarios

Scenario 1: Increased Organic Load from Industrial Wastewater

After completing the dynamic calibration and validation of the Mantis2 model using baseline data from 01–07 February 2019 where the average influent COD was approximately 379.62 mg/L a scenario analysis was undertaken to assess the WWTP's ability to maintain COD removal efficiency under elevated organic loads. In this scenario, the influent COD concentration was increased using the formula:

$$New_COD = Baseline_COD \times (1 + increased\ value\ \%) \quad \text{Equation 1}$$

the influent flow was increased by the same percentage to simulate the additional load from industrial wastewater. These modifications were implemented within the CODstat model, while the fractions of readily biodegradable substrate (SS) and slowly biodegradable substrate (XS) were kept unchanged to reflect the assumption of consistent organic composition. The modified influent parameters were then incorporated into the GPS-X simulation, underpinned by the Mantis2LIB library, to run dynamic simulations over the same period as the baseline. The target was to maintain effluent COD below 90 mg/L, in accordance with Algerian discharge standards. If the effluent exceeded this threshold for an extended period, further optimization strategies such as adjusting aeration rates, modifying sludge retention time (SRT), and implementing equalization measures were explored to mitigate performance degradation.

Scenario 2: the impact Population growth

The second scenario involves the wastewater treatment plant (WWTP) being forced to handle 100,000 m³/day extra flow from its influent due to population expansion. The presented figure serves as an estimated short-term value to account for the growing hydraulic load. Two biological basins and two clarifiers run in the WWTP because the facility maintains its design for higher flow volumes. The designed system enables performance evaluations of wastewater treatment in conjunction with identification of capacity constraints affecting large-scale wastewater processing.

being forced to handle 100,000 m³/day flow, due to population expansion. The presented figure serves as an estimated short-term value to account for the growing hydraulic load. Two biological basins and two clarifiers run in the WWTP because the facility maintains its design for higher flow volumes. The designed system enables performance evaluations of wastewater treatment in conjunction with identification of capacity constraints affecting large-scale wastewater processing.

The plant facilities receive an enhancement through the addition of a 10,584 m³ biological tank and a 2,507 m² sedimentation tank to boost treatment effectiveness and adapt to higher wastewater flow. A simulation of the enlarged system configuration helps determine how extra bioreactor space alongside a larger sedimentation tank benefits the wastewater treatment outcome.

Operating the WWTP under complete capacity utilizes four tanks for each process step to determine its maximum operational potential. The COD concentration in simulations maintains its basis in average values from confirmed studies to present constant realistic load patterns among simulation environments.

Scenario 3: operation at the capacity

This scenario evaluates the performance of the wastewater treatment plant (WWTP) when operating at its maximum design capacity. The objective is to determine whether the plant can sustain effluent quality while handling peak hydraulic and organic loading conditions. To simulate full-capacity operation, the influent flow rate was increased to match the plant's maximum design capacity of 1.526.000 inhabitants, with an average daily flow of 270.096 m³. The influent COD concentration was maintained at the validated baseline value to ensure that

only the effect of increased hydraulic load was analyzed. The simulation was performed in the GPS-X environment, utilizing the Mantis2 model to maintain consistency with previous calibration and validation processes. The fractions of readily biodegradable substrate (SS) and slowly biodegradable substrate (XS) were kept unchanged to reflect a consistent wastewater composition.

The plant's response was assessed based on several key performance indicators (KPIs). The effluent COD concentration was monitored to determine whether the plant could still meet regulatory discharge standards (≤ 90 mg/L). Sludge production was evaluated to assess potential issues related to excess biomass accumulation, while aeration demand was analyzed to ensure that oxygen supply remained sufficient for biological treatment. Additionally, the settling performance of the secondary clarifiers was examined to identify any risks of sludge bulking or poor settleability.

The expected outcomes of this scenario provide valuable insights into the WWTP's operational limits. If the effluent COD remains below 90 mg/L, it indicates that the plant can function effectively at full capacity while maintaining regulatory compliance. However, if the effluent COD exceeds discharge limits, potential causes may include insufficient aeration, inadequate sludge age, or poor clarifier performance, necessitating process adjustments. Additionally, an increase in sludge production may require optimization of sludge retention time (SRT) to prevent overloading the sludge-handling system. This scenario helps identify potential bottlenecks and informs decision-making regarding capacity upgrades or process modifications to enhance long-term performance. By simulating full-capacity conditions, this analysis provides critical insights into the WWTP's ability to handle future demand growth while ensuring sustainable treatment efficiency.

Chapter 4. Result and discussion

This chapter presents the comprehensive results and discussion of the wastewater treatment plant (WWTP) study, integrating data correction, calibration, validation, and scenario analyses to evaluate plant performance under varied operational conditions. Initially, the data correction methodology is described, highlighting the application of the Savitzky-Golay filter to smooth the influent and effluent COD and flow rate data, thereby reducing noise and ensuring an accurate representation of the system's behavior. Subsequently, the chapter details the calibration of kinetic, stoichiometric, and operational parameters using both literature values and empirical observations, followed by model validation against an independent dataset to confirm the robustness of the simulation approach. Finally, the performance of the WWTP is assessed under three distinct scenarios—an increased organic load, a response to population growth through phased infrastructural upgrades, and full-capacity operation each offering insights into the dynamic responses, process limitations, and potential optimization strategies for maintaining effluent quality and regulatory compliance.

4.1 - Data correction

The choice of the Savitzky-Golay filter was based on a comparative analysis of different smoothing techniques, where SG demonstrated the smallest Root Mean Square Error (RMSE), ensuring minimal distortion of the original dataset while effectively reducing noise. This correction was applied not only to influent COD but also to effluent COD and flow rate, providing a more comprehensive and accurate assessment of wastewater treatment plant performance. By refining these datasets, it becomes easier to detect anomalies, analyze seasonal variations, and evaluate treatment efficiency under different loading conditions. This approach enhances the reliability of wastewater treatment modeling, allowing for better predictive capabilities. Further statistical validation, such as R^2 analysis, could reinforce the effectiveness of this method, while correlating COD trends with flow rate and other operational parameters may offer deeper insights into system behavior and performance optimization. COD influent

Table 4. 1: The RMSE for Data correction method

Method \ Parameter	RMSE CODIN	RMSE COD_EFF	RMSE FLOW
Moving Average	128.80971	29.44493	12225.668
Exponential Smoothing	125.78792	29.90573	64081.542
LOWESS	159.94945	35.12164	20930.901
Savitzky-Golay	93.31858	21.31409	7578.396
Spline Interpolation	262.82945	60.85562	36005.447

COD influent

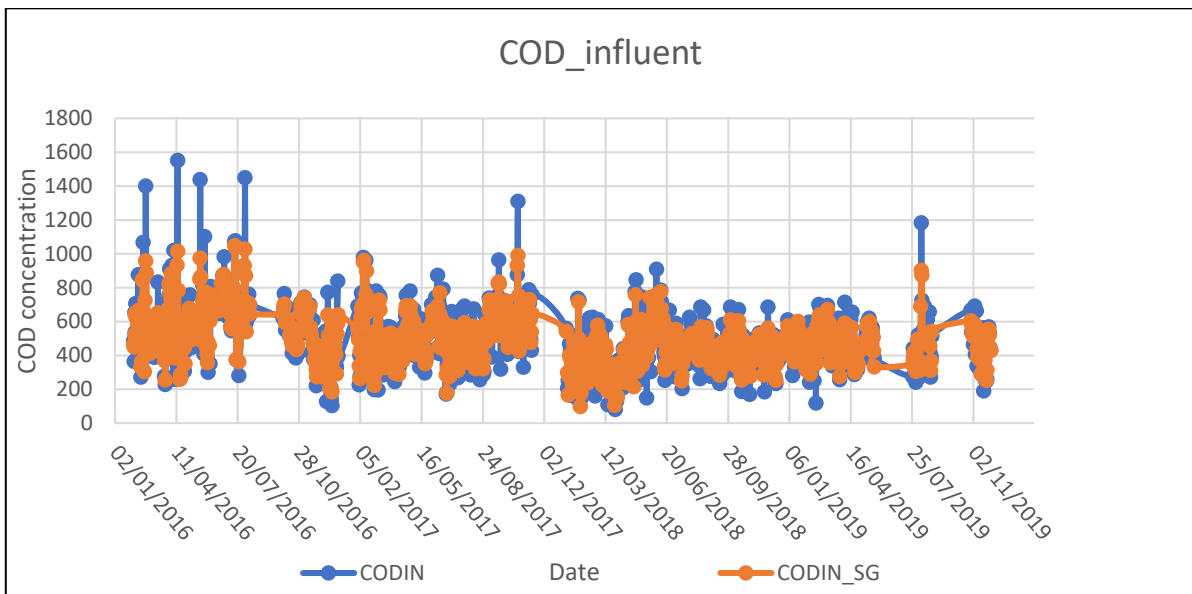


Figure 4. 1: The COD influent real and corrected data

The influent COD data exhibits noticeable fluctuations over time, reflecting variations in wastewater composition and organic load. These variations can be influenced by factors such as industrial discharges, domestic wastewater patterns, and seasonal changes in water usage. Peaks in COD levels may indicate periods of high organic pollution, while sudden drops could be linked to dilution effects, such as stormwater infiltration. Understanding these trends is essential for evaluating the treatment plant’s capacity to handle different loading conditions and ensuring stable treatment performance.

The raw influent COD data contained excessive fluctuations, making it difficult to observe long-term trends and seasonal variations. These fluctuations could be caused by measurement noise, sudden industrial discharges, or short-term anomalies. By applying data correction, we

were able to smooth out irregularities and obtain a more accurate representation of influent COD behavior, which is essential for assessing treatment efficiency and predicting future trends.

COD effluent

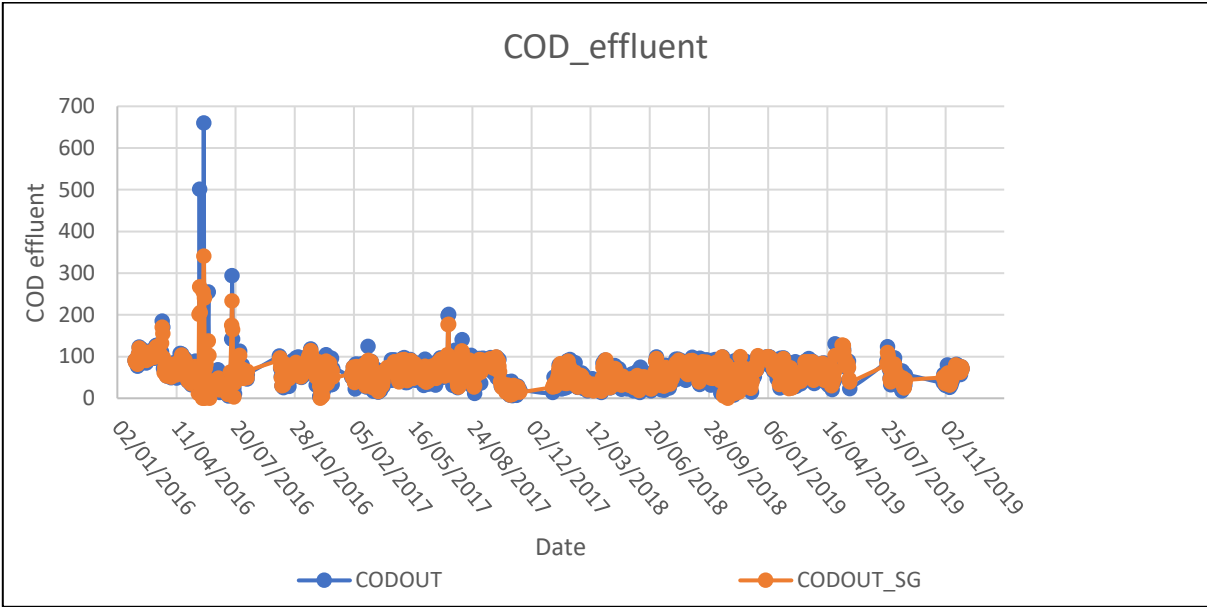


Figure 4. 2:The COD effluent real and corrected data

The effluent COD data represents the effectiveness of the wastewater treatment process in removing organic matter. While the trend remains relatively stable, occasional spikes suggest periods of lower treatment efficiency, which could be caused by fluctuations in influent quality, operational disturbances, or equipment malfunctions. Monitoring these variations is crucial to maintaining compliance with discharge regulations and ensuring environmental protection. By analyzing effluent COD trends, plant operators can optimize treatment performance and implement corrective actions when necessary.

