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Improving the Performance of the Karbala Wastewater Treatment Plant by Manipulating the Influencing Operational Parameters of the Plant Using GPS-X Model

A Thesis Submitted to the Council of the Faculty of the College Engineering/University of Kerbala as Partial Fulfillment of the Requirements for the Master Degree in Civil Engineering

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بسم الله الرحمن الرحيم

" يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنكُمْ وَالَّذِينَ
أُوتُوا الْعِلْمَ دَرَجَاتٍ"

صدق الله العلي العظيم

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Abstract

Conventional wastewater treatment plants, especially those containing tertiary phase and nutrient removal, have very complex chemical and biological kinetics. Because of the characteristics and nature of wastewater, it always needs continuous improvements, which must be carefully studied before they are made. An optimized operating system increases plant efficiency, reduces energy consumption, and achieves environmental limits for plant output. In the present study, a new strategy to reduce nutrient concentrations, reduce energy, and improve plant output in a large-scale plant is studied by the GPS-X model. The data were collected accurately from the management of the station.

Calibration and model validation were performed, some sensitive parameters were modified, and the results were validated by using statistical parameters of R and RMSE. Sensitivity analysis showed that the most important factor for reducing nitrogen and phosphorous concentrations is the biodegradable fraction Readily Biodegradable COD (rbCOD). Internal Recycl (IR), Return Activated Sludge (RAS), Dissolved Oxygen (DO), and waste Activated Sludge (WAS) fluxes were reduced from 3% to 1%, from 100 to 20%, from 3.5 to 2 mg/L, and from 3,500 to 1,000 m^3/day, respectively. Optimization results provided power of 688.4 kWh and sludge reduction by 32%. The results showed that it is not feasible to obtain an IR of 3% due to the deficiency of rbCOD at concentrations sufficient to contribute to the nitrate reduction. The decrease in rbCOD concentrations in the wastewater of Karbala city requires chemical upgrade, that was done by adding an external source of carbon represented by acetic acid, propionic acid, methanol, and glycerol, and the results were good, and this led to an improvement by reducing TN and TP by (60% and 77%), (68% and 79%), (71% and 77%), and (29% and 38%), respectively. The best external carbon source was methanol, while glycerol was less effective than the rest. The pre-denitrification process was compared with the post-denitrification process by adding methanol as an external carbon source. The results were good for reducing TN in the post-denitrification process, which reached 80%, while the effect was negative on the remaining pollutants.

The study concluded that process of organizing treatment plant and conducting a proper mass balance contributes to reducing energy and improving the biological processes of the plant. The GPS-X program has contributed to giving a complete effective and very close to reality, also its recommend use in the departments of sewage directorates and engineers working in this field.

Undertaking

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Dedication

I dedicate this work:

To whom I proudly bear his name; father .To whom did she drink the cup of misery to drink me nectar of happiness; mother .To my beloved husband, without his support, I can't have this much Knowledge Thank you from the bottom of my heart.I am grateful to them

Finally To those who gave their lives in order for us to live; Martyrs of Iraq

Acknowledgements

All praise and glory to Almighty ALLAH for providing me with the health and strength to finish this work and do something that will benefits humanity. I would want to express my gratitude to my beloved husband and close friend zahraa shubber for their unwavering and continuous support in helping me finish my research.My thanks and appreciations go to my supervisors Dr. Basim Khalil Nile Dr. Jabbar Hammoud Al-Baidani for their guidance, patience, motivation, support, and advice during the research.The management of the karbala wastewater treatment plant and Dr.Ahmed Maktoof Alshemmary deserve special gratitude for their invaluable assistance.

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List of Abbreviations

Abbreviations	Description
ASM	Activated Sludge Model
ASP	Activated Sludge Process
BNR	Biological Nutrient Removal
BOD	Biochemical Oxygen Demand
C/N/P	Carbon, nitrogen and phosphorus
CLR	Continuous Loop Reactor
COD	Chemical Oxygen Demand
DHR	Dwars, Heederik and Verhay
DO	Dissolved Oxygen
EAAS	Extended Aeration Activated Sludge
EBPR	Enhance Biological Phosphorus Removal
EPA	Environmental Protection Agency
F/M	Food to Microorganism
FC	Fecal Coliform
GIS	Geographic Information System
GRP	Glass Reinforced Plastics
HRT	Hydraulic Retention Time
IAWPRC	International Association on Water Pollution Research Control
IAWQ	International Association Water Quality
IFAS	The integrated fixed film activated sludge system.
KSOFM	Kohonen Self-Organizing Feature Map
MLD	Megalitre per day
MLSS	Mixed Liquor Suspended Solids
NH3	total ammonia
rbCOD	Readily Biodegradable COD

Ɵc	Sludge Age
PAOs	Poly Alpha Olefins
PHA	Poly Hydroxyl Alkanets
PO4	Phosphorus
RAS	Return Activated Sludge
SCADA	Supervisory control and data acquisition
SLR	Solids Loading Rate
SND	Simultaneous Nitrification And Denitrification
SOR	Surface Overflow Rate
SRT	Solid Retention Time
SVI	Sludge Volume Index
TC	Total Coliform
TKN	Total Kjeldahl Nitrogen
TSS	Total Suspended Solid
VFA	volatile fatty acids
WAS	Waste Activated Sludge
WWTP	Waste Water Treatment Plant
IR	Internal Recycle

List of Symbols

Symbols	Description
so	Dissolved oxygen
si	Soluble inert organic
scol	Colloidal organic substrate
ss	Fermentable substrate
sac	Acetate
spro	Propionate
smet	Methanol
sh2	Dissolved hydrogen
sch4	Dissolved methane
stic	Dissolved inorganic carbon
snd	Soluble organic nitrogen
snh	Ammonia nitrogen
snoi	Nitrite nitrogen
snoa	Nitrate nitrogen
S_{n2}	Dissolved nitrogen
snrio	Nitric oxide-Nitrogen
snroo	Nitrous Oxide
snh2oh	Hydroxylamine1
snoh	Nitrosyl radical
sp	Ortho-phosphate
smg	Dissolved magnesium
spot	Dissolved potassium
scat	Dissolved cation
sana	Dissolved anion

xi	Inert Particulate
xu	Un-biodegradable cell decay material
xs	Slowly biodegradable organics
xbt	PHA accumulated in PAO
xbh	Heterotrophic biomass
MLR	Mixed liquor recycle
A_2/O	Anarobic /Anoxic/Oxic reactor
PHB	Polyhydroxybutyrate
Q_{in}	Discharge Influent
Q_w	Discharge Wasted Sludge
Q_{rs}	Discharge Recycled Sludge
P_{s2}	Primary Sludge
S_{s2}	Specific Gravity
W_{BOD5}	Weight Biochemical Oxygen Demand
W_{TSS}	Weight Total Suspended Solid
Qeff	Discharge Effluent

Chapter One: INRTODUCTION

1.1 General background

Water scarcity in Iraq has begun to noticeably occur. Reducing water sources, especially the level of the Tigris and Euphrates rivers, has become an urgent necessity to find alternative sources or support these sources from wastewater recycling sources (Sulaiman, Kamel, Sayl, & Alfadhel, 2019). The large population growth in Iraq also had a significant impact on water consumption and the release of large quantities of polluted water. Wastewater treatment plants have become an urgent necessity to support water sources and reduce pollution in them. Population growth caused an increase in pollutant concentrations, especially nitrogen and phosphorous (Koné, 2010), which are essential nutrients to increase eutrophication in rivers. The growth of algae, reeds, and sedge in rivers causes very big problems (Zhao et al., 2022). Therefore, the process of improving plants has become a basic necessity to eliminate or reduce pollutants when the sewage is discharged into water sources.

Wastewater treatment plants face some challenges, especially in the biological and chemical phases (Solon, et al 2019). Biological processes depend on the donor electron sources and the acceptor electron, and in the event of any deficiency in these sources, the biological treatment processes will be affected (Di Capua, et al 2019). The addition of chemicals may cause an increase in operating costs. Therefore, in the process of improvement, it must be taken into account the above considerations. Increasing concentrations of pollutants require expansion in the plant units, but sometimes it needs improvement in treatment processes. Treatment plants are designed according to the required parameters, and sometimes for the lack of data, they are designed based on the highest values of pollutant concentrations, and in this case, they affect the efficiency of the plant during operation.

Conventional activated sludge processes are one of the most prominent wastewater treatment systems with numerous advantages (Metcalf et al., 2014). There are many studies dealing with the improvement of traditional activated sludge processes. There are many improvements made by different models. The GPS-X model is one of the most well-known and effective wastewater treatment models. The GPS-X model is the first commercially and educationally released dynamic simulation model for wastewater treatment plants. The model is considered the world's first in wastewater treatment plants to simulate it mathematically and to control the operations, improvement, and management. The system provides an easy-to-use, robust and high-speed platform with calibrated wastewater treatment plants (Faris, et al. 2022).

1.2 Problem statement

Wastewater treatment plants are the most effective tool for keeping water sources from pollution. In the treated wastewater, high concentrations of nitrates and phosphates were observed, which contributed to the growth of harmful plants in the source of sewage disposal for the Karbala sewage treatment plant (see Figure 1.1). The presence of these concentrations has affected public health and aquatic life. To understand and know the reasons for this deterioration in the elimination of nitrates and phosphates, a complete analysis of the parts of the plant and the concentrations of donor and acceptor electrons will be conducted and the improvement of the reduction of these concentrations using the GPS-X Model. To solve these challenges, multiple scenarios were used by optimizing mass balance processes to control energy consumption and improve cost and plant performance. The Karbala sewage treatment plant was also upgraded by removing or adding units to reduce nitrogen and phosphorous concentrations in the treated wastewater.

Figure 1-1:Effect of phosphorous and nitrogen concentrations on water sources.

1.3 Research objectives

The main objectives of the present study are:

1. knowing the performance of the Karbala wastewater treatment plant by collecting and testing samples for one full year.
2. improving the Karbala wastewater treatment plant in practice by regulating the operating system.
3. upgrading Karbala wastewater treatment plant by replacing the chlorination and adding a UV disinfection system.
4. reducing the TSS, COD, and BOD concentrations by adding a sand filter.
5. biological upgrades to reduce nutrient removal.
6. knowing the effect of external carbon sources on nutrient removal.
7. using the GPS-X Model to improve, upgrade, and get the most proper operation system for the Karbala wastewater treatment plant.

1.4 Research methodology

In the present study, the framework was as follows:

1. Data collection from Karbala wastewater treatment plant.
2. Testing samples from the plant according to units in the standard method of examination laboratory for one full year, and then analyzing them.
3. Evaluation of the efficiency of the Karbala wastewater treatment plant's performance according to the data obtained by the administrative staff of the plant.
4. Regulating the plant’s processes according to the quantity and quality of the real wastewater entering the plant.
5. GPS-X Model was used to design the Karbala sewage treatment plant.
6. Calibration and validation of the model used.

7. Upgrading the Karbala wastewater treatment plant physically, biologically, and chemically.
8. Collecting and analyzing the results of upgrading and regulating.

1.5 Outline of The Thesis

This thesis consists of five chapters and below are the details of each chapter:

1. **The first chapter** contains an overview of the research problem ,objectives , the framework of the research ,and building thesis.
2. **The second chapter** contains previous studies.
3. **The third chapter** includes working techniques for the Karbala sewage treatment plant, such as data collecting, and how to operate the Karbala sewage treatment plant using the GPS-X model after calibration and validation.
4. **The fourth chapter** includes data analysis and knowledge of the efficiency of the performance of processing sewage station Karbala and extracting results from modeler and analysis.
5. **The fifth chapter** contains conclusions and recommendations.

Chapter Two: LITERATUER REVIEW

2.1 Wastewater

Wastewater is water whose physical, chemical, or biological qualities have been altered by introducing of certain compounds, rendering it unfit for specific uses such as drinking (Englande Jr et al. 2015). Man's daily activities are largely dependent on water, and as a result, 'waste' is discharged into the water. Body waste (feces and urine), hair shampoo, fat, hair, food scraps, toilet paper, laundry powder, fabric conditioners, dirt, chemicals, detergent, household cleansers, and microorganisms (germs) are just a few of the items that can make people sick and harm the environment. It is well known that more of the water supplied ends up as wastewater, necessitating its treatment. Wastewater treatment is the technique and mechanism for removing the majority of hazards contained in wastewater to reduce pollution and environmental health. Wastewater management thus entails treating wastewater in a manner that protects the environment while also ensuring public health, social, economic, and political stability(Yaqoob, Parveen et al. 2020).