Effluent COD data needed correction to remove extreme spikes and noise that could distort performance evaluation. Some of these spikes may have been caused by temporary operational disturbances, equipment failures, or measurement errors. By correcting the data, we achieved a clearer representation of the plant’s overall treatment efficiency, making it easier to identify persistent trends and ensure compliance with discharge regulations.

Flow

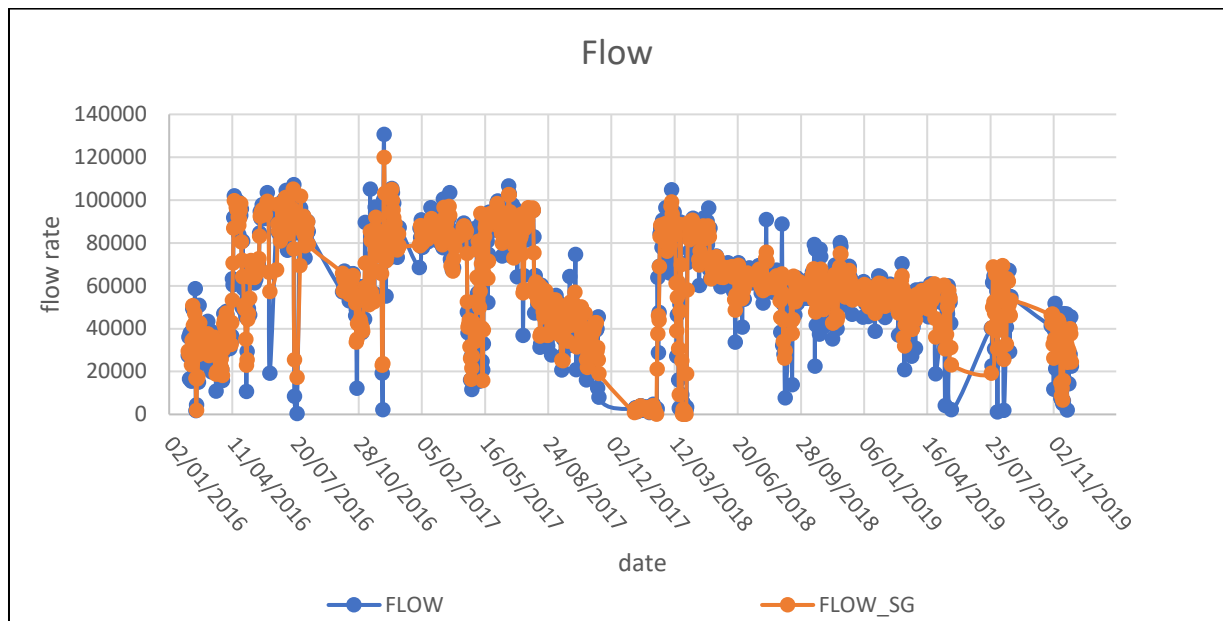


Figure 4. 3: The Flow t real and corrected data

The flow rate data shows significant variability, likely influenced by daily and seasonal changes in water consumption, industrial wastewater discharge, and stormwater infiltration. Peaks in flow may correspond to periods of heavy rainfall or increased domestic and industrial activities, while drops in flow could indicate reduced water use or issues within the sewer system. Flow rate variations directly impact the hydraulic load on the treatment plant, influencing treatment efficiency, retention time, and sludge management. Proper flow monitoring is essential for optimizing plant operations and ensuring smooth functioning under varying hydraulic conditions.

The raw flow data showed substantial variability, including extreme peaks and sudden drops that could be attributed to sensor errors, rainfall infiltration, or irregular discharge patterns. These inconsistencies made it challenging to analyze long-term trends and understand seasonal flow variations. Correcting the data allowed us to better identify flow patterns and assess the plant's ability to handle different hydraulic loads, which is crucial for optimizing treatment processes and infrastructure planning.

5.1 - Calibration result

The calibration of these kinetic, stoichiometric, and operational parameters is firmly grounded in both established literature and empirical observations, providing confidence in the design and performance of the wastewater treatment plant (WWTP).

Kinetic Parameters. The maximum heterotrophic growth rate (μ_{maxh}) dictates the speed at which heterotrophic bacteria convert substrates into biomass. Literature suggests values between 2.0 and 6.0 d⁻¹. with rates above 3.5 d⁻¹ particularly effective in high-loading scenarios for enhancing organic matter degradation and chemical oxygen demand (COD) removal (Pawel Król, 2019) ; (P. Sanghamitraa, 2021) . The selected value of 4.00 d⁻¹ not only fits within this range but also supports robust microbial activity under high organic loads. Meanwhile. the heterotrophic decay rate (b_h). calibrated at 1.22 d⁻¹. falls within the acceptable range of 0.02 to 1.6 d⁻¹. Although higher than some default values. this elevated rate is beneficial for preventing excessive sludge accumulation in demanding operational contexts (Bashir Adelodun, 2020)

Stoichiometric Parameters. The autotrophic yield (Y_a) of 0.4 g COD/g COD aligns with literature estimates of 0.38 to 0.75 g COD/g COD. striking a balance between efficient biomass formation and minimal excess sludge generation. further validating this choice. The volatile suspended solids to total suspended solids (VSS/TSS) ratio of 0.83 g VSS/g TSS. comfortably within the typical 0.6–0.9 range (V. E. Etuk, 2021). ensures a substantial fraction of active biomass for effective organic matter degradation.

Operational Parameters. Both return activated sludge (RAS) and waste activated sludge (WAS) flows are critical for sustaining biological processes. A RAS flow rate of 4000 m³/d. within the standard 20–100% of influent flow (Khadija Lihi, 2023). recycles sufficient microorganisms to maintain a stable reactor population. The WAS flow rate of 445 m³/d is carefully calibrated to manage sludge age and retention time. preserving an optimal microbial community and preventing excessive biomass loss (Khadija Lihi, 2023)

Table 4. 2: The kinetic, stoichiometric and operational calibrated parameter

Parameters	Symbol	OUR CASE	Typical range	Source	Interpretation
Stoichiometric parameter					
Yield for Autotrophic	Y_A (COD/g COD)	0.4	0.38-0.75	(Ekaterina Sergeevna Antonova1, 2019)	lower than default (0.66). improves sludge quality and nitrification
volatile suspended solids/total suspended	VSS/TSS	0.83	0.6-0.9	(V. E. Etuk, 2021)	Indicates a high fraction of active biomass.
Kinetic parameter					
Maximum specific growth rate for heterotrophic biomass	$\mu_{\max H}$ (d ⁻¹)	4	2-6	(Paweł Król, 2019); (P. Sanghamitraa, 2021)	Within a reasonable range; enhances organic matter degradation.
Heterotrophic decay Coefficient	b_H (d ⁻¹)	1.22	0.02-1.6	(Bashir Adelodun, 2020)	Higer than default (0.62). ensuring proper sludge stabilization
Operational parameter					
Underflow rate	RAS (m ³ /d)	4000	20-100% of influent flow	(Khadija Lihi, 2023)	Matches standard WWTP practices for biomass recycling.
Pumped flow	WAS (m ³ /d)	445	Optimized per plant design	(Khadija Lihi, 2023)	Adjusted to maintain optimal sludge retention time.

Dynamic Simulation and Model Refinement. Under fluctuating influent flow and COD. initial simulations showed discrepancies between observed and predicted values. Through iterative refinement of key parameters. effluent COD predictions improved significantly. Regression analysis yielded an R^2 of 0.76. indicating a strong correlation between measured and simulated COD levels. This high correlation underscores the model's robustness in capturing real-world conditions. while also highlighting potential areas for further enhancement.

By integrating dynamic calibration with numerical optimization. the model effectively tracks COD variations under diverse operational scenarios. thereby increasing confidence in its

predictive capabilities. Future efforts may involve refining calibration targets, incorporating additional influent characteristics, or exploring advanced control strategies to further elevate model performance and ensure consistent effluent quality.