2.2 Wastewater Sources and Types

While the sources of wastewater vary by place. The list below gives an outline of common sources (Naidoo and Olaniran 2014, Kataki et al. 2021):

1. Domestic wastewater
2. Industrial Wastewater
3. Municipal Wastewater
4. Surface Wastewater
5. Groundwater Infiltration
6. Agricultural Wastewater

Domestic wastewater is water that has been used by families or other similar facilities, and it may be split into two groups:

1. **Black water** is water that has been contaminated by human or animal feces and urine.
2. **Greywater** has been contaminated by washing, bathing, cooking, and other similar behavior.

The bulk of the time, grey and black water are not separated and end up in the same sewer network. The fact that these processes result in a certain composition of pollutants/nutrients in the wastewater is critical for the treatment procedure.

Industrial wastewater, has been contaminated during industrial processes such as fabrication, cleaning, or cooling is referred to as industrial wastewater. Industrial wastewater can have a completely different nature than domestic sewage, and it is largely dependent on the type of industry discharge. As a result, each source has its specific qualities. Although one industrial discharger (for example, the food processing business) releases large levels of COD into the stream, others have high nitrate levels. If the manufacturing process is arranged in batches, the composition of the final product can vary dramatically from day to day. The implementation of control and optimization strategies is complicated by these imponderables. Additionally, industrial effluent may contain contaminants that can only be detected in a laboratory setting.

Municipal wastewater is a phrase that relates to water from a city and includes both domestic and industrial sewage.

Surface wastewater is water that has runoff from parking lots, streets, and other sealed surfaces near a sewer network. As a result, petrol, oil, exhaust, rubber, street abrasion, and other contaminants may pollute it. When the

WWTP is connected to a combined sewer, it becomes important for the treatment plant and the control mechanism during rain events since the influent on the plant increases dramatically.

Groundwater Infiltration is a particular form of pollution. It may be argued that it is not wastewater in the strictest sense. Infiltration water is water that has leaked into the sewer system (typically from the ground). It is then mixed with other types of wastewater in the sewer and delivered to the wastewater treatment facility. As a result, it is processed in a WWTP; however, it primarily results in the diluting of other forms of sewage. Because the amount varies throughout the year and changes with the groundwater level, it must be considered during optimization or controller development.

Agricultural wastewater is water that has been utilized in farming. Fertilizers, feces, pesticides, and other pollutants are common contaminants. Only agricultural wastewater from point sources, such as live breeding facilities, is of importance to treatment processes. In most cases, contaminated water in fields is not collected and instead flows directly into groundwater or river banks.

2.3 Wastewater Treatment Infrastructure

2.3.1 Sewer System

The sewer system's goal is to convey wastewater speedily from a source to a treatment plant. It is usually an underground network of pipelines with little or no technology. There are two main types (Kuliczkowska 2015, Panasiuk, et al. 2015, Malek et al. 2020):

1. Sanitary Sewers: This type of sewer network is just for wastewater. A runoff drainage system collects rainwater separately. These systems have the advantage of just requiring the linked treatment plant to manage with pure

sewage, as changes in the input are created solely by sewage producers. Additionally, the input typically follows a diurnal cycle that is easily predicted and can be used to optimize control. In practice, however, it is difficult to avoid infiltration water, particularly if the network is older. As a result, when groundwater levels increase, diluting effects must be expected. In general, these systems have the disadvantage of necessitating the installation of a second system for stormwater runoff. As a result, the costs are much more than with combined sewers.

2. Combined Sewers: Wastewater and stormwater are transported by combined sewers. On the other hand, the network is significantly less expensive than sanitary sewers because only one subterranean system is required. However, it has some disadvantages:

- The connected treatment plant must be built in such a way that it can handle greater inputs.
- To buffer wastewater during heavy rain events, additional stormwater tanks must be incorporated into the system.
- The network must be designed to accommodate the additional stormwater runoff.
- Peak flows appear during rainstorms.

2.4 The Evolution of Wastewater Treatment

Since the early Mesopotamian Empire in Iraq (ca. 4000–2500 BC), drains in the streets have been recognized. However, the Minoan and Harappan civilizations in Crete and the larger Indus valley, respectively, adopted well-organized and operational sewerage and drainage systems for the first time in human history after ca. 3000 BC. Even though the huge underground drain of ancient Rome was the world's first sewer, sewage treatment is a relatively new technique coming from the late 1800s and early 1900s. In England, treated wastewater was not given much thought until the mid-1800s, when sewerage systems were built in the aftermath of the cholera epidemic, which claimed over 25,000 lives during 1848 and 1854 (De Feo, et al. 2014). Because the rivers in the United Kingdom are relatively tiny, untreated wastewater released into them quickly became a hazard. The development of extensive wastewater treatment systems became necessary as rivers got contaminated and the area of land suitable for wastewater disposal via irrigation remained limited. So because the effect of pollution caused by sewage discharged into relatively rivers and lakes was small and because there were large areas available for wastewater treatment on land in the United States, wastewater treatment and disposal did not receive as much attention as they did in England. According to, the first septic tanks were utilized in the United States in 1876, and the Massachusetts State Board of Health built the Lawrence Experiment Station in 1887 to examine both water and sewage treatment. The earliest approach to improving the quality of the water via treatment was to use physical methods like sedimentation and dilution. According to (Spellman ,2003), the first sewage treatment facility in Germany (Frankfurt/Main, based on grit removal, screens, and a settling tank) was installed in 1887 (Rustum 2009). But, as populations became larger and environmental rules got stricter, this became insufficient. That led to the development of biological treatment processes such as trickling filters and biological beds, which date back to the late nineteenth century and were further refined and enhanced in the early 1920s. The revelation that additional aeration of sewage resulted in better and faster purification was another milestone in biological sewage disposal. Studies on the activated sludge system, which was found in 1913 by Ardern and Locket from laboratory experiments at the Davyhulme treatment facility in Manchester, England, were carried out at the turn of the twentieth century. It was given the name activated sludge because it contributes to the development of an activated population of bacteria capable of aerobically stabilizing pollutants. Many variations of the original procedure are still in use today, but they are all fundamentally the same. Activated sludge operations with two may be more aeration basins, for example, may be designed to operate in a variety of modes. The method of operation is determined by the feed point of primary clarifier effluent or activated sludge influent and return activated sludge. Complete mix, plug-flow, step feed, and contact stabilization are some of the mechanisms for wastewater treatment. Chemical additives were then applied to improve the waste's settleability during clarifying. Tertiary treatment, including nutrient elimination processes and sand filtering, is also used in some sensitive locations to optimize the performance of the treatment plants. Wastewater treatment has evolved into a highly sophisticated sector over the previous few decades(Zhang and Chen ,2020).

2.5 Treatment goals for wastewater

For the reasons stated above, wastewater treatment is essential. It is more important for the(Awaleh and Soubaneh 2014, Metcalf, et al., 2014):

1. **Environmental elimination of biodegradable organic compounds:** Organic components, such as carbon, nitrogen, phosphorus, and sulfur, the inorganic matter must be decomposed by oxygen into gases that are either emitted or stay in sewage.
2. **Reduce nutrient:** Nutrients from sewage in the environment enhance watercourses or make them eutrophic, allowing algae and other aquatic

plants to proliferate. These plants reduce oxygen in water bodies, causing aquatic life to suffer.

3. **Reduce pathogens:** Pathogens are microorganisms that cause disease in people, animals, and plants. They're called microorganisms because they're so small that they can't be seen with the naked eye.
4. **Water reuse and recycling**: Water is a limited and precious resource that is frequently overlooked. Population growth in the second part of the twentieth century put further strain on already limited water resources. The agrarian nature of many locations has also changed as a result of urbanization. Population growth necessitates the cultivation of more food, and agriculture, as we all know, is by far the largest user of available water, implying that economic growth places growing challenges on existing water supplies. Groundwater resources are being depleted, making the distribution of water both temporally and spatially a considerable concern. Recycling and reuse are critical for long-term sustainability for these reasons.

2.6 Wastewater characteristics

Wastewater has different qualities depending on where it comes from. Water makes up 99.9% of municipal wastewater. Suspended (settleable and nonsettleablel) and dissolved solids with organic and inorganic components, as well as microorganisms, make up the remaining elements(Yang, et al. 2020). These elements provide residential, commercial, and industrial wastewaters with their physical, chemical, and biological features. Physical, chemical, and biological pollutants are the three types of contaminants found in sewage. Some of the indicators used to identify these pollutants include(Metcalf, et al., 2014, Slavov 2017):

1. Physical
    - **TSS**: Solid particles suspended (but not dissolved) in water are known as total suspended solids (TSS).
    - **TDS:** Inorganic compounds and small quantities of organic materials dissolved in water make up total dissolved solids (TDS).
    - **EC**: The salt concentration is indicated by the electrical conductivity (EC).
2. Chemical
    - **DO**: The quantity of oxygen dissolved in wastewater is known as dissolved oxygen (DO).
    - **BOD:** The amount of oxygen required by aerobic bacteria to degrade the organic matter in a sample of wastewater in a given period is known as biochemical oxygen demand (BOD).
    - **COD:** The oxygen equivalent of the organic matter content of a sample that is sensitive to oxidation by a powerful chemical oxidant is known as chemical oxygen demand (COD).
    - **TOC**: The total organic carbon (TOC) test is a popular test for small amounts of organic matter because it may be done quickly. Wet oxidation or introducing a known quantity of sample into a high-temperature furnace are also methods for measuring it. The amount of carbon dioxide produced is calculated quantitatively.
    - Theoretical organic carbon is another way to measure organic matter (ThOC).
    - **NH4-N and NO3-N**: Dissolved nitrogen is represented by NH4-N and NO3-N. (Ammonium and Nitrate, respectively).

- **Total Kjeldhal Nitrogen** is a test of ammonia nitrogen bonded to organic matter.
- **Total-P** measures the total quantity of phosphorus in a sample.

3. Biological

- **Total coliforms (TC)** is a comprehensive indicator of potential environmental pollution that includes fecal coliforms as well as typical soil microorganisms.
- **Fecal coliforms (FC)** are a marker for fecal matter pollution in water. The bacteria Escherichia coli, or E. coli, is a typical lead indicator.
- **Helminth** analysis examines the water for worm eggs.

2.7 Process of wastewater treatment

The unit operations and processes in treating wastewater can also be classified as such depending on the nature of the pollutants in sewage physical, chemical, and biological. The following are the units' operations and processes in sewage treatment as shown in Figure 2.1 (Qasim and Zhu ,2017, Canton ,2021):

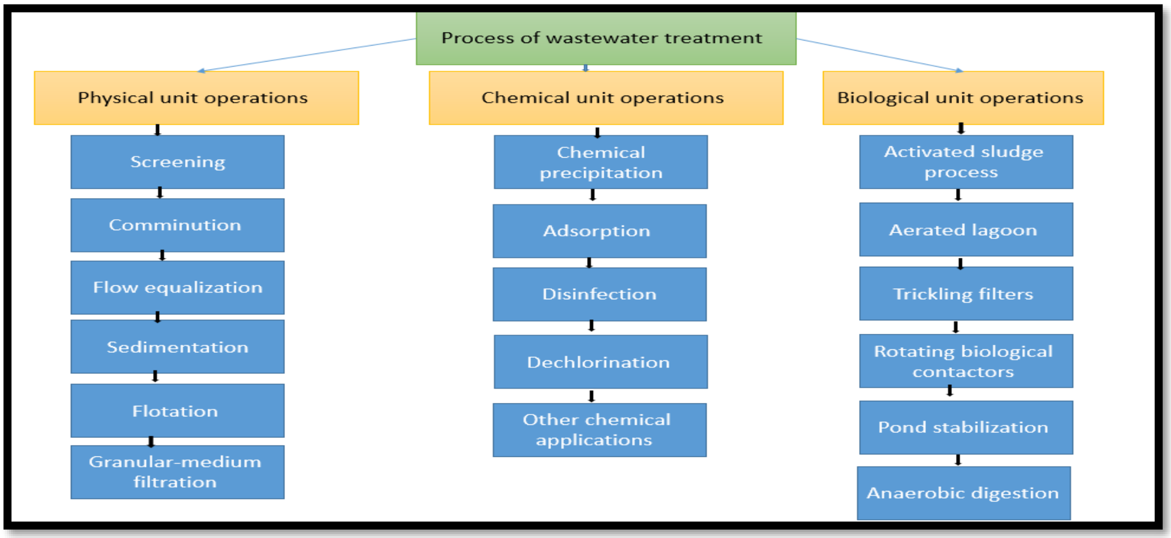


Figure 2-1:Process of wastewater treatment.

2.8 process of wastewater treatment

According to the traditional conditions in which the treatment plant is selected, there are five levels of treatment that are often present in any treatment plant, and these levels are explained in detail below (Figure 2.2) (Ullah, et al., 2020):

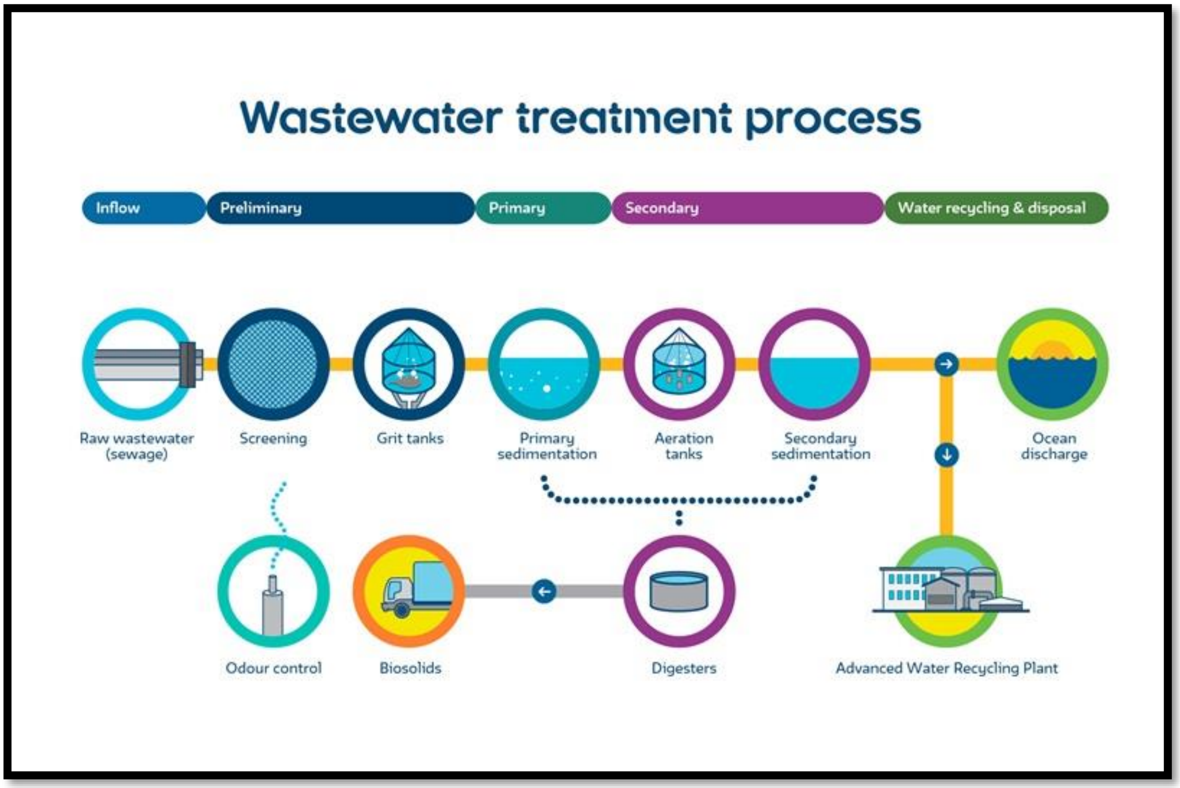


Figure 2-2:Levels of wastewater treatment(Ullah, et al., 2020).

- **The preliminary treatment** removes oil, grits, and coarse suspended particles. Screening and grit chambers can be used to get rid of them. This makes it easier to operate and maintain successive treatment units. At this step of the treatment, flow monitoring instruments, such as standing-wave flumes, are required.
- **Primary treatment:** By sedimentation, removes settleable organic and inorganic solids, as well as floating contaminants (scum) by scraping. This step allows for the removal of up to 50% of BOD5, 70% of

suspended particles, and 65% of fats and oil. Heavy metals, organic nitrogen, and organic phosphorus are also eliminated. At this phase, however, no colloidal or dissolved elements are eliminated. Primary effluent is the effluent produced by primary sedimentation units (Shatu ,2016).

- **Secondary treatment:** Secondary treatment is the process of removing leftover organics and suspended particles from the primary effluent. Aerobic biological treatment techniques also remove biodegradable and colloidal organic waste. When organic matter is eliminated, nitrogen and phosphorus compounds, as well as harmful microbes, are removed. Technical treatment, such as trickling filters, activated sludge processes and rotating biological contactors (RBC), or non-mechanical treatment, such as anaerobic treatment, oxidation ditches, and stabilization ponds, are examples (Rajesh Banu, et al., 2021).
- **Tertiary treatment:** When specific wastewater elements that cannot be removed by secondary treatment, tertiary treatment is used. Significant amounts of nitrogen, phosphate, heavy metals, biodegradable organics, bacteria, and viruses are removed during tertiary treatment. Traditional sand (or similar medium) filters and newer membrane materials can both be utilized to successfully filter secondary effluent. Some filters have been enhanced, and helminths are removed by both filters and membranes. The most recent technology is disk filtration, which uses enormous cloth media disks mounted to rotating drums to filter water. At this level, disinfection with UV irradiation, chlorination, and ozonation, can be used to bring the water up to current international requirements for urban re-use and agriculture (Comber, et al. 2019).

- **Sludge treatment:** Sludge from treating wastewater is a byproduct**.** It contains a high quantity of plant nutrients, organic compounds, and pathogens, as well as organic and inorganic elements. As a result, it is critical to correctly handle such sludge to reduce its environmental impact. There are four conventional processes or steps for sludge treatment as follows (Martí, t et al. 2017, Qasim ., 2017): **First process-Sludge Thickening:** Thickening is the first process in the sewage sludge treatment process. The sewage sludge is thickened in a gravity thickener in this process to reduce its overall volume and make it easier to manage. Sometimes the primary sludge is separated from the secondary sludge produced by the secondary sedimentation tanks due to the difference in density. The secondary sludge is treated by a mechanical thickener.
- **Second process- Sludge Digestion:** The sludge digesting process begins once all the solids from the sewage sludge have been collected. This is a biological process that decomposes the organic materials in the sludge into stable compounds. This technique also aids in the reduction of total solids bulk while also killing any pathogens present, allowing for easier dewatering. The digestion of sludge is a 3-phase process. The dry solid sludge is heated and combined in a closed tank in the first stage to allow anaerobic digestion by acid-forming bacteria. These bacteria break down the big molecules of proteins and lipids in the sludge into smaller water-soluble molecules, which they subsequently ferment into different fatty acids. After the stage of converting easily degradable materials into acids, the third stage begins, which is the process of producing methane. Methane is captured and

reused to power the digestion tank and generate electricity (depending on the quantity retrieved).

- **Third process – Dewatering:** After retrieving useful gases and other byproducts, the remaining sludge is then dewatered before final disposal. Despite its solidified nature, dewatered sludge frequently contains a large quantity of water, up to 70% in most situations. As a result, it is necessary to dry and dewater the sludge ahead of time. While the most popular method of carrying out this operation is to use sludge-drying beds, it is incredibly time-consuming and can take weeks to accomplish. But the maintenance of the drying beds is very low compared to the rest of the techniques for drying the sludge.
- **Forth process– Disposal:** Depending on its chemical makeup, sludge can be buried underground in a sanitary landfill or used as fertilizer once it has been adequately dewatered. If the sludge is too poisonous to be reused or buried, it can be incinerated and turned into ash. While wastewater sludge is typically treated using a standard plan of action, it is critical to consider factors such as the source of the sewage, the treatment process used to reduce the sewage to sludge, and the potential byproducts that can be recovered from it for further use before deciding on a sludge treatment plan.

2.9 Wastewater treatment microbiology

Conventional biological plants are dependent on biological processes that take place in a body of water. Decomposition of organic substances with the help of existing microbes in wastewater is one of these biological processes (Grandclément,et al., 2017). Because treatment technologies are complex, involving a variety of processes such as nitrification, denitrification, and others, it is critical to make use of the vast quantity of information technology to optimize and design such systems (Jia and Yuan., 2016). The major purpose of implementing this technology is to allow the purifying process to run at higher speeds and under more controlled circumstances. Although most sewage treatment plants are developed using engineering principles, they still rely on creatures such as bacteria, algae, fungi, and protozoa to break down organic pollutants (Birkett , 2018). The activity of the microorganisms in the water body, on the other hand, can determine the performance of a biological wastewater treatment facility. As a result, it's necessary to study the microbiology and ecology of sewage treatment. Autotrophs and heterotrophs are naturally present in biological wastewater treatment facilities and can be influenced by system operating parameters, location of facilities, and typical wastewater properties (Kumwimba and Meng, 2019). Heterotrophs rely on carbon absorption to survive and are responsible for the decomposition of readily biodegradable COD (rbCOD) in anaerobic, anoxic, and aerobic environments (Aragaw, 2021). Autotrophic organisms, on the other hand, rely on either light or inorganic compounds to survive and are responsible for the conversion of ammonia to nitrate or nitrite (nitrification). Because autotrophic nitrifiers have a slower growth rate and lower oxygen usage kinetics, WWTPs with autotrophic nitrification are more expensive than aerobic heterotrophs (Reino, Suárez-Ojeda et al. 2016).

2.9.1 Ecology

Depending on the process, microorganisms play an important role in sewage treatment plants. Bacteria and protozoa are the two main types of microorganisms engaged in aerobic treatment. Fungi, rotifers, and other species play a little role in the ecosystem (Madoni 2011, Adebayo and

Obiekezie, 2018). The two main categories for the breakdown of organic compounds are bacteria and protozoa. Bacteria are prokaryotic unicellular bacteria with a hard cell membrane. Autotrophic bacteria are more sensitive than bacteria that are heterotrophic (Dehghani, et al., 2018). Furthermore, the ideal temperature and pH ranges for bacteria development are limited. Organic matter is divided into two categories: readily biodegradable and slowly biodegradable (Choi, et al., 2017). The majority of the stuff in regular home sewage is easily biodegradable. Protozoa are single-celled eukaryotic creatures that lack a cell membrane. Protozoa's major role in sewage treatment is to decompose organic and inorganic nutrients. Several forms of protozoa, such as flagellates, amoebas, and ciliates, can be found in sewage treatment plants with extended sludge retention times and low loads. Protozoa cleanse the effluent in terms of suspended particles, in addition to removing organic waste (Verma, 2021). The absence of protozoa in mixed liquor increased organic carbon, effluent Biological Oxygen Demand (BOD), and mixed liquor suspended particles(MISS), according to some researchers. The two most common biomass growth configurations are (Machineni, 2019):

a) suspended growth
b) attached growth.

suspended growth is characterized by the absence of a supporting structure for the biomass, and it grows in a dispersed form in a liquid media. Stabilization ponds, activated sludge, and up-flow anaerobic sludge blanket reactors are common applications. Biofilms are formed when biomass is attached to a surface. When the flow rate is high, these biofilms allow the biomass to cling to the reactor and prevent it from washing out (Bajpai, 2017).compared biofilms to dispersed growth and found that biofilms have several advantages over suspended growth, including the capacity to use diverse biological particles of various sizes, shapes, and sizes, as well as the ability to change growth rates while working in continuous reactors (Wells, et al., 2017).

2.9.2 Reaction Kinetics

Knowledge about the type of reactor being utilized, as well as the components moving in and out (mass balance) and reaction kinetics, are critical in any biological sewage treatment plant. Because the reactions in sewage treatment plants are typically sluggish, the reaction kinetics must be considered. Monod proposed one of the most often used formulas for connecting substrate concentration and specific growth rate in any biological wastewater treatment system. The expression is as follows (Metcalf, et al. 2014, Yousefi, et al., 2019):

$$\frac{ds}{dt} = r_{max} \ \frac{S}{S + K_s} \tag{2.1}$$

where:

$ds/\ dt$ = $reaction\ rate,$ $ML^{-3}T^{-1}$

r_{max} = $maximum\ reaction\ rate$, $ML^{-3}T^{-1}$

S = $substrate\ concentration$, ML^{-3}

KS = $half\ saturation\ coefficient,$ ML^{-3}

Both zero order and first-order kinetics can be used to define this equation. In zero-order kinetics, ds/dt = r_{max}, the rate of reaction becomes constant and no longer depends on the substrate concentration. In first-order kinetics, the substrate conversation is proportional to the reaction rate, which begins at a relatively low concentration and increases to the maximum concentration.