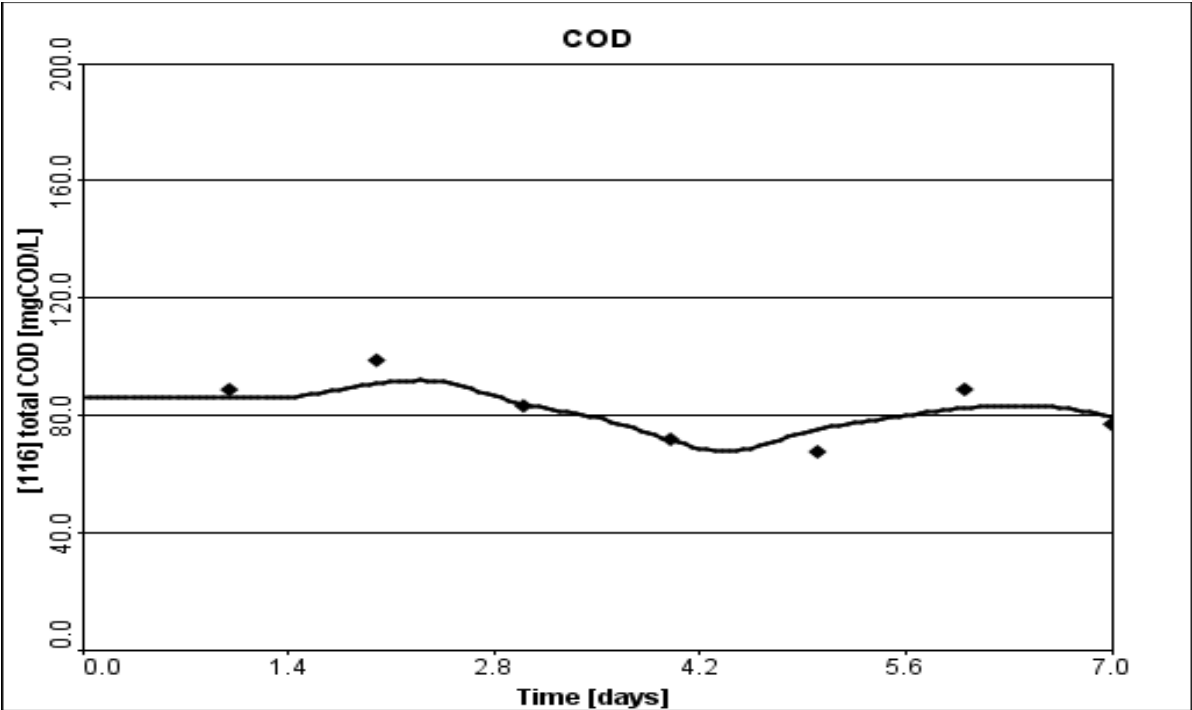


Figure 4. 4:Dynamic calibration for COD effluent

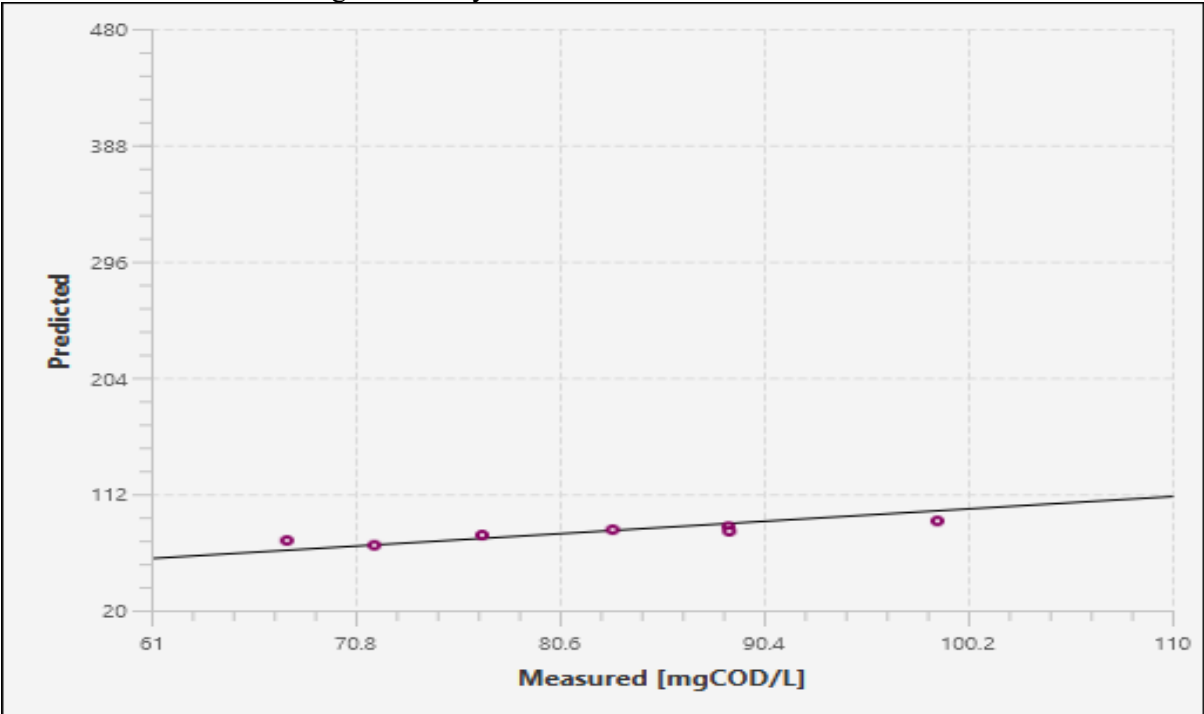


Figure 4. 5:Linear Regression test (measured COD/simulated COD).

4.2- Validation result

Following the calibration phase, in which key kinetic, stoichiometric, and operational parameters were refined to align with observed plant performance, the model was subjected to validation using an independent dataset. This step is critical for confirming that the calibrated parameters not only fit the initial data but also generalize to new conditions. The validation exercise demonstrated a reliable predictive capability, achieving an R^2 value of 0.79 when comparing measured and simulated effluent COD concentrations. Such a correlation indicates that the model captures the essential dynamics of the biological treatment process under real-world operating conditions. While the results confirm a robust level of accuracy, further refinements, such as incorporating additional data or adjusting calibration targets may enhance the model's predictive power and accommodate a broader range of influent characteristics. Overall, the validation underscores the effectiveness of the calibration strategy and reinforces confidence in the model's applicability for ongoing process optimization.

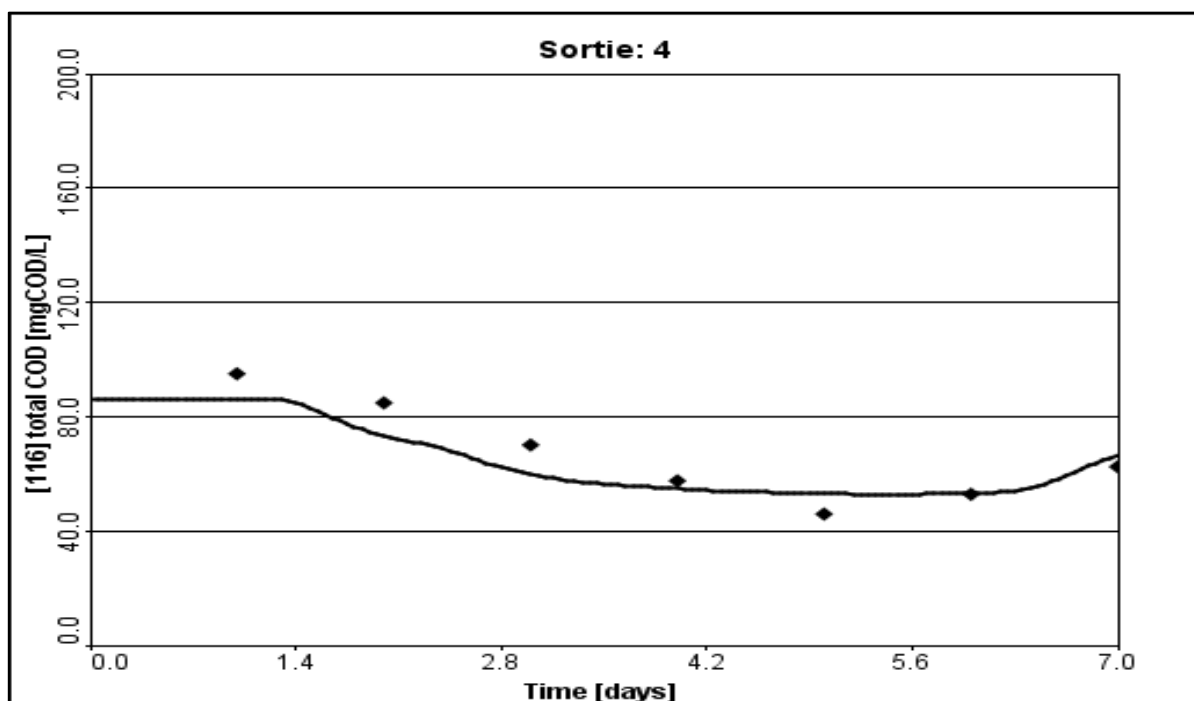


Figure 4. 6:Dynamic Validation results for the effluent COD.

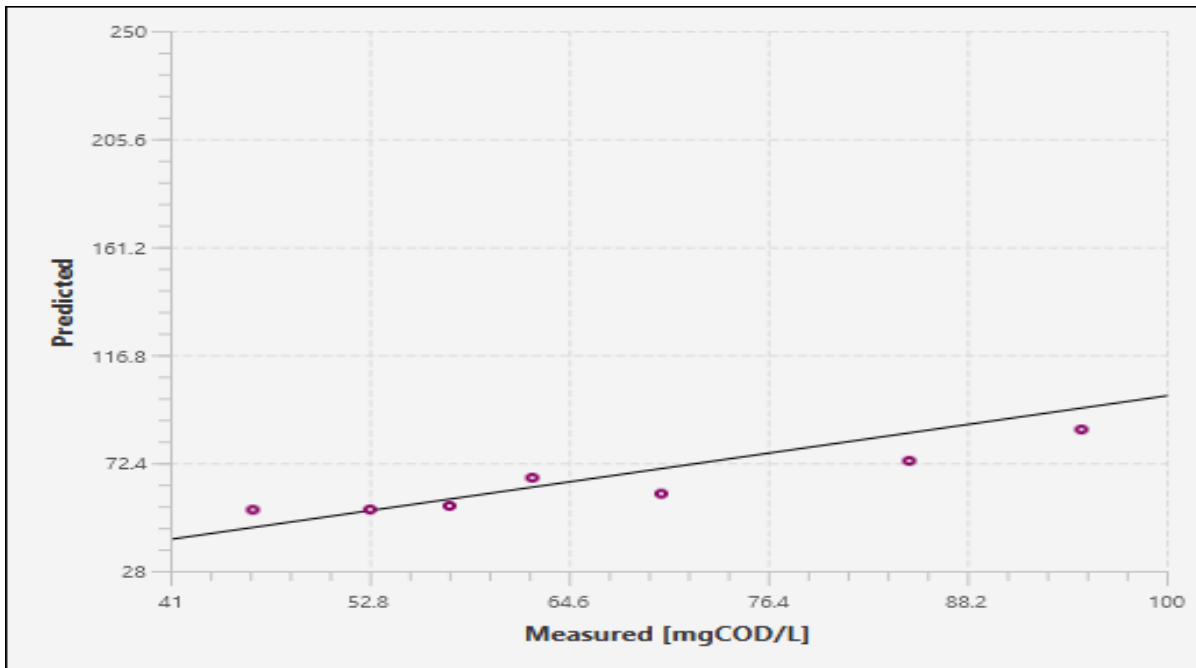


Figure 4. 7; Linear Regression test (measured COD/simulated COD).

4.2- Scenario

Scenario 1: Increase in Organic Load:

Scenario 1: Increase in Organic Load

Increasing 10%:

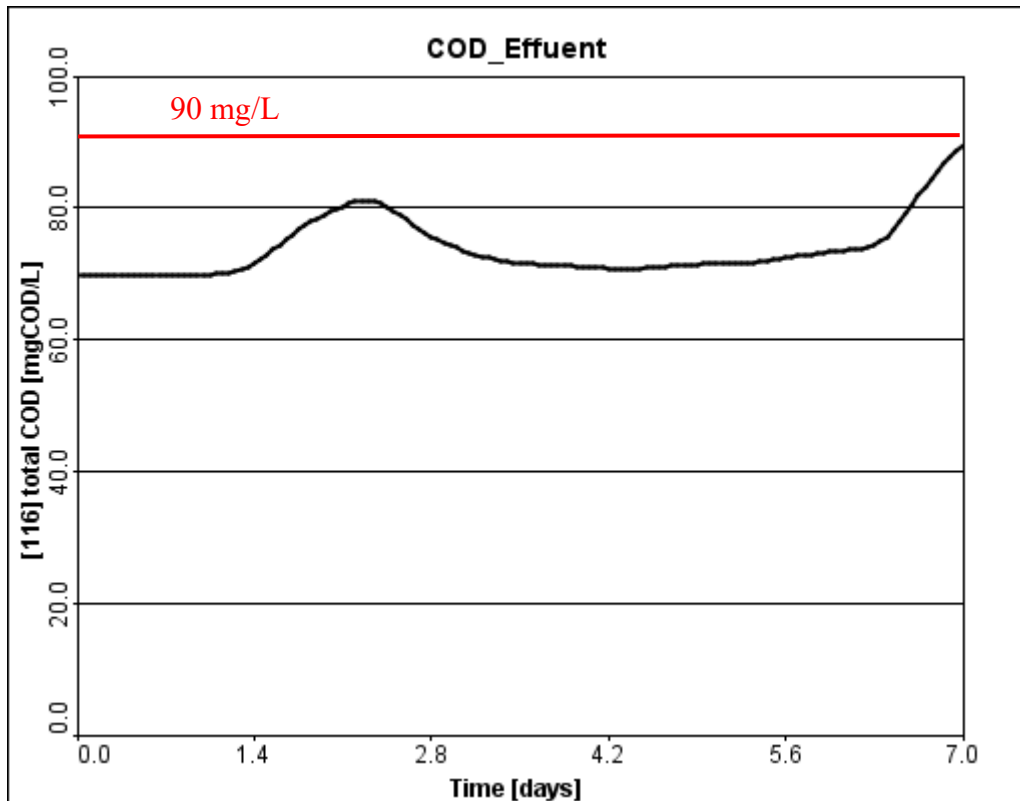


Figure 4. 8:COD effluent after increased load of 10%

During the simulated seven-day period, the wastewater treatment plant (WWTP) experiences a sudden increase in organic loading, introducing higher-than-usual levels of biodegradable material into the influent. The effluent COD profile exhibits three key stages in response to this disturbance.