2.10 Activated Sludge Process

The traditional activated sludge system will be the focus of this study, since it is one of the treatment approaches for the suspended growth of bacteria. Activated sludge is the most extensively used biological wastewater treatment technique by several biological reactors (aerated vessels) and solid-liquid separators make up the majority of the system (sedimentation tank or settlers) (Karpinska and Bridgeman ,2016). It can perform four key sewage treatment processes: carbonaceous waste degradation or oxidation; nitrogenous waste degradation or oxidation; fine particles removal; and heavy metal removal. These activities are mostly accomplished by the development and maintenance of a large, diversified, and active bacterial population. As a result, it uses the dissolved oxygen supplied by the aerators to convert the biodegradable elements (COD) into new biomass, carbon dioxide, water, and leftover organic compounds (Tawfik, et al,2022). The clarifier's purpose is to remove suspended solids and biomass from aerated sewage and thicken the sludge before returning it to the reactor (Patel, et al, 2020). As a result, the main requirement of the activated sludge system is to maintain a high concentration of a mixed population of microorganisms in an artificially aerated vessel, known as the mixed liquid suspended solids (MLSS). The mixture of microorganism species is influenced not only by the influent sewage but also by the sewage treatment facility's operation. In the aeration basin, the microorganisms gradually grow and are kept suspended by blowing air into the tank or using mixers (Pittoors, et al,2014). Microbes use oxygen to oxidize organic materials. The MLSS is clarified and thickened in the sedimentation tank after exiting the aeration basin (hydraulic retention time is typically (6-30) hours). A portion of the thickened sludge from the settling tank is re-circulated back to the aeration basin to sustain the microbial population; the excess thickened sludge is then wasted. Normally, 30 to 150 % of the raw wastewater is returned to the aeration tank as sludge. Figure 2.3

depicts a basic schematic of the biological process in an activated sludge process (Metcalf, Eddy et al. 2014).

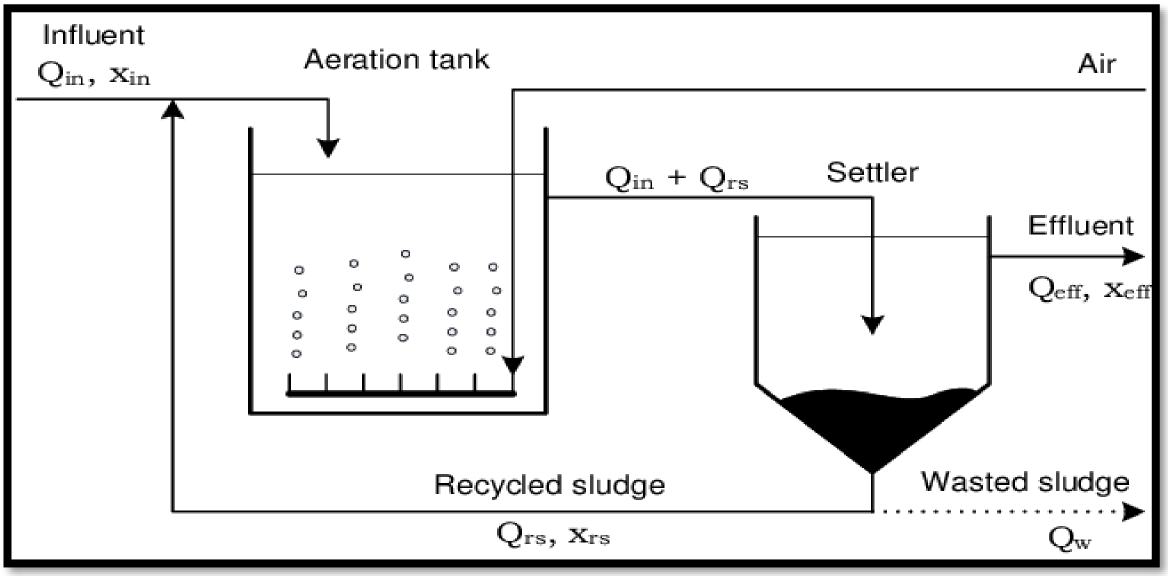


Figure 2-3:The biological process in an activated sludge process is depicted in a simplified diagram.

The rate of biomass growth is affected by some factors, including the amount of the substrate, biomass, pH, temperature, and the presence of toxins. Bacterial diversity and population increase over time as the mean cell resident time (MCRT) or sludge age increases. The COD is converted into new, less polluting wastes and more new bacterial cells or sludge at this time (Pang, et al, 2020). Fine particulates and heavy metals are removed from the bulk solution by bacteria, ciliated protozoa, and metazoans. The consumption of scattered cells is another important duty played by ciliated protozoans and metazoans. Cropping activity is the eating of scattered bacteria by these organisms. Biologically inert (non-biodegradable) matter is created during bio-reduction (the decomposition of microorganisms). Influent sewage will also contain inert substances. This material flows through the process unharmed, and it is collected and eliminated in the settlement (Metcalf, et al. 2014).

2.10.1 Control Strategies

Wastewater treatment plants using activated sludge systems are relatively dependable and can withstand shock loads, but they still require a lot more management and control. As a result, for sewage treatment plants to operate more efficiently, proper operation and control procedures are required. Reviewing the operating data and lab data is critical for controlling the activated sludge process and selecting the parameters that would deliver the best performance at the lowest cost (Krzeminski, et al,2019).

2.10.1.1 Dissolved Oxygen and Aeration Control

Aeration accounts for over half of the total energy consumed in biological nutrient removal systems (Keene, et al, 2017). As a result, maintaining the Dissolved Oxygen (DO) concentration in the aeration basin is critical. Controlling the levels of DO depending on the ammonia content in the effluent which is considered one of the most efficient techniques to monitor aeration. It is because of the nitrification process consumes the majority of the DO (Du, et al. 2018). A feedback controller with an integral connection to an integrated DO controller is known to save energy and have high effluent standards for such applications. In systems with small reactors and highly dynamic fluids, it is sometimes beneficial to utilize a combination of feedforward and feed backward controllers to obtain optimal performance. The DO level should be kept between 1–4 mg/L in most cases. When the concentration falls below 1 mg/L, the activity of bacteria decreases, resulting in their death. As a result, it is critical to maintain the DO concentration at all times to accomplish enough mixing, microbial activity, and complete degradation of organic wastes (Metcalf, et al, 2014).

2.10.1.2 Returned Activated Sludge (RAS) Control

The quantity of mixed liquor suspended solids (MLSS) that is returned to the aeration basin after being settled in the sedimentation tank is known as Return Activated Sludge (RAS). As a result, the MLSS must settle well in the sedimentation tank before being returned. In normal operations, the RAS returned to aeration is typically 30-100 % of the influent flow, whereas, in extended aeration, it can range from 50-150 %. Controlling RAS can be done in two ways (Metcalf, et al, 2014, Qasim and Zhu, 2017, Singh, et al. 2018):

1. A consistent percentage of the influent flow rate is sent back to the aeration basin when the RAS flow is monitored as a constant percentage of the influent. This ensures that the quantity of MLSS returned to the aeration tank remains constant at all flow rates, high and low.

2. The RAS flow rate is controlled independently by the influent flow rate for example, the RAS flowrate is set constant, resulting in the highest concentration of MLSS when the influent flow rate is lowest and vice versa. This is because the quantity of MLSS entering the clarifier varies depending on the intake, but the amount leaving the clarifier remains constant.

2.10.1.3 Waste Activated Sludge (WAS) Control

The amount of MLSS that is wasted is referred to as Waste Activated Sludge Control (WAS). It's done to maintain the availability of food and the microorganisms in check. Because the bacteria are constantly ingesting substrate from the sewage, they begin to reproduce and grow. As a result, it is critical to dispose of any extra biomass. Rather than sludge from the sedimentation tank, sludge from the mixed liquor in the aeration basin can be wasted. However, due of the huge volume of sludge, adequate sludge treatment facilities are necessary, which are not readily available at most facilities. Whenever sludge is excessed from RAS, the level of volatile suspended solids (VSS) in the RAS can be measured and managed. If the quantity to VSS in the RAS is decreasing, it is recommended that the WAS flow rate be increased to ensure that a sufficient amount of VSS is wasted, and vice versa. The following are the main strategies for manipulating the WAS(Metcalf, et al,2014, Yi, et al., 2021):

1. MCRT Control at a Constant Level
2. F/M Control at a Constant
3. Controlling the age of Sludge
4. MLVSS Control at a Constant Level
5. Control of Sludge Quality

2.11 Biological nutrients removal (BNR)

In an activated sludge system, there are many biological processes to remove nutrients; these processes are called biological nutrients removal (BNR) (Inyang, et al., 2016). The partition of the bioreactor to enable multiple biochemical conditions is a distinctive feature of BNR technology. Biological phosphorus removal, biological nitrogen removal, or combined biological phosphorus and nitrogen removal can all be part of a BNR system. A BNR system's bioreactor is also separated into anaerobic, anoxic, and aerobic regions, with sludge recycling involved, as shown in Figure2.3 (Pathak, et al. 2020).

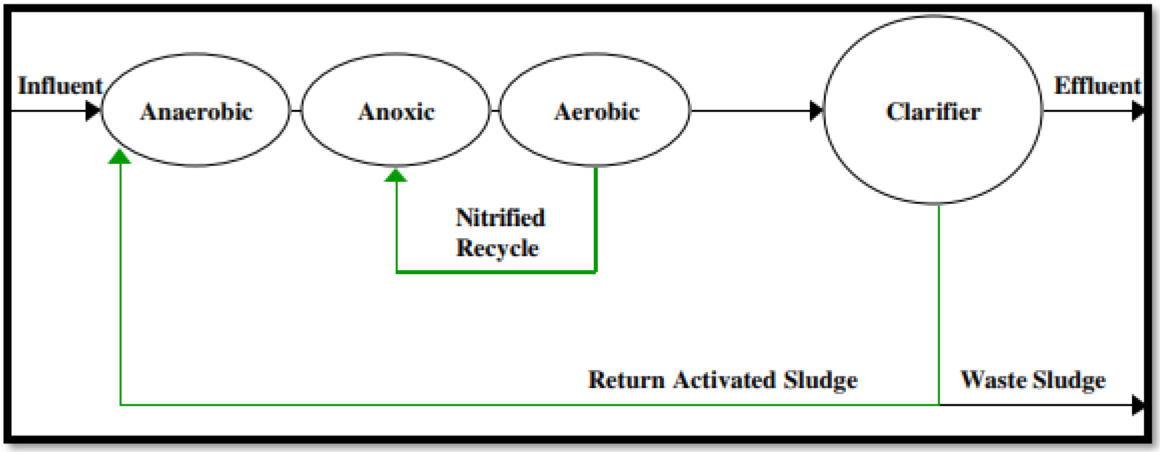


Figure 2-4:The anaerobic, anoxic, and aerobic zones of a BNR systems bioreactor.

The terminal electron acceptor used distinguishes three zones. The aerobic zone uses oxygen as an electron acceptor, while the anoxic zone uses nitrate as an electron acceptor, and the anaerobic zone has neither oxygen nor nitrate (Keene, et al., 2017). The aerobic zone is a required component of all BNR processes, and it denotes areas where dissolved oxygen is present. The anaerobic zone is required for phosphorus elimination and is defined as a zone with rbCOD input, no DO, and no nitrate-nitrogen intake (Izadi, et al., 2020). The anoxic zone, which has a DO of less than 0.5mg/L and a nitrate-nitrogen intake, is required for nitrogen elimination (Jiang,et al., 2019). Biological techniques for the regulation of phosphorus and nitrogen in sewage effluent have attracted a lot of attention and research during the last ten years. Essentially, the developed techniques are adaptations of the conventional activated-sludge process. Nitrogen removal through biological nitrification and denitrification only, biological phosphorus removal solely, and nitrogen and phosphorus removal in dual or combination systems have all been established. Some chemicals may be added to augment these procedures, depending on the discharge residual requirements and dependability objectives (Kelly and He, 2014). The development of several system modifications has resulted from more research into the processes, microbiology, stoichiometry, and kinetics of BNR processes. Each variation is usually called after the individual who devised the new method or the treatment plant where it was found or used for the first time. Variations in zone order as well as recycle flows are common phenomena in the BNR process. Different components of the biological nutrient removal can be improved because of the differences. Some procedures are excellent at removing phosphorus, whereas others are only for removing nitrogen. BNR modes are chosen on a site-by-site basis and are based on a variety of parameters, including influent sewage characteristics and the level of treatment required. Table 2.1 shows a review of the benefits and drawbacks of each biological nutrient removal (BNR) process variant (Metcalf, et al. 2014, Qasim and Zhu, 2017).