Initially, from Days 0–1, the effluent COD remains relatively stable, with only a slight increase, suggesting that the microbial community is gradually beginning to adapt to the influx of organic matter. Unlike a sharp rise, the system demonstrates some buffering capacity, likely due to microbial acclimation and dilution effects within the treatment tanks.

Between Days 1.5–3, the COD reaches a peak of approximately 82 mg/L, indicating that the treatment efficiency temporarily declines as the microbial community adjusts its metabolic pathways. However, the peak is moderate rather than extreme, suggesting that while the system experiences stress, it retains partial capacity to process the increased load.

From Days 3–6, the effluent COD stabilizes at around 70 mg/L, showing a slower recovery phase than initially expected. Instead of a steady decline, the graph suggests that the system maintains a prolonged period of moderate COD levels before a final increase towards the end of the simulation. By Day 7, the COD rises again, reaching nearly 90 mg/L, indicating a possible

secondary disturbance, residual effects of the high organic load, or incomplete degradation of accumulated organic matter.

These results suggest that while the WWTP demonstrates resilience, the process may require additional operational adjustments to prevent prolonged COD fluctuations. The completely mixed reactor configuration ensures uniform distribution of substrates and microorganisms, facilitating microbial adaptation. However, the late-stage COD rise suggests that optimizing aeration, adjusting sludge retention time, or implementing load equalization strategies could further enhance performance and prevent secondary COD spikes.

Increasing 30%

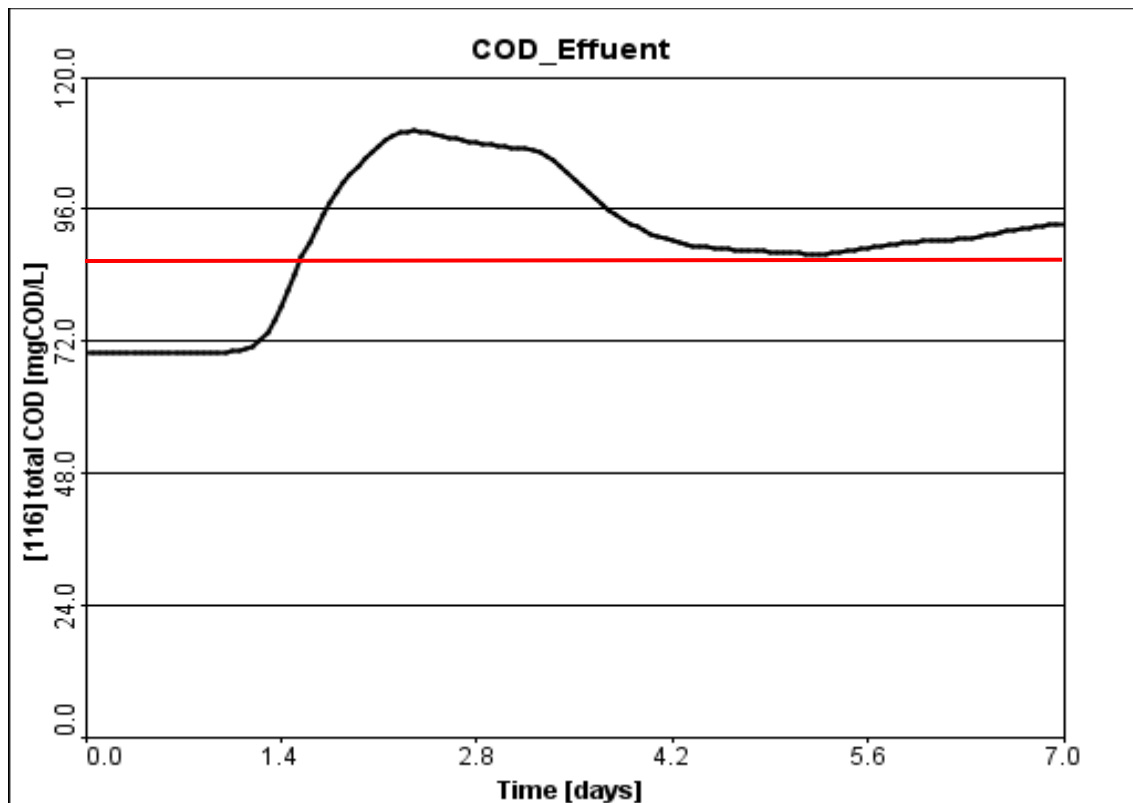


Figure 4. 9:COD effluent after increased load of 30%

In this simulation, the wastewater treatment plant (WWTP) is subjected to a 30% increase in organic loading, simulating conditions where the influent carries significantly higher levels of biodegradable material. The effluent COD profile over seven days reveals three distinct stages in the system's response to this elevated organic load.

During the initial phase (Days 0–1), the effluent COD remains relatively stable at around 72 mg/L, indicating that the microbial community initially absorbs the increased load without immediate disruption. However, this is followed by a sharp increase between Days 1–2, where COD rises steeply and reaches a peak of approximately 110 mg/L. This suggests that the system experiences a temporary reduction in treatment efficiency as the microbial population struggles to metabolize the excess organic matter. The peak is significantly higher compared to the previous case, reflecting the greater challenge posed by the increased load.

Between Days 2–4, COD begins to decline as the microbial community adapts, but the recovery is slower than in the previous scenario. Instead of stabilizing at pre-disturbance levels, the COD remains above 80 mg/L for the remainder of the simulation. By Days 5–7, a gradual upward trend emerges, suggesting that the system is still under stress, potentially due to accumulated organic matter, increased oxygen demand, or limitations in biomass adaptation.

Unlike the previous scenario, where the effluent COD eventually stabilized well below the regulatory limit of 90 mg/L, this case shows that the COD remains near or slightly above the threshold, highlighting the need for operational interventions. The prolonged recovery phase and late-stage increase indicate that the system is approaching its capacity limits under the given conditions. To mitigate such effects, strategies such as optimizing aeration, increasing sludge retention time, or implementing step-feed aeration could help enhance the system's resilience and improve COD removal efficiency.

Increasing 50%:

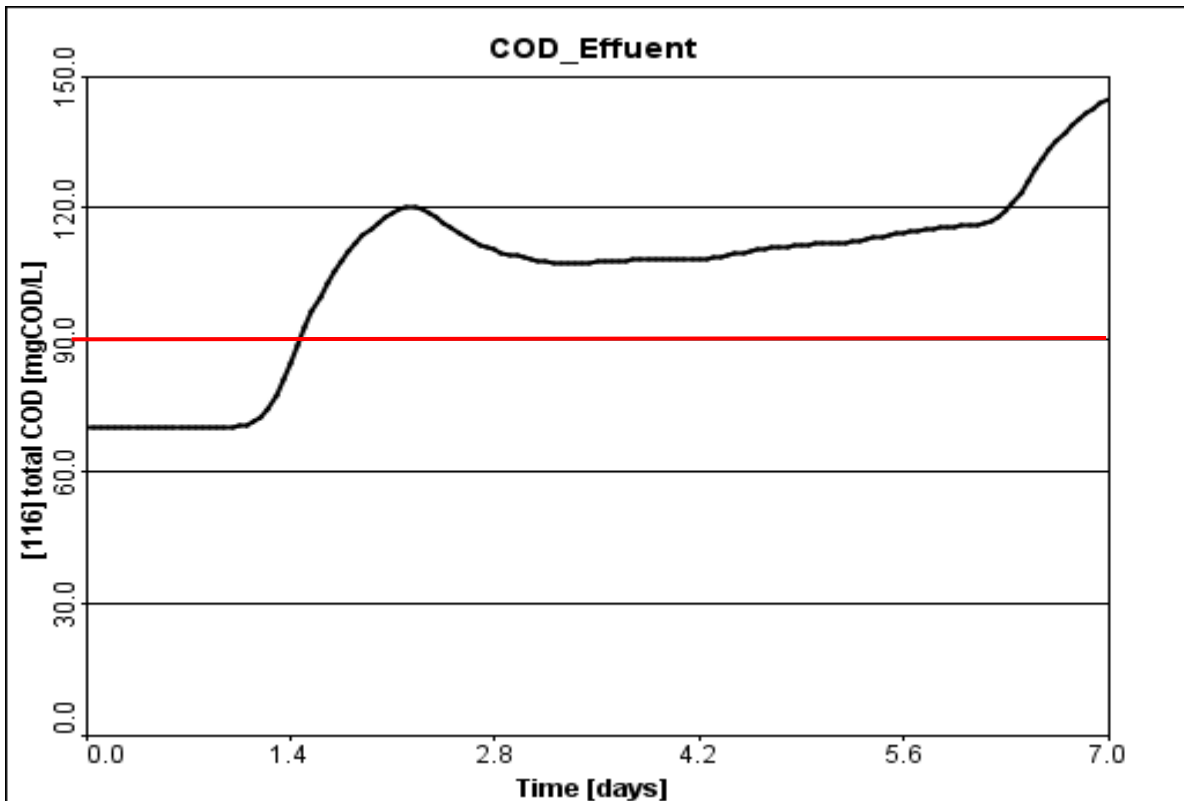


Figure 4. 10:COD effluent after increased load of 50%

This simulation evaluates the impact of a 50% increase in organic loading on the performance of the wastewater treatment plant (WWTP). The effluent COD response over the seven-day period reveals key trends and challenges. In the initial phase (Days 1–2), the effluent COD is relatively low, indicating that the system is still managing the organic load effectively.

However, as the excess organic matter accumulates, a rapid increase occurs between Days 1–2, with COD peaking at approximately 125 mg/L. This reflects a severe temporary decline in treatment efficiency, as the microbial population struggles to metabolize the elevated organic load.

Between Days 2–4, COD decreases slightly but remains above 90 mg/L, suggesting a partial recovery as the microbial community adjusts. However, the decline is not as pronounced as in previous scenarios, indicating that the system is nearing its performance limits. Unlike in the 30% load increase case, where COD remained relatively stable after the initial peak, this scenario exhibits a steady rise from Days 4–7. By the end of the simulation, COD reaches nearly 145 mg/L, well above the typical regulatory threshold of 90 mg/L, highlighting persistent treatment challenges.

The continuous increase in COD beyond Day 5 suggests that the system is overloaded, potentially due to oxygen limitations, excessive sludge production, or insufficient microbial adaptation. This indicates that the WWTP is struggling to fully recover under this level of organic loading. Without intervention, prolonged exposure to such high loads could lead to process failure.

Scenario 2: population growth

- **Phase 1: Existing Configuration at 100,000 m³/day**

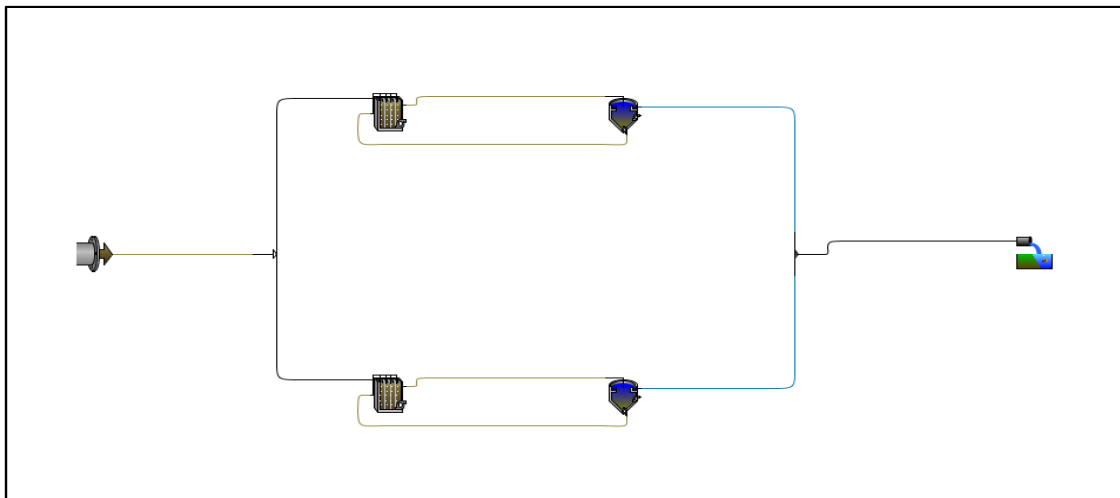


Figure 4. 11: the baseline designed system

Operating flow at the WWTP reaches 100000 m³/day for an amount that surpasses its original design capability by 100%. An analysis of simulation output reveals that the measured effluent COD ranges between 200 mg/L as well as 400 mg/L through daily time intervals. Light variation in organic waste content of the influent and changes to operational parameters such as sludge recirculation rates and aeration intensity produce these noticeable variations. Short-term microbial stress occurs after sudden organic matter spikes cause momentary drops in COD removal ability which generates peaks of COD in the discharge water. The plant continues its operation during such conditions yet the noticeable peaks in COD levels demonstrate the difficulty to sustain steady low COD performance when flow rates increase.

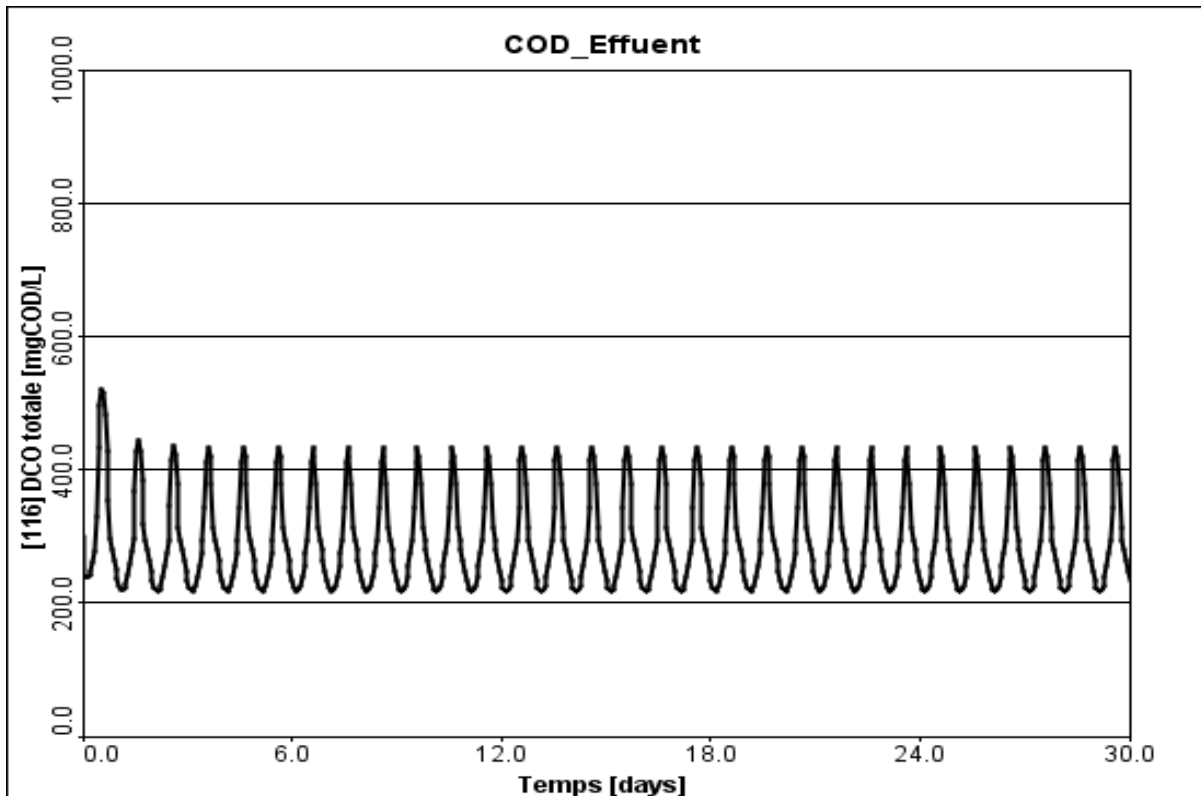


Figure 4. 12: the COD effluent with the baseline system after increasing the flow

- **Phase 2: Upgraded Configuration with an Additional Biological Tank and Sedimentation Tank**

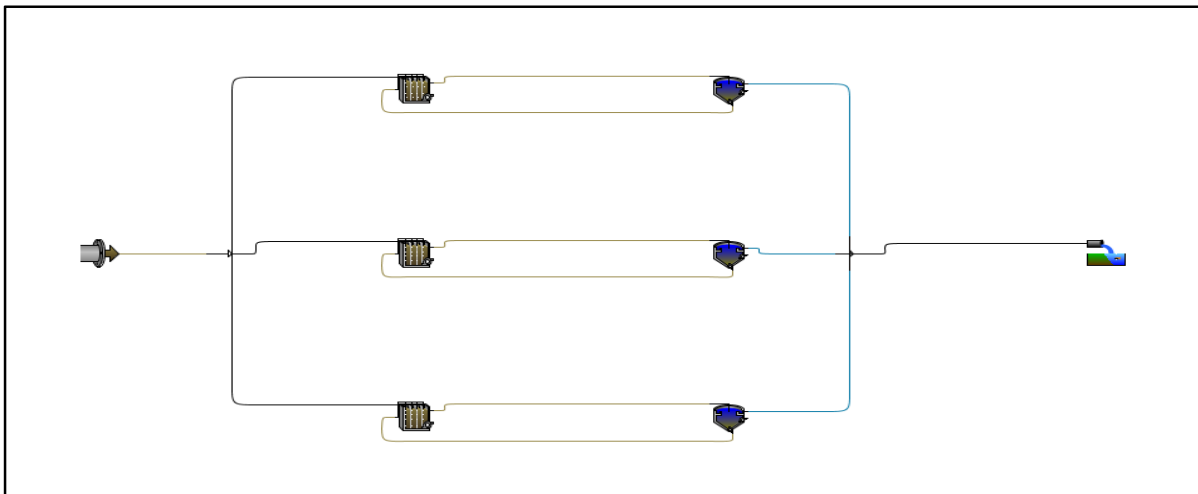


Figure 4. 13: Upgraded Configuration

The wastewater treatment plant (WWTP) entrance into the second phase received a 10,584 m³ biological tank along with a 2,507 m² sedimentation tank that delivered better effluent COD stability. The upgradable system maintains effluent COD elevation between 80 mg/L and 120 mg/L after the basic scenario presented daily COD readings between 200 mg/L and 400 mg/L.

Improved performance results from the enlarged biological volume that extends contact duration for microorganisms to break down organic matter thus boosting the entire biodegradation process. The enlarged sedimentation tank obtains additional space for sedimentation which minimizes particle movement from the biological stage to the final product. The combined solution delivers superior COD stabilization benefits that enhance the system's operational durability under varying high-flow and higher organic substance conditions. The upgraded system maintains lower average COD concentrations and more stable fluctuations despite minor variations that likely relate to diurnal changes in influent composition or operational changes because of its improved design capabilities.

Better clarification emerged due to the expanded sedimentation area which improved the solid suspension settlement capability. The improved settling efficiency prevents the return of suspended matter to the biological unit which results in lower organic quantities needing biological treatment. Better biological treatment coupled with enhanced sedimentation function together in a harmonious way to deliver reduced average COD along with stabilized periodic patterns documented in initial operation conditions. The improved infrastructure proved essential for process stability at elevated hydraulic and organic loads in the upgraded system although it allowed some minute operational fluctuations to remain