Table 2-1:Offers a comparison of the advantages and disadvantages of each biological nutrient removal (BNR) procedure.

Process	**Advantages**	**Disadvantages**
MLE	Good N removal	In most cases, a high amount of nitrogen removal is not practicable.
	Reactor volume is moderate.	
	Alkalinity recovery	Not designed for phosphorus removal
	Good solids settleability	
	Reduced oxygen requirement	
	Simple control	
removal Four Stage Bardenpho	Excellent nitrogen removal	Large reactor volume
	Alkalinity recovery	Not designed for phosphorus removal
	Good solids settleability	
	Reduced oxygen requirement	
	Simple control	

Process	**Advantages**	**Disadvantages**
A/O	Minimum reactor volume	Phosphorus removal is adversely impacted if nitrification occurs
	Good phosphorus removal	
	Good solids settleability	Not designed for nitrogen removal
	Simple operation	
Phostrip	Good phosphorus removal	Complex operation
		Phosphorus removal is adversely impacted if nitrification occurs
		Cost of chemicals to precipitate Phos
		Not designed for nitrogen removal
A2/O	Good nitrogen removal	A high level of nitrogen removal is not generally possible
	Moderate reactor volume	
	Alkalinity recovery	Moderate phosphorus removal
	Good solids settleability	
	Reduced oxygen requirement	
	Simple control	
VIP	Good nitrogen removal	High level of nitrogen removal is not generally possible
	Good phosphorus removal	
	Moderate reactor volume	An additional mixed liquor recycle step is required
	Alkalinity recovery	
	Good solids settleability	
	Reduced oxygen requirement	
	High rate process	
	Simple control	
UCT	Good nitrogen removal	A high level of nitrogen removal is not generally possible
	Good phosphorus removal	
	Moderate reactor volume	An additional mixed liquor recycle step is required
	Alkalinity recovery	
	Reduced oxygen requirement	
	Simple control	
MUCT	Good nitrogen removal	A high level of nitrogen removal is not generally possible
	Good phosphorus removal	
	Moderate reactor volume	An additional mixed liquor recycle step is required
	Alkalinity recovery	
	Multiple anoxic cells to improve performance	
	Good solids settleability	
	Reduced oxygen requirement	

	Simple control	
Five-Stage Bardenpho	Excellent nitrogen removal	Large reactor volume
	Alkalinity recovery	Moderate to poor phosphorus removal
	Good solids settleability	
	Reduced oxygen requirement	
	Simple control	
OWASA	Good phosphorus removal	Not configured to optimize nitrogen removal
	Sidestream anaerobic zone	
		Phosphorus removal is adversely impacted if nitrification occurs
CNC	Good nitrogen removal	An additional mixed liquor recycle step is required
	Good phosphorus removal	
	Sidestream anaerobic zone	External VFA source is required
	Multiple anoxic cells to improve performance	

2.11.1 Biological Nitrogen Removal

Organic, ammonium, and NO3 are the most common types of nitrogen in municipal wastewater that may require treatment. For some reason the presence of nitrogen in an effluent discharge is undesirable. Free ammonia is hazardous to fish and many other aquatic animals, and an ammonium ion or ammonia is an oxygen-consuming molecule that depletes dissolved oxygen in receiving water, as is well known. Nitrogen can be present as a nutrient to water plants in any form, which can lead to eutrophication (Ke, et al., 2022). In addition, nitrate ion is a possible public health threat in infants' drinking water (Sadler, et al., 2016). In summary, depending on the local conditions, all types of nitrogen or only ammonium may need to be removed. Aerobic zones for nitrification, anoxic zones for denitrification, and mixed liquor recirculation (MLR) to return the Nitrate-N created in the aerobic zone to the initial anoxic zone are all used in nitrogen removal techniques (Sobczyk 2019). Because nitrification is an aerobic process, it will only take place in aerobic zones. In the absence of dissolved oxygen, heterotrophic bacteria use nitrate-N as their terminal electron acceptor to oxidize organic materials (Qiao, et al., 2020). Nitrogen can appear in a variety of forms in wastewater and undergo a variety of changes during treatment. Several processes allow ammonia-nitrogen to be converted into products that can be easily eliminated from sewage. The elimination of nitrogen is performed in two conversion phases in nitrification-denitrification (Tan, Yang et al. 2020).

2.11.1.1 Nitrification process

Nitrosomonas and Nitrobacter are the microorganisms that cause nitrification. Nitrosomonas converts ammonia to nitrite as an intermediate product. Nitrobacter converts nitrite to nitrate, as shown in Equations 2.2 and 2.3, respectively (Metcalf, Eddy et al. 2014, Wang, Zheng et al. 2021).

$$2NH4 + 3O2 \longrightarrow 2NO2 + 4H^+ + 2H2O \qquad (2.2)$$

$$2NO_2 + O_2 \longrightarrow 2NO_3 \qquad (2.3)$$

As indicated by the lack of nitrite build-up in the system, the conversion from ammonia to nitrite includes a complicated series of reactions that control the overall conversion process. The number of chemicals required for the operations can be determined using these equations. Nitrifying bacteria are delicate organisms that are easily harmed by a wide range of inhibitors. The growth and action of organisms can be inhibited by a range of organic and inorganic substances. Ammonia and nitrous acid in high amounts can be inhibiting (Wang, et al, 2016). If there are considerable industrial discharges, inhibition is usually a concern. pH has a huge impact as well. As alkalinity is depleted, pH drops, lowering the rate of nitrification. The growth of nitrifying microorganisms is also influenced by temperature (Ganesh, et al. 2015). The rate of nitrification increases with temperature until it reaches a particular degree, after which it decreases. Nitrification requires dissolved oxygen values greater than 2 mg/L. Nitrification slows or stops when DO levels fall below 2 mg/L (Cao, et al, 2017).

2.11.1.2 De-nitrification process

Denitrification is the second stage in the nitrification-denitrification process, which removes nitrogen. This is the process of removing nitrogen in the form of nitrate by converting it to nitrogen gas, which can be done under anoxic (without oxygen-free) conditions (Mehrabi, et al, 2020). Many microorganism's genera, including Bacillus, Achromobacter, Alcaligenes, Aerobacter, Brevibacterium, Spirillum, Micrococcus, Proteus Lactobacillus, Pseudomonas, and Flavobacterium, can convert NO3 to a readily removable form. These microorganisms are heterotrophs that may reduce NO3 in a two-step process called dissimilatory nitrate reduction (Pankivskyi and Wang 2021). The change of nitrate to nitrite is the initial stage, followed by the formation of nitric oxide, nitrous oxide, and nitrogen gas (Chen, et al, 2015). The presence of nitrates, the absence of DO, and a source of rapidly biodegradable organic matter (rbCOD) are all required for denitrification. The microorganisms will choose to utilize free oxygen if DO is present (Phung 2018). Influent wastewater, endogenous decay, and an external carbon (methanol) supply are all sources of rbCOD. When the rbCOD source is inlet sewage or methanol, significantly higher denitrification rates are obtained. The key parameter in denitrifying systems is the DO concentration (Bauhs 2021). The enzyme system required for denitrification will be suppressed in the presence of DO (Wang and Chu, 2016). When nitrate is converted to nitrogen gas, alkalinity is created, resulting in a pH rise. The ideal pH ranges from 7 to 8, with varied optimums for various microorganism populations.

The rate of NO3 elimination and growth of microorganisms are both affected by temperature. Temperature variations have an impact on the microorganisms (Metcalf, et al, 2014, Rajta, et al., 2020).

2.11.2 Biological Phosphorus Removal

Phosphorus is a critical macronutrient that helps in the growth of photosynthetic algae and cyanobacteria, causing eutrophication of lakes and rivers to increase (Facey, et al., 2019). Discharge of sewage that reaches eutrophication-prone lakes and rivers frequently require additional phosphorus removal beyond what is routinely done in primary and secondary treatment. The practice of eliminating phosphorus from municipal wastewaters to restrict the growth of noxious aquatic plants is now in its third decade. Localized water quality issues are likely to result in progressively lower effluent phosphorus limits. As our knowledge of the mechanics underpinning biological phosphorus removal improves, we will be able to apply this method more widely and efficiently (Daneshgar, et al., 2018). Orthophosphate (ortho-P) ions, polyphosphates, and organic phosphorus compounds are the three main types of phosphorus present in sewage. Much of the polyphosphate and organic phosphate content in sewage is transformed to ortho-P during treatment, and inorganic phosphates are used to generate biological floc. Total phosphorus entering the plant in raw sewage and total phosphorus emitted in the plant effluent must be used to calculate removal efficiency (Yu, et al., 2021). Phosphorus accumulating organisms (PAO) in biomass can be introduced to influent containing volatile fatty acids (VFA) in a zone devoid of NO3 and DO for biological phosphorus removal. Phosphorus is released from the biomass in this zone. The PAOs re-accumulate phosphorus over their real synthesis demands in the next zone, the aeration zone(Lopez-Vazquez, et al., 2020). Nitrates will be present in the return activated sludge (RAS) if nitrification occurs in the aeration basin, and must be eliminated by some kind of denitrification before the RAS reaches the anaerobic zone, where the nitrates would obstruct genuine anaerobic conditions (Chen, et al., 2015). Acinetobacter is one of the most important PAOs for phosphorus removal. Under anaerobic conditions, these organisms release accumulated phosphorus in response to volatile fatty acids (VFAs) in the influent sewage. As a result, the VFAs are necessary for the acinetobacter. Both anaerobic and aerobic zones are required for biological phosphorus elimination. When an anaerobic zone is followed by an aerobic zone, bacteria take in more phosphorus than usual. Phosphorus is used by bacteria for cell upkeep, synthesis, and energy transmission, as well as being stored for later use (Li, et al., 2020).

2.12 BNR Design Computer-Based Modeling Tools

Modeling of activated sludge systems has become a standard aspect of sewage treatment plant operation and design. Models are utilized in the design, control, education, and research today (Brdjanovic, et al., 2015). The ease with which biological process modeling may be implemented has substantially enhanced since the integration of computer-based modeling tools into the design. Process computer simulation, such as BioWin and GPS-X allows engineers and operators to investigate what-if situations in wastewater treatment facilities without changing operations for the sake of trial and error, which could be harmful to the plant's performance. With the variable volume bioreactor element, a simulation software like GPS-X may configure model stoichiometric and kinetic parameters, schedule operating parameters like temperature, dissolved oxygen, and airflow, simulate biological activity, and simulate plant start-up situations (Amrutha and Haseena 2020). Because of the extended sludge retention durations and low growth rates of the bacteria, actual effluent substrate concentrations between different activated sludge treatment plants did not differ much during the early development of the process models. The concentrations of MLSS and electron acceptor, on the other hand, were significantly different (oxygen or nitrate). As a result, the activated sludge model is primarily concerned with estimating the amount and change of solids and electron acceptors. Because mass balances can be performed on COD, the model uses it as the measurement for the quantity of organic material (Urdalen, 2015). The degradability of the organic substance is one of the qualities that is used to classify it. Biomass is classified as heterotrophic or autotrophic, and nitrogenous material is classified according to its biodegradability and physical state. Carbon oxidation, nitrification, and denitrification are all included in the simulation of activated sludge systems, which account for a high number of reactions between a big number of materials(Metcalf, et al., 2014). The models depict the essential underlying events that occur in the system to generate realistic predictions. Each process' kinetics and stoichiometry are also quantified by the simulations. Environmental professionals can use simulation models such as GPS-X to precisely simulate the functioning of the activated sludge process. Building and calibrating the models, on the other hand, necessitates a high level of knowledge and a significant amount of time. Optimization of aeration basin design, examination of the effectiveness of alternative treatment strategies, evaluation of the impacts of future water quality standards, and identification of influences of dynamic process variations on daily effluent quality are among the benefits that outweigh the drawbacks. The use of such programs results in a design with great flexibility, unique biological nutrient removal arrangements that are easily adaptable to a variety of alternative treatment configurations, and operators with significant flexibility to meet future output wastewater requirements changes (Mabrouki, et al., 2020).

2.13 Literature review of previous studies

In the following sections, previous studies are presented related to performance Improving of WWTP and GPS-X program.