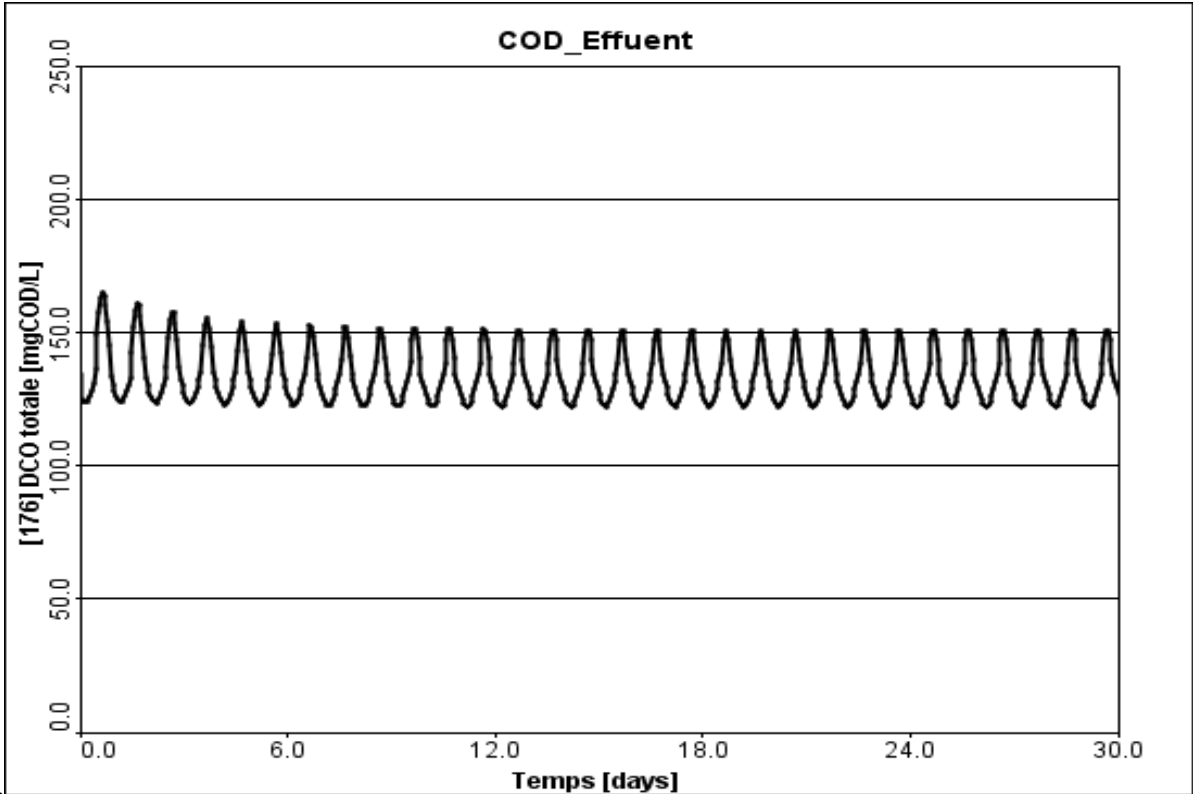


Figure 4. 14; the COD effluent after upgrading the system

- **Phase 3: Full-Capacity Operation with Four Tanks per Process**

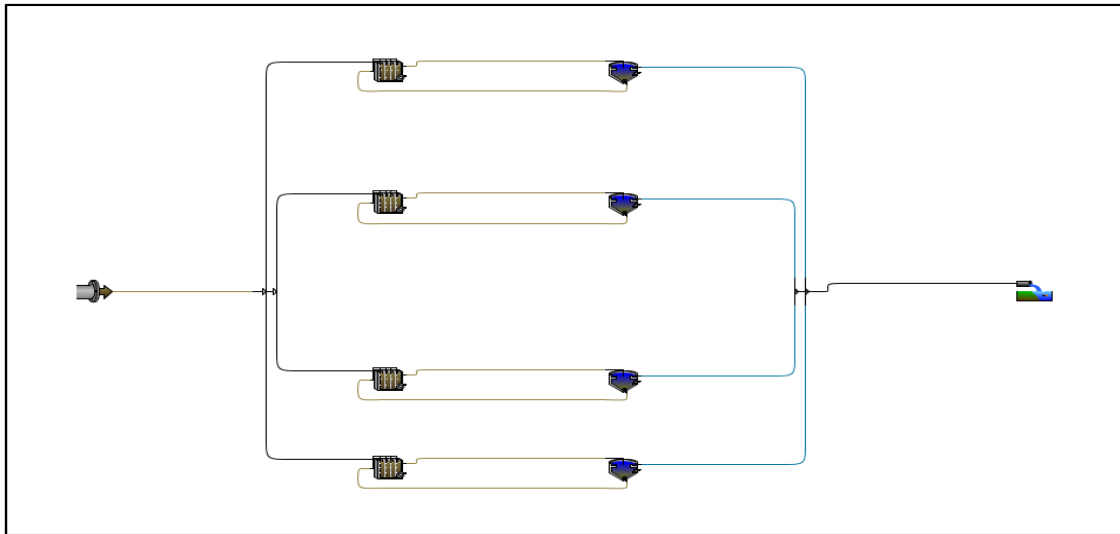


Figure 4. 15: Full-Capacity system

Under full operation the WWTP operates with four tanks assigned to each treatment process to achieve additional improvements in the effluent COD performance. The full-time operation using two basins and one extra sedimentation tank produces a COD average of 90 mg/L while peaks rise to 100 mg/L and lows decrease to 80 mg/L. More process tanks enhance biological volume and sedimentation capacity thus enabling the microbial community to adapt effectively to changes in organic load and day-night developments. This system operates with better stability alongside lower COD measurements because either substrate exposure to microorganisms and solids separation effectiveness improves. The plant demonstrates improved treatment performance combined with greater resilience at full capacity because minor variations in influent still exist.

Addition tanks to the system enable better distribution of influent and internal recirculation flows that decreases operational condition variations across the treatment process. The complete system enhancement delivers advanced organic material separation while suppressing periodic changes in output quality levels. The experimental results prove that operating at full capacity produces superior outcomes despite continuing minor fluctuation effects from the influent system. The results demonstrate why operators must track operational parameters such as aeration methods and sludge management to maintain a reliable treatment performance that fulfills discharge standards.

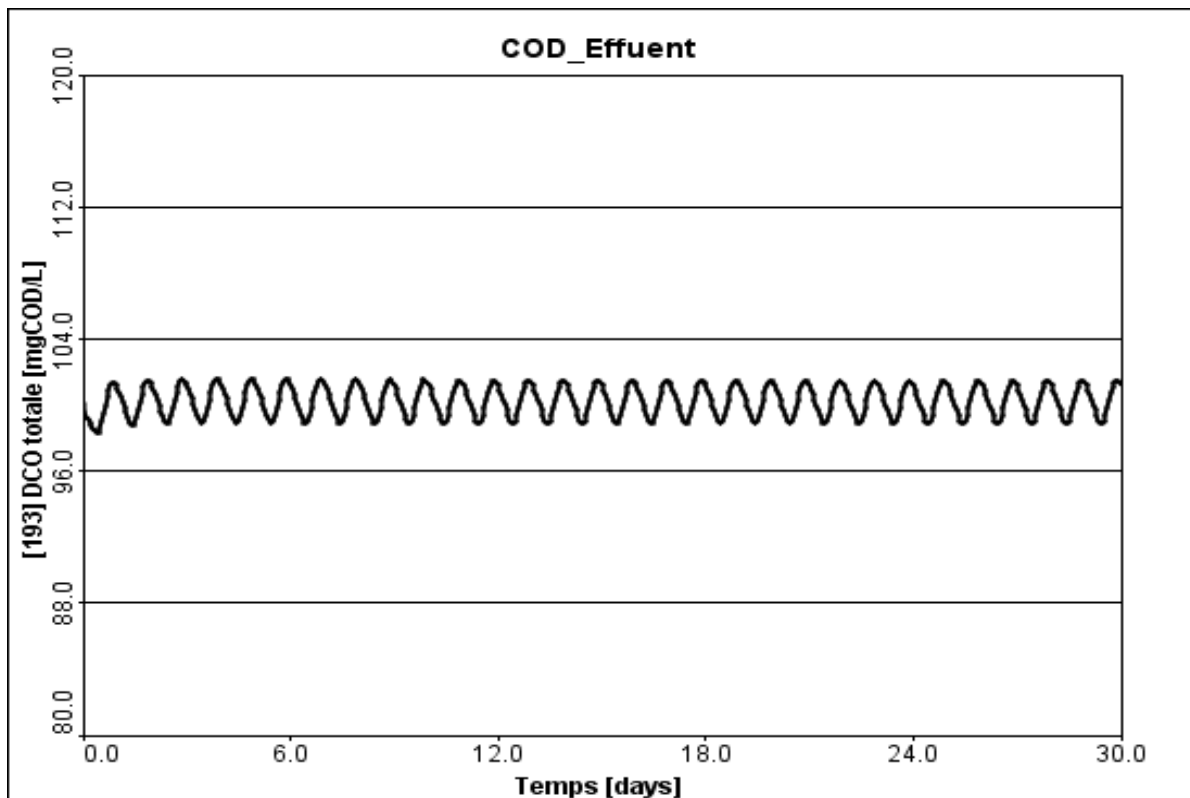


Figure 4. 16: the COD effluent for the Full-Capacity system

SCEANARIO 3: Operation at full Capacity

The simulation of the wastewater treatment plant (WWTP) at full capacity, with an influent flow of 270,096 m³/day and a COD of 330 mg/L, was conducted under steady-state conditions over a 30-day period. The resulting effluent COD profile exhibits periodic oscillations, indicating that while the system is operational, it is experiencing dynamic fluctuations. These fluctuations suggest possible instability in the treatment process, which may be linked to variable microbial activity, hydraulic and organic shock loads, or sludge retention issues. The activated sludge system might still be adjusting to the increased organic load, leading to periodic variations in substrate degradation. Additionally, the fluctuations could indicate uneven oxygen availability, affecting microbial metabolism and COD removal efficiency.

To address the issue of negative values in soluble organic nitrogen (SON), the influent ammonia nitrogen (NH₄⁺-N) was increased from 25 mg/L to 27 mg/L. This adjustment suggests that the initial nitrogen concentration may have been insufficient to support microbial metabolism, particularly for heterotrophic bacteria responsible for COD degradation. The observed oscillations in effluent COD could also be linked to oxygen limitations, which may have impacted nitrification efficiency. If ammonia oxidation is incomplete, nitrifiers may not be

receiving adequate dissolved oxygen, further influencing the nitrogen cycle and overall treatment performance.

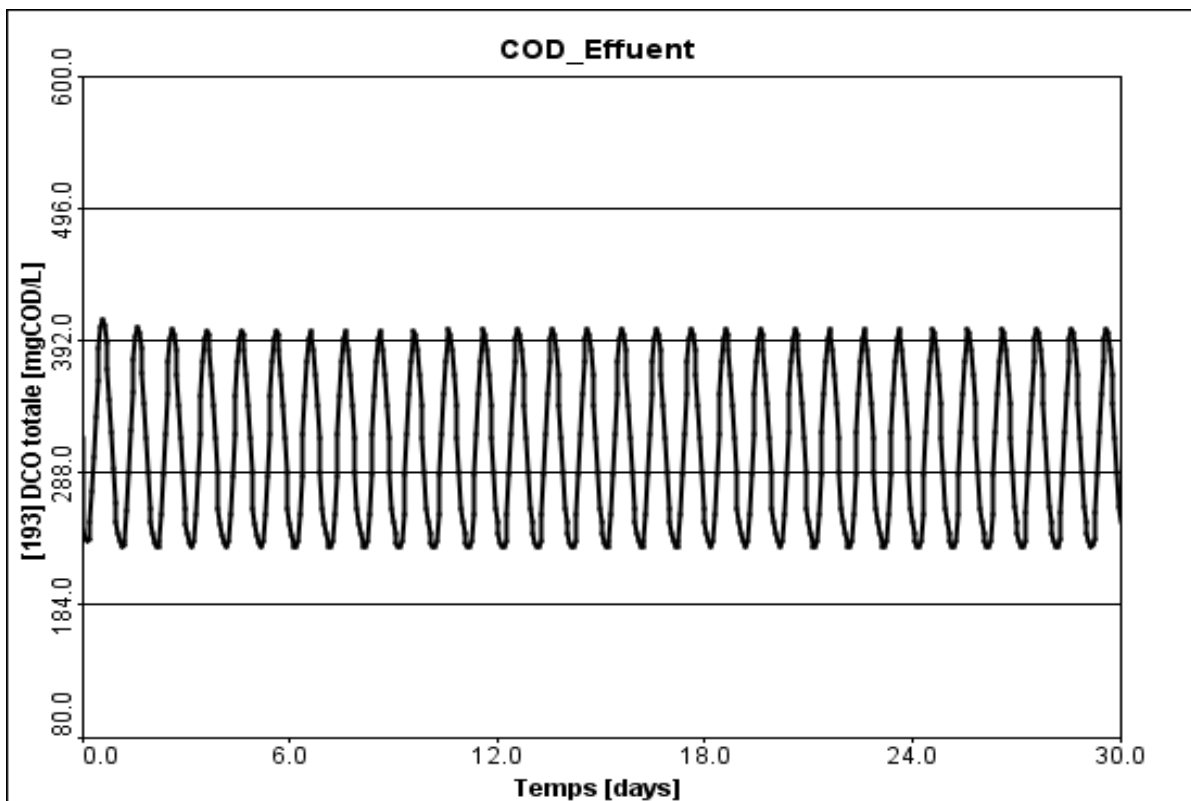


Figure 4. 17: the COD effluent for the designed flowrate

The fluctuating effluent COD levels raise concerns about the WWTP’s ability to consistently meet discharge standards, which in Algeria typically require effluent COD to remain below 90 mg/L. If these variations persist, it may indicate oxygen supply limitations, inadequate sludge age control, or inefficient recirculation rates. To improve treatment stability and performance, several operational adjustments should be considered. These include optimizing aeration to ensure sufficient oxygen transfer, adjusting sludge retention time (SRT) to balance microbial growth and sludge wastage, and monitoring ammonia and nitrate levels to confirm efficient nitrogen removal. Additionally, evaluating effluent COD trends over an extended period may help identify whether the observed cyclic instability is due to influent variability or internal process dynamics.

4.2- Conclusion :

This chapter presented the calibration, validation, and dynamic simulation results for the wastewater treatment plant (WWTP) model, offering a comprehensive evaluation of its performance under varying operational scenarios. The calibration process refined kinetic,

stoichiometric, and operational parameters using both literature values and empirical data, ensuring that the model accurately represents the biological treatment dynamics. Validation of the model confirmed its robustness, as evidenced by a strong correlation ($R^2 = 0.79$) between simulated and observed effluent COD concentrations.

Dynamic simulations were then conducted to assess the WWTP's response to different conditions. Under a 30% increase in organic load, the plant demonstrated its capacity to manage additional organic material while maintaining effluent quality within acceptable limits. However, when subjected to a 50% increase in organic loading, the system experienced a marked deterioration in performance, with effluent COD levels rising above regulatory thresholds. Similarly, simulations addressing population growth represented by an increased flow rate of 100,000 m³/day revealed significant fluctuations in effluent COD in the existing configuration, indicating challenges in maintaining stable treatment performance under elevated hydraulic loads.

The full-capacity scenario, which involved operating the plant with four tanks per process stage, produced the lowest variability and most consistent reduction in effluent COD. Although this expanded configuration enhanced organic matter removal and stabilized overall performance, periodic instabilities were still observed, likely reflecting intrinsic challenges in microbial adaptation, oxygen transfer, and sludge management under maximum design conditions.

the chapter provides a detailed account of how the WWTP model performs across a range of operational scenarios, highlighting both its strengths and the inherent challenges of managing variable hydraulic and organic loads.

Chapter 5: Summary, Conclusions & Perspectives

5.1- Summary

This study presents an in-depth investigation into the dynamic modeling and simulation of the El Kerma Wastewater Treatment Plant (WWTP) using the GPS-X platform and the Mantis2 model. The research was designed to capture both steady-state and dynamic behaviors of the plant under various operational scenarios by integrating laboratory experiments, historical monitoring data, and advanced data correction techniques. Initially, data correction was performed using the Savitzky-Golay filter, which significantly reduced measurement noise in influent and effluent COD as well as flow rate data. This improved dataset served as the critical input for the subsequent calibration phase.

During calibration, key kinetic, stoichiometric, and operational parameters were refined based on established literature and empirical observations. Parameters such as the maximum specific growth rate for heterotrophic biomass ($\mu_{\max H}$), heterotrophic decay coefficient (b_H), autotrophic yield (Y_A), and the VSS/TSS ratio were adjusted to accurately simulate the biological treatment processes in the activated sludge system. The model calibration achieved strong agreement with observed data, as indicated by a high correlation ($R^2 = 0.79$) between simulated and measured effluent COD concentrations. This validation confirmed the model's robustness and its ability to replicate the complex interactions within the treatment process.

Dynamic simulations were then conducted to assess the plant's performance under different stress conditions. The study examined scenarios including moderate (30%) and severe (50%) increases in organic loading, as well as the impacts of population growth, simulated by doubling the hydraulic flow rate to 100,000 m³/day. Additionally, a full-capacity scenario was evaluated by operating the plant with four tanks per process unit. Each scenario provided insights into how variations in hydraulic and organic loads affect the microbial degradation processes, solids separation, and overall stability of the effluent quality. The results revealed that while the plant can manage moderate increases in organic load and hydraulic flow through its existing configuration, significant stress either from a 50% increase in organic load or from full-capacity operation leads to observable fluctuations and occasional performance instabilities.

5.2- Conclusions

The results of this study demonstrate that the GPS-X-based Mantis2 model, when dynamically calibrated, can effectively simulate the performance of a WWTP under a wide range of operational conditions. Key conclusions are as follows:

1. Model Robustness and Calibration Accuracy:

The calibration process, which involved adjusting biological, stoichiometric, and operational parameters, led to a model that accurately reflects the behavior of the activated sludge process. The high correlation ($R^2 = 0.79$) between simulated and observed effluent COD confirms that the model captures the essential dynamics of organic matter removal. The refined parameters, particularly the values for $\mu_{\max H}$ (4.00 d^{-1}) and b_H (1.22 d^{-1}), reflect an environment optimized for high organic load conditions while preventing excessive sludge accumulation.

2. Dynamic Response to Increased Organic Loading:

The simulations under increased organic loads revealed that the WWTP maintains COD removal efficiency under moderate stress (30% increase). However, when the organic load is increased by 50%, the plant experiences a prolonged period of elevated effluent COD levels. This behavior suggests that the microbial community becomes overwhelmed under severe loading conditions, leading to temporary declines in treatment efficiency and potential regulatory non-compliance.

3. Impacts of Population Growth and Hydraulic Stress:

Simulating population growth by increasing the hydraulic flow rate to $100,000 \text{ m}^3/\text{day}$ indicated that the existing configuration of two basins and two clarifiers struggles to stabilize effluent quality. Significant fluctuations in COD were observed, implying that the plant's current design may be inadequate for sustained long-term growth without additional capacity enhancements. The dynamic response under increased flow emphasizes the need for considering hydraulic stress in WWTP design and operation.

4. Performance Under Full-Capacity Operation:

The full-capacity scenario, which involved operating with four tanks per process, resulted in the most consistent and reduced effluent COD values. This configuration achieved superior organic matter removal and demonstrated enhanced stability in effluent quality, even though minor periodic oscillations were still present. The results indicate that a fully expanded treatment system can better distribute influent loads, thereby minimizing localized overloads and improving overall process stability.

the study illustrates that while the current WWTP design is robust enough to handle moderate increases in organic and hydraulic loads, the performance becomes challenged under extreme conditions. The dynamic simulation approach not only validates the calibration of the model but also highlights the critical interplay between microbial activity, hydraulic distribution, and operational controls in achieving consistent effluent quality.

5.3- Perspectives

This research establishes a solid foundation for the use of dynamic modeling in the optimization and management of wastewater treatment plants, particularly in regions facing rapid population growth and increasing industrial discharges. The detailed calibration and scenario analyses underscore the importance of integrating advanced simulation techniques with empirical data to understand and predict plant behavior under variable conditions. Looking ahead, further studies could explore the incorporation of additional real-time data streams, enhanced dynamic calibration techniques, and the application of machine learning algorithms to refine predictive capabilities. The insights gained from this study offer valuable guidance for the design of future WWTPs and the implementation of operational strategies that ensure reliable and efficient treatment performance under a broad spectrum of loading scenarios.

References

1. Abdelmoumene, H., Lallam, F., Lallam, M., & Boumediene, M. (2024). *Assessment of the operational status of a wastewater treatment plant using the FAHP Process : case study of the Ain El Houtz WWTP in Algeria* *Avaliação do estado operacional de uma estação de tratamento de águas residuais utilizando o Processo FAHP : estud.* 1–24. <https://doi.org/10.54021/seesv5n2-177>
2. Abou-Elela, S. I., Hamdy, O., & El Monayeri, O. (2016). Modeling and simulation of hybrid anaerobic/aerobic wastewater treatment system. *International Journal of Environmental Science and Technology*, 13(5), 1289–1298. <https://doi.org/10.1007/s13762-016-0966-7>
3. Ahmed Abou-Shady. (2022). Challenges and Opportunities to Overcome Global Water Crisis Particularly in Arid and Semi-arid Regions. *Water*. https://www.mdpi.com/journal/water/special_issues/water_crisis_arid_semi_arid
4. Alex, J. (2024). Model-Based Construction of Wastewater Treatment Plant Influent Data for Simulation Studies. *Water (Switzerland)*, 16(4). <https://doi.org/10.3390/w16040564>
5. Ali MORADVANDI. (2024). *ADVANCING RESOURCE RECOVERY FROM WASTEWATER*.
6. Aliyu, A., Mohamed, T. S., ElSayed, N. B., Abdelbaki, C., Bessedik, M., & Kumar, N. (2025). Modeling Biological Nutrients Removal for Wastewater Treatment Plant (WWTP) Management: A Case Study of Ain El Houtz WWTP (Algeria). *Water, Air, and Soil Pollution*, 236(1), 1–15. <https://doi.org/10.1007/s11270-024-07735-9>
7. An, T., Feng, K., Cheng, P., Li, R., Zhao, Z., A, X. X., & Zhu, L. (2024). Adaptive prediction for effluent quality of wastewater treatment plant: Improvement with a dual-stage attention-based LSTM network. *Journal of Environmental Management*.
8. Arabzadeh, R., Grünbacher, D. M., Insam, H., Kreuzinger, N., Markt, R., & Rauch, W. (2021). Data filtering methods for SARS-CoV-2 wastewater surveillance. *Water Science and Technology*, 84(6), 1324–1339. <https://doi.org/10.2166/wst.2021.343>
9. Aroua-Berkat, S., & Aroua, N. (2022). Opportunities and Challenges for

- Wastewater Reuse in Algeria. *Larhyss Journal*, 2022(51), 7–17.
10. Behrendt, J. (2025). *Wastewater Modelling Environment with Openmodelica* (www.openmodelica.org) Motivation.
<https://publications.europa.eu/en/publication-detail/-/publication/8448ef88-37dd-4d1a-823f->
 11. Benstaali, I., Talia, A., & Benadela, L. (2024). Optimized wastewater management utilizing multivariate statistical analysis: a case study of the Mascara wastewater treatment plant, Algeria. *Water Science and Technology*, 90(4), 1290–1305.
<https://doi.org/10.2166/wst.2024.276>
 12. Beres, R. P. (2015). *Mantis2: Motivation, Features, Model Structure, Model Processes and Additional Considerations*.
<https://www.linkedin.com/pulse/mantis2-motivation-features-model-structure-processes-robert-p-beres/>
 13. Bodaka, H., Farhoud, N., & Hlali, E. (2023). Modeling of wastewater treatment plant in Hama city using regression and regression trees. *Environmental Health Engineering and Management*, 10(3), 293–300.
<https://doi.org/10.34172/EHEM.2023.33>
 14. Breulmann, M., Khurelbaatar, G., Sanne, M., van Afferden, M., Subah, A., & Müller, R. A. (2022). Integrated Wastewater Management for the Protection of Vulnerable Water Resources in the North of Jordan. *Sustainability (Switzerland)*, 14(6), 1–18. <https://doi.org/10.3390/su14063574>
 15. Cambi. (2021). *An Introduction to Wastewater Treatment*.
<https://www.cambi.com/blog/wastewater-treatment>
 16. Chaoui, A., Elkhoumsi, W., Laaouan, M., Bourziza, R., & Sebari, K. (2023). Forecasting Wastewater Influent Parameters Using ARIMA and Holt-Winters Models (A Case Study). *Environment and Ecology Research*, 11(3), 493–504.
<https://doi.org/10.13189/eer.2023.110309>
 17. Chirane, M. S., Belmeskine, H., Boudjellaba, S., & Megatelli, S. (2024). Assessment of chemical and bacteriological status of treated wastewater of the Baraki WWTP (Algeria) for agricultural purposes. *Water Supply*, 24(7), 2383–2394. <https://doi.org/10.2166/ws.2024.134>
 18. Cieżak, W., & Kutylowska, M. (2023). Application of exponential smoothing method to forecasting daily water consumption in rural areas. *Archives of Civil Engineering*, 69(3), 445–456. <https://doi.org/10.24425/ace.2023.146090>