2.13.1Performance Improving of WWTP

For the Improving of performance of WWTPs, several studies have been conducted around the world where these studies included the work of examinations for influent and effluent wastewater, as well as calculation of the percentage of removal for each pollutant.

Çinar, 2005 provided a study on new tool for Improving of performance of WWTP: Artificial neural network. The artificial intelligence approach of Kohonen self-organizing feature maps was used to categorize operational data from the Pelham WWPT and to discover the causes of high effluent levels of TSS, BOD and fecal coliform. The results showed that the use of Kohonen Self-Organizing Feature Map (KSOFM) neural network on assessment of performance of WWTPs is a quick and easy approach to figure out the intricate interdependencies between process variables; as a result, the best method for solving operational difficulties in WWTPs can be determined. **Nikmanesh et al., 2018** carried out a study on the performance Improving of the system of aeration in the removal of microbial and physicochemical parameters from the WWTP. The obtained results showed that the mean removal efficiency of these parameters was 61.4%, 57.7%, 84.3%, 84.6%, and

70.8% for COD, BOD, fecal coliform (FC), total coliform (TC), and TSS, respectively. For the tank of aeration, the values of the time of hydraulic retention (HRT), the sludge age (ϴc), the index of sludge volume (SVI), the ratio of food to mass (F/M), and the mixed liquor suspended solids (MLSS) were determined, which were 25 h, 5.64 days, 48.83 ml/g, 0.28 day-1, and 180 mg/l, respectively. It was also found that the average value of pollutants after treatment in the hot months was greater than the cold months.

Awad, 2020, 2020 presented a study on improving the performance of the Albarrakiya trickling filter wastewater treatment plant, as well as modeling the plant using the GPSX program. The results showed the average annual concentrations of COD, TSS and NH3 were 120 mg/L, 92 mg/L and 11 mg/L, which exceeds the Iraqi quality standards, while BOD and PO4 was acceptable, but with critical values of 35 mg/L and 2.8 mg/L, respectively. The results of modeling and simulation using GPS program showed good performance according to the standards of input and output under real and hypothetical scenarios.

2.13.2 GPS-X program

Nowadays, many modifications and improvements have been made to simulate the GPS-X program, so, some global and local researchers presented and investigated a study and used the GPS-X program's ability to model and simulate any part or whole wastewater treatment plant to achieve their research objectives as shown below.

Kader, 2009 conducted a comparison study between sequencing batch reactor (SBR) and conventional activated sludge (CAS) to investigate the performance and treatment capability of both systems under different cases of operation by utilizing GPS-X (version 5.0). The results revealed that the SBR system has a greater ability to remove total nitrogen TKN (Total Kjeldahl Nitrogen) and total ammonia NH3 concentrations than the CAS system in all.

Arif et al., 2018 conducted a study to present a three alternative process using GPS-X including; complete mix activated sludge with nitrogen removal, complete mix activated sludge without nitrogen removal and membrane bioreactor and the results showed a good agreement between design values and simulated values.

Łagód et al., 2019 Using the GPS-X software program, I created a computer model of a sequencing batch reactor (SBR) at a laboratory scale. The simulation results for a 12-hour operating cycle were given; each cycle included six phases: filling, mixing, aeration, settling, decantation, and idling. Two distinct types of aeration were used in the simulations. The findings revealed that the second variation was characterized by lower levels of pollutant indicators in treated sewage, as well as lower power usage, both of which contributed to improved effluent quality and substantial dephosphatation.

Awad et al., 2019 used GPS-X software to prepare modeling of Banias's Refinery Treatment Plant to evaluate its performance in order to make sure that it operates adequately. An activated sludge model was used in this plant. The results showed that the output simulation values were in agreement with the measured data in terms of TSS, VSS and COD. Also, they showed the death of bacteria and presence of high inert organic matter in the plant wastewater.

Jasim, 2020 used a GPS X modelling technique to design treatment units for Al-Hay wastewater treatment plant (WWTP) to fit the population size of Al-Hay city. It was found that there is a typical enhancement in the total suspended solids and solids with the increase of simulation time. The results also showed that the suspended solids in mixed liquor (MLSS) are correlated with the sludge age that is related to the observed yield which its value ranged between 0.2 and 0.6 kgVSS/kg (BOD). As well, the retention time and the produced sludge were found equal to 27.7 days and 3339.18 kg/day, respectively. According to these results, it can be concluded that the biological tank of Al-Hay WWTP is worked with a high efficiency.

2.14 Summary of previous studies

1- The performance improving of the A_2/O plant depends on influent wastewater characteristics, operational conditions and maintenance program on the different plant units.

2- Many improvements have been made to the GPS-X program, which made it widely used by researchers in the modeling and simulation of wastewater treatment plants and applying of different scenarios to know the response of the plant in a way that simulates reality.

Chapter Three: MATERIALS AND METHODS

3.1 Introduction

The most significant aspect of scientific study preparation is the research approach, which provides a clear image of working procedures and how to yield research results, solve problems, and attain objectives. This chapter covered the components of the Karbala wastewater treatment plant, as well as the qualities of Karbala city's sewage and the plant's regulating operations. It also discussed how to use the GPS-X model, how to calibrate and validate it, and how to improve and update the Karbala wastewater treatment facility to meet local environmental requirements

3.2 Research Framework

The research technique is the most significant aspect of a study because it explains the complete strategy for reaching the goals. The following diagram shows the research framework applied in this study.

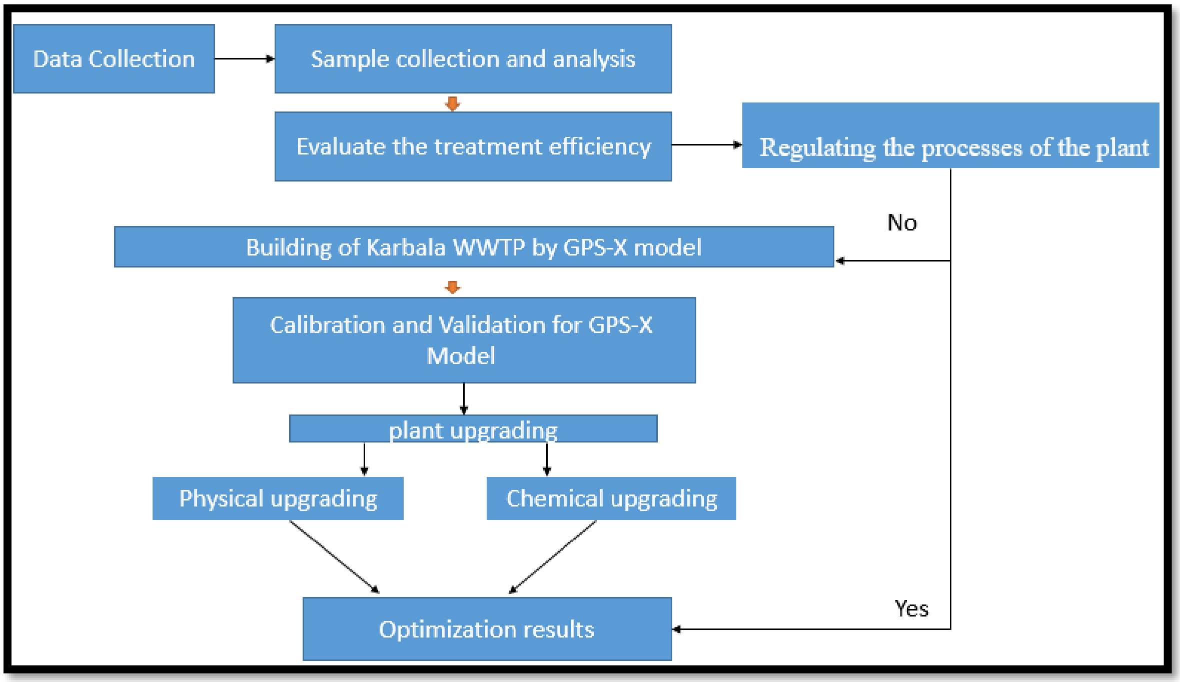


Figure 3-1:study framework.

3.3 Study Area

3.3.1 Karbala WWTP

The study was conducted in Karbala Governorate, which locates about more than 100 km approximately to the south of the Iraqi capital, Baghdad. The city of Karbala is of tourist and agricultural importance (Farhan, etal, 2018). The city of Karbala receives more than 50 million visitors annually; thers constitutes an additional burden on water and sewage services (see figure 3.2) (Memish, Stephens, Steffen, & Ahmed, 2012).

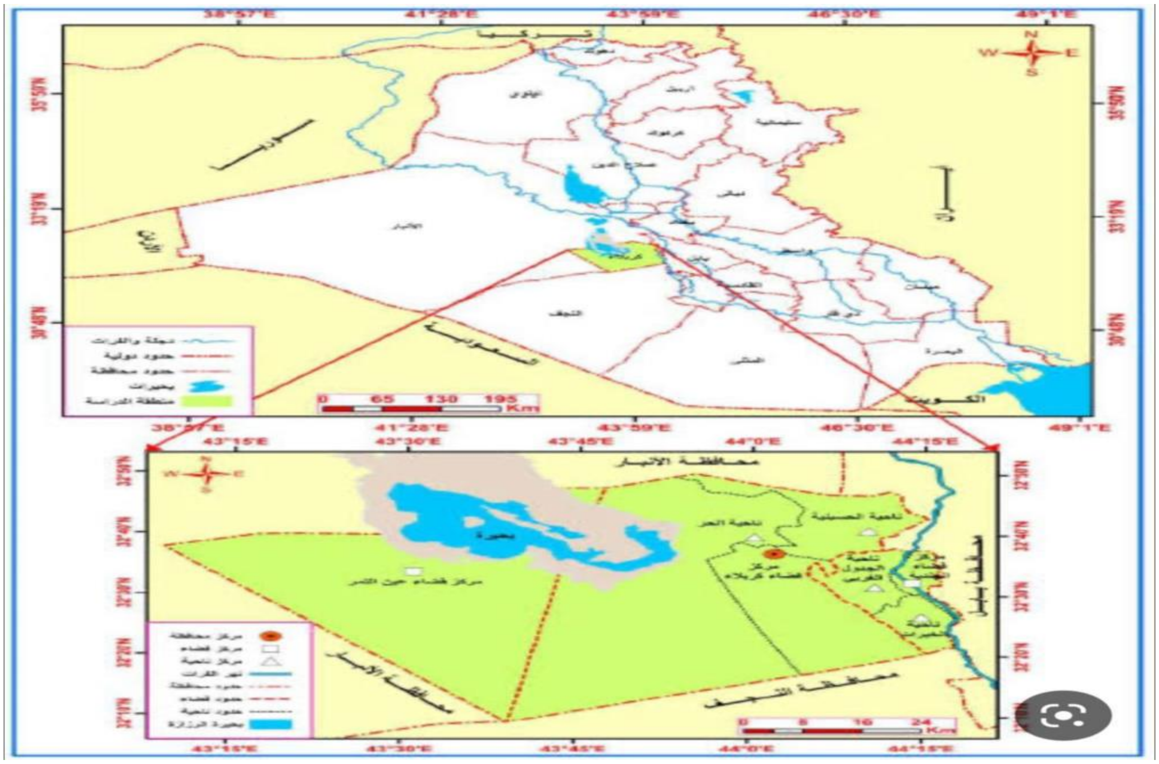


Figure 3-2:The location and map of Karbala goverorate.

The city of Karbala contains many sewage treatments plants to treat fewage more than two million five hundred thousand people. One of the most important processes used in the sewage treatment plants of Karbala is the conventional activated sludge. Karbala Consolidated Project includes four sewage treatment plants running on the conventional activated sludge system type A2/O (see Figure 3.3). Each of these plants operates with a discharge capacity of 100,000 m^3/d. This plant is located within the geographical coordinates are 32.525590°N and 44.074909°E.

Figure 3-3:Karbala WWTPs

3.3.2 Design Determinants

The process of designing a sewage treatment plant depends on the parameters required for the outflow of that plant. The plant design based on the parameters shown in Table(3-1).

Table 3-1:Characteristics of sewage for the designed WWTP of Karbala

Parameter	Inlet concentration	Outlet concentration	EPA Standards
PH	6.8-7.5	7-7.4	
COD (mg/L)	350-500	<30	
BOD5 (mg/L)	150-250	<100	
TN (mg/L)	45	<10	
PO4-P (mg/L)	6	2	

3.3.3 Stages of treatment

In the Karbala sewage treatment plant, there are six treatment stages shown as follows:

1- Preliminary treatment stage: In this stage, large and small solids, as well as gravel, sand, and fat are removed. This stage consists of four main units as follows:

- Coarse screen: This unit is located at the beginning of the plant to remove solids coming with wastewater (see Figure 3-4).
- The fine screen, located after the coarse screen, remove solids with a diameter of more than 6 mm (see Figure 3-4).

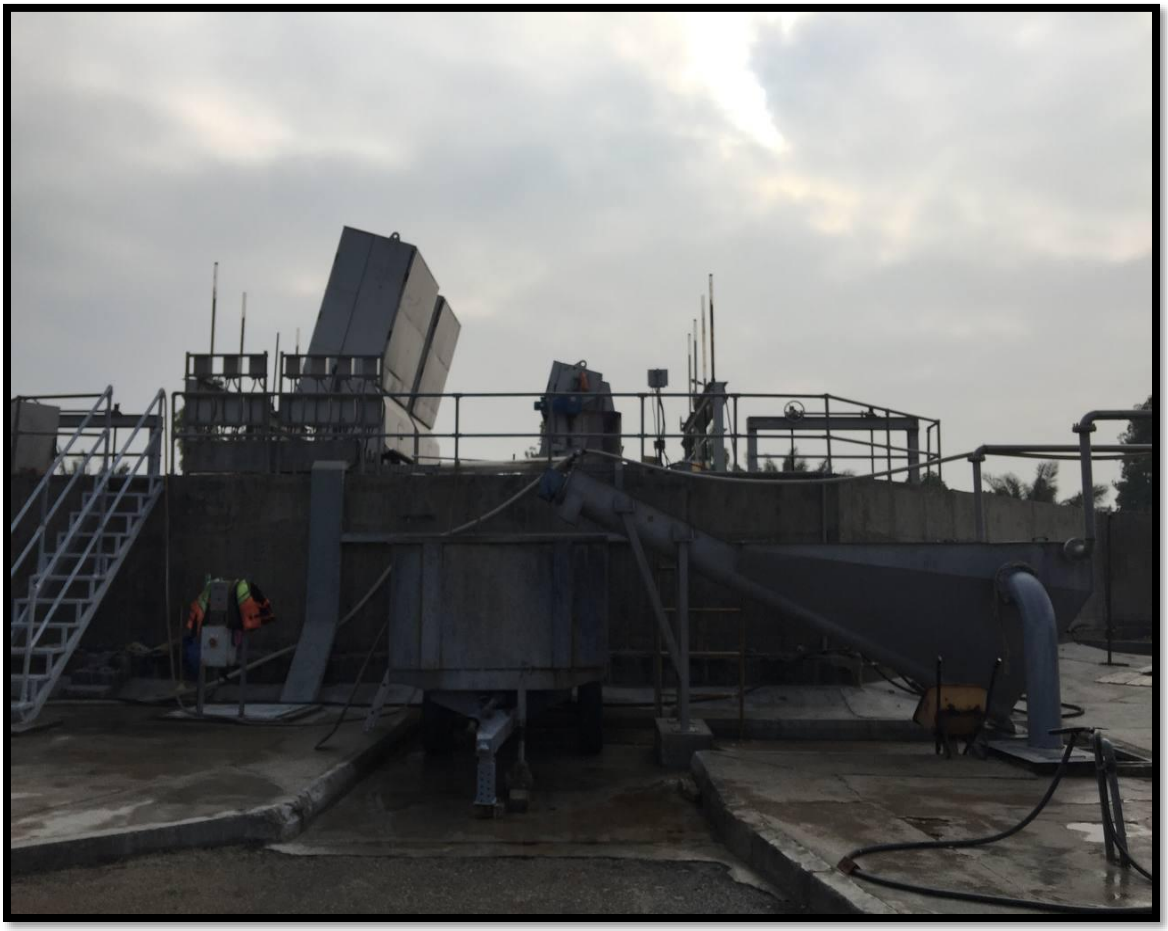


Figure 3-4:Course and fine screen units in Karbala WWTP.

Grit chamber: This basin is located between the fine screen and the primary sedimentation basins, and its funetion removes sand through sedimentation and removes fat through aeration (see Figure 3-5).

Figure 3-5:Grit chamber in Karbala WWTP.

Parshall flume: it is the last unit that is located at the end of the pretreatment and the funetion of this unit is measuring the daily flow and suspended solids to regulate the work of the plant (see Figure 3-6).

Figure 3-6:Parshall flume unit in Karbala WWTP.

2-Primary treatment stage: This stage is represented by the four primary sedimentation basins that remove suspended solids of more than 55% (see Figure 3-7).

Figure 3-7:Primary sedimentation tank in Karbala WWTP.

3-Secondary treatment with nutrient removal stage: At this stage, three basic units operate biologically, namely, the anaerobic tank, the anoxic tank, and the aeration tank. In these three basins, phosphorous, nitrogen, and organic substrate are eliminated (see Figure 3-8).

Anaerobic Anoxic

Oxic reactors

Figure 3-8:Anaerobic/Anoxic/Oxic reactors in Karbala WWTP

Secondary sedimentation basins: These basins are an integral part of this stage and is considered an important part in the Regulating of treatment, as its function is to remove suspended solids. The Karbala sewage treatment plant contains eight secondary sedimentation basins, each 32 m in diameter (see Figure 3-9).

Figure 3-9:Secondary clarifier tank in Karbala WWTP.

4-Tertiary treatment stage: in Karbala sewage treatment plant Chlorination is the chemical treatment used to eliminate pathogenies (see Figure 3.10).

Figure 3-10:Chlorination basin in Karbala WWTP.

5-Sludge treatment stage: this stage is one of the most important and complex stages, and it includes four main units, which are as follows:

- Gravity thickener: In this unit, sludge is received from the primary sedimentation basins, in which suspended solids are thickened to be then transferred to the digestion basins to stabilize them. There are two basins in the Karbala sewage treatment plant with a surface area of 400 m^2 (see Figure 3.11).

Figure 3-11:gravity thickener basin in Karbala WWTP.

- The mechanical thickener receives wastewater from the secondary sedimentation basins, and some chemicals such as polymer are added to help thicken this sludge, and then it is transferred to the digestion tanks to reduce its size and treat it. There are three basins in the Karbala sewage treatment plant (see Figure 3-12).

Figure 3-12:Mechanical thickener units in Karbala WWTP.

Anaerobic digestion tanks: in these reactors, the sludge is fixed and its size is reduced. The Karbala sewage treatment plant consists of four reactors that produce methane gas to be used in generating electric power
(see Figure 3-13).

Figure 3-13:Anaerobic digester in Karbala WWTP.

Drying beds: in these basins, the installed sludge is spread over these vast areas and through sunlight and winds, it is dried and is considered the last unit of the sludge treatment stage (see Figure 3-14).

Figure 3-14:drying bed in Karbala WWTP.

6-Biogas treatment stage: In this stage, hydrogen sulfide gas and the rest of the gases are removed to be pure methane gas that does not contain impurities (see Figure 3-15).

Figure 3-15:Biogas treatment reactor in Karbala WWTP.

3.4 Operational data collection

In this study, operational data were collected from the administration of the Karbala sewage treatment plant as shown in Table 3.2. Operational and physical data are very important for entering them correctly into the model.

Table 3-2:The parameters of the Karbala WWTP.

Parameter	Value
Flowrate	60,000 m^3/d
V. anaerobic reactor	8736 m^3
V. anoxic reactor	14112 m^3
V. aeration reactor	54054 m^3
Primary sludge	230 m^3/d
Surface area for primary sedimentation	3216 m^2
Surface area for final clarifier	6432 m^2
V. anaerobic digester	13600 m^3
Surface area for gravity thickener	400 m^2
Surface area for mechanical thickener	60 m^2
Volume chlorination tank	3000 m^3
Surface area for drying bed	50,000 m^2
Dissolved Oxygen	2-3 mg/L
Mixed liquor suspended solids	3500 mg/L
SLR	2.17 kg mlss/m^2h
HLR	9 m^3/m^2d
WAS	3000-4000 m^3/d
RAS	36000 m^3/d
F/M	0.05
IR	3
SVI	80 mL/g

3.5 Sample collection and analysis

Sampling is critical to give a complete impression of the plant's performance for a full year. Samples were collected for a full year from the plant management, and all tests were conducted according to the Standard Methods for the Examination of Water and Wastewater, and the measurement methods were shown in Table 3-3 (APHA, 2017).

Table 3-3:Physico-chemical parameters and methods of analysis

Parameters	Method of analysis	Measuring devices
pH	Direct measurement	pH Meter
Dissolved oxygen (mg/l)	Direct measurement	DO meter
Temperature (°C)	Direct measurement	Thermometer
Biochemical oxygen demand (BOD5) (mg/l)	Manometric/respirometric	Using WTW MARK 6 OxiTop®
Chemical oxygen demand (COD) (mg/l)	Colorimetric (closed reflux)	Using WTW C2/25 COD1500 photometer
Total nitrogen (mg/l)	Kjeldhal	Using 0.02N H2SO4 Titration
Total phosphorus, nitrate and nitrite (mg/l)	Colorimetric	Using SP75UV/VIS Spectrophotometer

3.6 Treatment Efficiency Determination

The efficiency of the plant is determined based on the percentage of the average concentration of incoming and outgoing pollutants. Each pollutant is measured in a different proportion based on the physical, chemical, and biological processes inside the reactor, and the efficiency is measured based on equation 3-1

$$Removal\ Efficiency = \frac{Cin - Ceff}{Cin} \times 100\% \qquad (3.1)$$

Where:

% = Removal efficiency;

C_{in} = Concentration of pollutant in the influent (mg/L).

C_{eff} = Concentration of pollutant in the effluent (mg/L).

3.7 Regulating the processes of the plant

The Regulating of the operation process is very necessary for the operation process to match the reality of the quantity and quality of the characteristics of the wastewater. Operation is different from the design but is more difficult than design because it deals more realistically. There are many factors on which the operational operations of the plant depend to operate with the best efficiency and at the lowest cost. Below are the most important operational factors on which the operation of the station depends and their comparison with the global determinants shown in Table 3.4 (Hreiz, 2015; Metcalf et al., 2014).

Table 3-4:Typical design parameters for commonly used activated sludge processes Typical design parameters for commonly used activated sludge processes

Process name	Type of reactor	SRT,d	F/M Kg BOD/ Kg MLVSS, d	Volumetric loading		MLSS Mg/L	Total τ, h
				Ib BOD 1000 ft^3, d	kg BOD $1000m^3$, d		
High-rate aeration (first step in AB process)	CMAS or plug flow	0.5-2	1.5-2	75-150	1.2-2.4	500-1500	1-2
Contact stabilization	CMAS or plug flow	5-10	0.2-6	60-75	1-1.3	1000-3000^a 6000-10000^b	0.5-1^a 2-4^b
High-purity oxygen	staged	1-4	0.5-1	80-200	1.3-3.2	2000-4000	1-3
Conventional plug flow	plug flow	3-15	0.2-0.4	20-40	0.3-0.7	1000-3000	4-8
Step feed	plug flow or staged	3-15	0.2-0.4	40-60	0.7-1	1500-4000	3-5
Complete mix	CMAS	3-15	0.2-0.6	20-100	0.3-1.6	1500-4000	3-6

Extended aeration	CMAS or plug flow	20-40	0.04-0.1	5-15	0.1-0.3	2000-4000	20-30
Oxidation ditch	CMAS + plug flow	15-30	0.04-0.1	5-15	0.1-0.3	3000-5000	15-30
Batch decant (ICEAS, CAAS)	plug flow	12-30	0.04-0.1	5-15	0.1-0.3	2000-5000	20-40
Sequencing batch reactor	Batch	15-30	0.04-0.1	5-15	0.1-0.3	2000-5000	15-40
Counter current aeration system (CCASTM)	plug flow	15-30	0.04-0.1	5-10	0.1-0.3	2000-4000	15-40

3.7.1 Flow Rate Measurements

In the Karbala sewage treatment plant, there are five important flows: the mainstream, the side stream, the returned activated sludge, internal recycling, and wasted activated sludge. All of these flows depend on the quality and quantity of wastewater entering the plant. Regulating these flows ensures the good operation of the plant. As for IR, RAS, and WAS, they are calculated through the three equations below (Metcalf et al., 2014):

$$RAS = \frac{Q \times mlss}{Xr - mlss} \qquad (3-1)$$

Where, RAS= returned activated sludge, m^3/d

Q= mainstream, m^3/d

MLSS= mixed-liquor suspended solids, mg/L

Xr= returned activated sludge suspended solids, mg/L

$$WAS = \frac{V \times mlss}{SRT \times Xr} \qquad (3-2)$$

Where, V= volume of the reactor, m^3

SRT= sludge retention time, d

$$IR = \frac{NO_x}{N_{NO3-N}} - (1 + R_{RS}) \qquad (3-3)$$

Where, IR= Internal recycle, m^3/d

NO_X = TKN –NH4-N effluent – $0.12P_x/Q$ (g/m^3) (3- 4)

Px= biomass as VSS wasted, g/d

NNO3-N = NO3-N concentration in the effluent or internal recycle from aeration basin,mg/L or g/m^3.