19. ConceptDraw. (n.d.). *Environmental, Social, and Corporate Governance*.
<https://www.conceptdraw.com/solution-park/management-esg>
20. Dairi, S., Mrad, D., Djebbar, Y., & Hammar, Y. (2011). Dynamic simulation for the requirements of oxygen about the Municipal Wastewater Treatment Plant - Case of Souk-Ahras/Algeria. *Journal of Materials and Environmental Science*, 2(SUPPL. 1), 507–512.
21. Deepak, M., & Rustum, R. (2023). Review of Latest Advances in Nature-Inspired Algorithms for Optimization of Activated Sludge Processes. *Processes*, 11(1).
<https://doi.org/10.3390/pr11010077>
22. Duarte, M. S., Martins, G., Oliveira, P., Fernandes, B., Ferreira, E. C., Alves, M. M., Lopes, F., Pereira, M. A., & Novais, P. (2024). A Review of Computational Modeling in Wastewater Treatment Processes. *ACS ES and T Water*, 4(3), 784–804. <https://doi.org/10.1021/acsestwater.3c00117>
23. Fang, K. T., Li, R., & Sudjianto, A. (2005). Design and modeling for computer experiments. *Design and Modeling for Computer Experiments*, 1–303.
<https://doi.org/10.1201/9781420034899>
24. Fao. (1992). *Wastewater treatment*. <https://www.fao.org/4/t0551e/t0551e05.htm>
25. Faris, A. M., Zwain, H. M., Hosseinzadeh, M., & Siadatmousavi, S. M. (2022). Modeling of novel processes for eliminating sidestreams impacts on full-scale sewage treatment plant using GPS-X7. *Scientific Reports*, 12(1), 1–17.
<https://doi.org/10.1038/s41598-022-07071-0>
26. Frank Water. (2017). *Wastewater Treatment and Reuse in MENA Countries*.
<https://water.fanack.com/publications/wastewater-treatment-reuse-mena-countries/>
27. Frank Water. (2019). *Water Challenges in Algeria*.
28. FundsforNGOs. (2022). *Sustainable Sanitation Systems: Addressing Water Scarcity in Arid Regions*.
29. Gao, F., & Han, L. (2012). Implementing the Nelder-Mead simplex algorithm with adaptive parameters. *Computational Optimization and Applications*, 51(1), 259–277. <https://doi.org/10.1007/s10589-010-9329-3>
30. Ge, M. S., Wu, P. T., Zhu, D. L., & Zhang, L. (2018). Application of different curve interpolation and fitting methods in water distribution calculation of mobile sprinkler machine. *Biosystems Engineering*, 174(2001), 316–328.
<https://doi.org/10.1016/j.biosystemseng.2018.08.001>
31. Golubović, J. (2016). *Mutual intelligibility in the Slavic language area*.

32. Goosen, M. (2025). *Algeria Commits \$5.4B to Desalination for Long-Term Water Security*. <https://energycapitalpower.com/algeria-commits-5-4b-to-desalination-for-long-term-water-security/>
33. *GPS-X Technical Reference - v8.0*. (2019).
<https://www.hydrumantis.com/help/GPS-X/docs/8.0/Technical/index.html>
34. Harrou, F., Dairi, A., Dorbane, A., & Sun, Y. (2023). Energy consumption prediction in water treatment plants using deep learning with data augmentation. *Results in Engineering*, 20(October), 101428.
<https://doi.org/10.1016/j.rineng.2023.101428>
35. Hvala, N., Vrečko, D., Levstek, M., & Bordon, C. (2017). The use of dynamic mathematical models for improving the designs of upgraded wastewater treatment plants. *Journal of Sustainable Development of Energy, Water and Environment Systems*, 5(1), 15–31. <https://doi.org/10.13044/j.sdewes.d5.0130>
36. Hydromantis. (2023). *Hydromantis*.
37. Khechekhouche, A., & Bouchemal, F. (2020). Performance of a wastewater treatment plant in south-eastern Algeria. *International Journal of Energetica*, 5(2), 47–51. <https://doi.org/10.47238/ijeca.v5i2.139>
38. Lagarias, J. C., Reeds, J. A., Wright, M. H., & Wright, P. E. (1998). Convergence properties of the Nelder-Mead simplex method in low dimensions. *SIAM Journal on Optimization*, 9(1), 112–147. <https://doi.org/10.1137/S1052623496303470>
39. Lilley & Pybus. (1997). Operating Manual for Biological Nutrient Removal Wastewater Treatment Works. *Water Research Commission Report No. TT 83/97*, 1(1), 148.
40. Mallik, A., Arefin, M. A., & Shahadat, M. M. Z. (2018). Design and feasibility analysis of a low-cost water treatment plant for rural regions of Bangladesh. *AIMS Agriculture and Food*, 3(3), 181–204.
<https://doi.org/10.3934/AGRFOOD.2018.3.181>
41. Mehta, V. K., & Dasgupta, B. (2012). A constrained optimization algorithm based on the simplex search method. *Engineering Optimization*, 44(5), 537–550.
<https://doi.org/10.1080/0305215X.2011.598520>
42. Moussaoui, T., Derdour, A., Hosni, A., Ballesta-de los Santos, M., Legua, P., & Pardo-Picazo, M. Á. (2023). Assessing the Quality of Treated Wastewater for Irrigation: A Case Study of Ain Sefra Wastewater Treatment Plant. *Sustainability (Switzerland)*, 15(14). <https://doi.org/10.3390/su151411133>

43. Nesmerak, I., & Blazkova, S. D. (2014). Analysis of the time series of waste water quality at the inflow of the wastewater treatment plant and transfer functions. *Journal of Hydrology and Hydromechanics*, 62(1), 55–59.
<https://doi.org/10.2478/johh-2014-0009>
44. Ngila, J. C., Matheri, A. N., Muckoya, V., Ngigi, E., Ntuli, F., Seodigeng, T., & Zvinowanda, C. (2020). *MATHEMATICAL MODELLING FOR BIOLOGICAL WASTEWATER TREATMENT PLANTS, GAUTENG, SOUTH AFRICA Report to the WATER RESEARCH COMMISSION* (Issue 2563). www.wrc.org.za
45. Pereira, S. (2014). *Modelling Of A Wastewater Treatment Plant Using GPS-X. September*. https://run.unl.pt/bitstream/10362/13621/1/Pereira_2014.pdf
46. Radaideh, J. A. (2022). Treated wastewater for meeting challenges of climate change in arid regions. *International Journal of Weather, Climate Change and Conservation Research*, 8(1), 6–19.
<https://doi.org/10.37745/ijwcccr.15/vol8n1pp619>
47. Rauch, W., Schenk, H., Insam, H., Markt, R., & Kreuzinger, N. (2020). *Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID- 19 . The COVID-19 resource centre is hosted on Elsevier Connect , the company ' s public news and information . January.*
48. Rob J Hyndman and George Athanasopoulos. (2018). *Simple exponential smoothing*. <https://otexts.com/fpp2/ses.html>
49. Roche, C., Valle Medina, M. E., Schmitt, P., Pallarès, A., Pallarès, G., Meilliez, M., & Laurent, J. (2022). Densification of activated sludge for better settling performances: experimental characterization in batch column and model parameters calibration. *Water Science and Technology*, 86(1), 110–127.
<https://doi.org/10.2166/wst.2022.192>
50. Sabri, D., Yassine, D., Yahia, H., & Dounia, M. (2017). Dynamic simulation for wastewater treatment plants management: Case of Souk-Ahras region, north-eastern Algeria. *Journal of Water and Land Development*, 34(1), 221–231.
<https://doi.org/10.1515/jwld-2017-0057>
51. Sabry Zaki. (2022). *Climate Change in Algeria and its Impacts*.
<https://assafirarabi.com/en/48562/2022/11/05/climate-change-in-algeria-and-its-impacts/>
52. Silva, J. A. (2023). Wastewater Treatment and Reuse for Sustainable Water

- Resources Management: A Systematic Literature Review. *Sustainability (Switzerland)*, 15(14). <https://doi.org/10.3390/su151410940>
53. Simon-Várhelyi, M., Cristea, V. M., & Brehar, M. A. (2020). Efficient calibration methodology of the wastewater treatment plant model based on asm3 and application to municipal wastewater. *Desalination and Water Treatment*, 189(1), 108–118. <https://doi.org/10.5004/dwt.2020.25612>
54. Simon Judd. (2025). *Wastewater treatment modelling*. <https://www.thembrsite.com/wastewater-treatment-modelling>
55. Simplilearn. (2025). *No Title*. An Introduction to Exponential Smoothing for Time Series Forecasting in Python. <https://www.simplilearn.com/exponential-smoothing-for-time-series-forecasting-in-python-article>
56. Tiar, S. M., Bessedik, M., Abdelbaki, C., ElSayed, N. B., Badraoui, A., Slimani, A., & Kumar, N. (2024). Steady-State and Dynamic Simulation for Wastewater Treatment Plant Management: Case Study of Maghnia City, North-West Algeria. *Water (Switzerland)*, 16(2). <https://doi.org/10.3390/w16020269>
57. Vangheluwe, H., Claeys, F., & Vansteenkiste, G. (n.d.). *The WEST ++ Wastewater Treatment Plant Modelling and Simulation Environment 1 Abstract 2 The WEST ++ Environment 3 MSL-USER versus MSL-EXEC 4 Activated Sludge WWTPs*.
58. Von Sperling, M., & Chernicharo, C. A. D. L. (2005). Biological Wastewater Treatment in Warm Climate Regions. *IWA Publishing*, 1–856. <http://choicereviews.org/review/10.5860/CHOICE.45-2633>
59. Wang, R., Pan, Z., Chen, Y., Tan, Z., & Zhang, J. (2021). Influent quality and quantity prediction in wastewater treatment plant: Model construction and evaluation. *Polish Journal of Environmental Studies*, 30(5), 4267–4276. <https://doi.org/10.15244/pjoes/132821>
60. Wei, X. P. (2013). Modeling and Optimization of Wastewater Treatment Process With a Data-Driven Approach. *Tesis de Doctorado*, 53(9), 1689–1699.
61. Weik, M. H. (2000). Entry Format. In *Computer Science and Communications Dictionary* (Issue 4). https://doi.org/10.1007/1-4020-0613-6_6303
62. Xing, Z., Chen, J., Zhao, X., Li, Y., Li, X., Zhang, Z., Lao, C., & Wang, H. (2019). Quantitative estimation of wastewater quality parameters by hyperspectral band screening using GC, VIP and SPA. *PeerJ*, 2019(12). <https://doi.org/10.7717/peerj.8255>

63. Xu, J., Buchanan, I., & Luo, Z. (2020). Application of Biowin to Biological Nutrient Removal (Bnr) Modeling. *Science and Technology*, 2(1), 112–121. <https://doi.org/10.25236/FSST.2020.020116>
64. Yasmin, A. A., Azahra, A. S., & Purwani, S. (2024). the Application of Cubic Spline in Rainfall Modelling in Bogor and Its Impact on Paddy Production. *Communications in Mathematical Biology and Neuroscience*, 2024, 1–13. <https://doi.org/10.28919/cmbn/8430>