RRS = ratio of return sludge flows to influent flow, dimensionless.

3.7.2 Organic Loading Rate (OLR)

The organic loading rate (OLR) is defined as the quantity of organic material per day applied across a surface area, such as kg of COD or BOD5 per day per m3. The BOD5 is a calculation that measures how much oxygen is needed to break down organic compounds dissolved in sewage over five days. BOD5 is a procedure for calculating the amount of rapidly degraded organic material in sewage. (Metcalf et al., 2014). The first step in calculating organic loading is to convert BOD5 in mg/l to kg/m^3.

Organic Loading Rate (kg BOD5/m^3.day) = (BOD5in. x Q) / (V) (3-5)

3. Hydraulic retention time (HRT)

HRT is the residence time of the liquid in the reactor, and this time varies depending on the type of reactor or processes used in the system. Equation (6) can be used to calculate HRT.

HRT = CODin. / OLR (3-6)

4. Solid Loading Rate (SLR)

The mass loading rate of mixed liqour suspended solids (MLSS) per unit area of the secondary clarifier, expressed in kg/m^2.h (Takács & Ekama, 2008)

$$\text{SLR (kg MLSS/m}^2\text{. h)} = \text{MLSS} \times (\text{Q+RAS}) / (\text{area of the secondary clarifier}) \qquad (3\text{-}7)$$

5. hydraulic loading rate (HLR)

The hydraulic load is one of the most important factors on which sedimentation basins depend when designing, and it is expressed by the flow divided by the surface area of the sedimentation basin, and it is measured in m^3/m^2.d (Karia & Christian, 2013).

$$\text{HLR(m}^3\text{/m}^2\text{.d.)} = \text{Q/(areaof the secondary clarifier)} \qquad (3\text{-}8)$$

6. Sludge Volume Index (SVI)

The sludge volume index (S.V.I), which is defined as the ratio of the quantity in milliliters of mixed liquor activated sludge settled from a 1,000 ml sample in 30 min to the concentration of mixed liquor (in mg/l) multiplied by 1,000, is used to measure sludge settleability. The SVI is a calculation that shows how well-aerated activated sludge solids thicken or concentrate during the settling or clarification operation; it is calculated using the formula (Mursalim, Pallu, Selintung, & Rahim, 2021):

$$\text{SVI} = \text{V} \times 1000/\ \text{MLSS} \qquad (3\text{-}9)$$

S.V.I (ml/gm): (settled sludge amount in milliliters after 30 min in a one-liter cylinder or beaker divided by MLSS concentration in mg/l) multiplied by 1,000 mg/gm.

Vs (mL/L): Volume of settled sludge after 30 min.

MLSS (mg/L): mixed-liquor suspended solids.

7. **F/M ratio**

The link between the load (i.e. kg/day as opposed to mg/l) of BOD (or bacterial 'food') entering the aeration plant and the mass of bacteria in the aeration tank available to treat the incoming BOD is one of the most fundamental control factors for the activated sludge system. As a result, this is referred to as the Food to Mass Ratio (F: M ratio) (Metcalf et al., 2014).

$$F\backslash M\ Ratio = (BOD_5in. * Qin.) / (MLSS * V) \qquad (3\text{-}10)$$

3.8 Chemical additives

Chemicals are added to improve processing processes or to reach very stringent parameters. In the Karbala sewage treatment plant, only chlorine is used as a chemical additive to eliminate pathogens, and there are dangerous residues due to the addition of this substance. As for the removal of nutrients such as ammonia, nitrates, and phosphates, they are removed biologically, but their removal is not at the required level according to modern global determinants, due to the lack of a rapidly decomposing carbon source in the wastewater of Karbala city. The lack of rbCOD in sewage water caused some problems in removing nitrates and phosphates, so it requires improving the process by adding chemicals that contribute to removing these pollutants and reaching the required parameters (Bertanza, etal., 2013). Choosing a chemical or external carbon source depends on the nature of this material, its quality, its cost, its safety, and its lack of impact on operators. The most important of these chemical additives are an alum, lime, acetic acid, propionic acid, methanol, and glycerol.

3.9 Karbala WWTP ASP Modelling in GPS-X

In this study, Hydromantis Environmental Software Solutions, Inc.'s GPS-X application version 8 (Academic license) was utilized. The GPS-X model is one of the most important models used in sewage treatment plants. It includes all physical, chemical, and biological processes and the anaerobic digestion system (Jasim, 2020). The Mantis model, which is part of the GPS-X application, rewrote(ASM1) to include several extra growth mechanisms for autotrophic and heterotrophic bacteria. The Mantis model also included aerobic denitrification as one of its parts. There are many libraries in GPS-X simulation, in this study, which focused on (carbon, nitrogen, and phosphorus processing), pH library was selected, as shown in Figure 3.16.

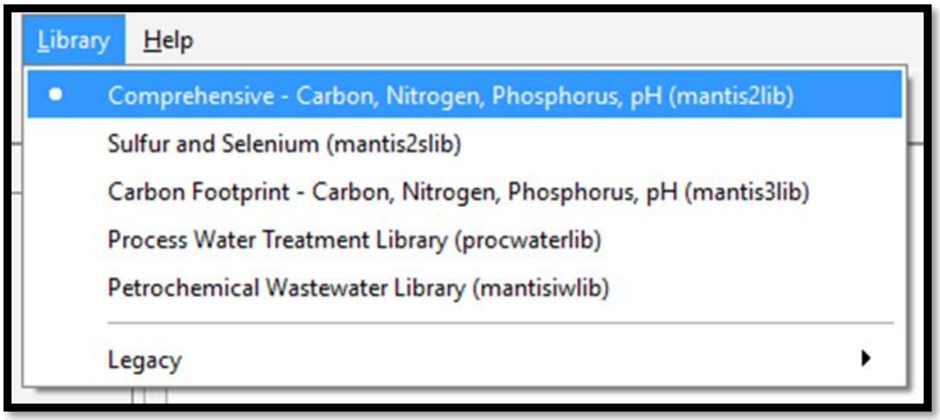
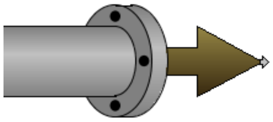
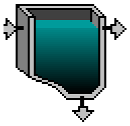
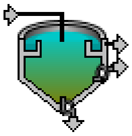
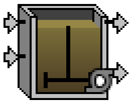


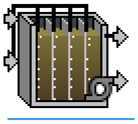
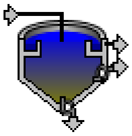
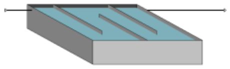
Figure 3-16:Library in GPS-X model.

More than 60 composite and state variables, as well as various libraries of expressions characterizing. The operations, are included in the model, together with more than 30 stoichiometric and 24 kinetic input and output factors (Mu’azu, et al., 2020) After collecting the operational and physical data of the plant, they were entered into the GPS-X program as shown in

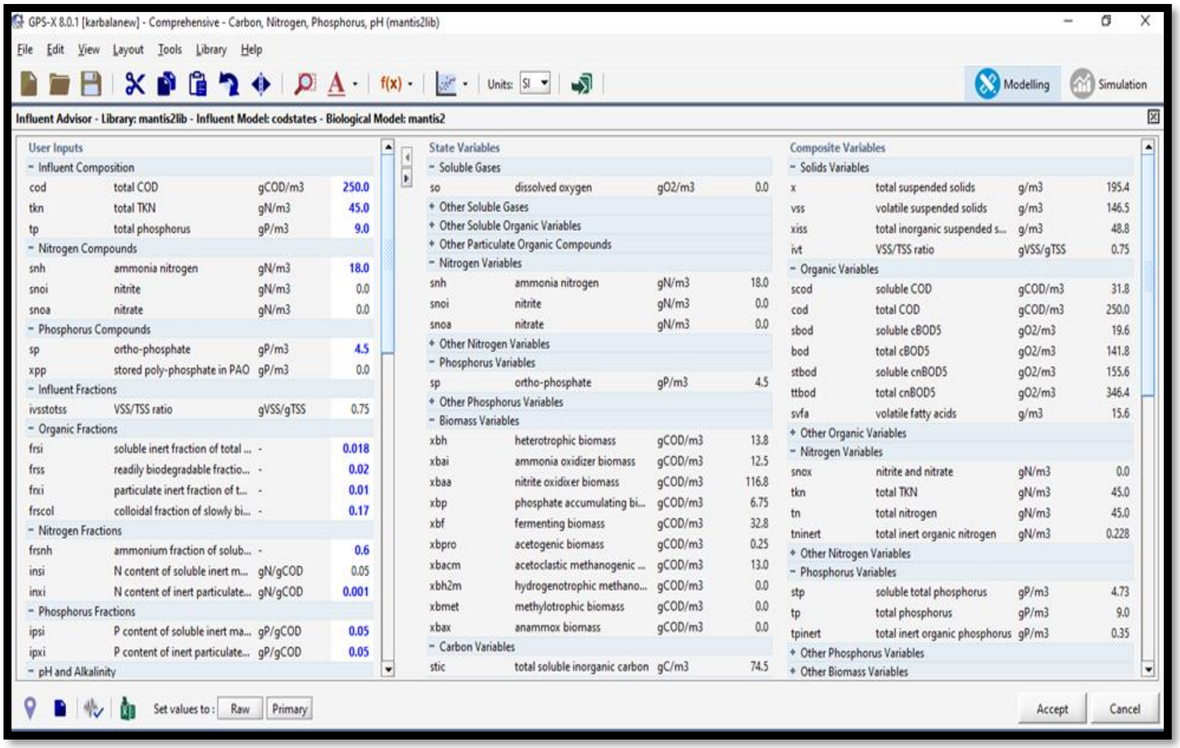
Table(3-5).

Table 3-5:Physical and operational data used within GPS-X simulation.

Unit process	Variable	Input Value
Influent Wastewater 	Flow	60000 m^3/d
	COD	255 mg/L
	BOD	149 mg/L
	TSS	180 mg/L
	NO2&NO3	0 mg/L
	TKN	45 mg/L
	TP	9 mg/L
	NH4	18 mg/L
Grit chamber 	Grit production per flow	20 mg/L
Primary clarifier 	Clarifier type	Sloping bottom
	Surface area	3216 m^2
	Water depth at center	4.5 m
	Water depth at sidewall	3.5 m
	Underflow rate	230 m^3/d
Anaerobic tank 	Maximum volume	8736 m^3
	Tank depth	6 m

Anoxic tank 	Maximum volume	14112 m^3
	Tank depth	6 m
Aeration tank 	Maximum volume	54054 m^3
	Tank depth	6 m
	Aeration method	Mechanical (surface aeration)
	DO set point	3.5 mg/L
	Pumping flow	150000 m^3/d
Secondary clarifier 	Clarifier type	Sloping bottom
	Feed point from bottom	4.3 m
	Surface area	6432 m^2
	Water depth at sidewall	5.5 m
	Water depth at center	6.5 m
	Under flow rate	36000 m^3/d
	Pumped flow	3500 m^3/d
Chlorination basin 	Volume	3655
	Chlorine dosage	6 mg/L

The process of entering the physical and operational data for the plant is followed by entering the chemical, physical and biological properties of wastewater such as COD, TKN, and TP, as shown in Figure 3-17.



Influent Advisor - Library: mantis2lib - Influent Model: codstates - Biological Model: mantis2

User Inputs			
- Influent Composition			
cod	total COD	gCOD/m3	250.0
tkn	total TKN	gN/m3	45.0
tp	total phosphorus	gP/m3	9.0
- Nitrogen Compounds			
snh	ammonia nitrogen	gN/m3	18.0
snoi	nitrite	gN/m3	0.0
snoa	nitrate	gN/m3	0.0
- Phosphorus Compounds			
sp	ortho-phosphate	gP/m3	4.5
xpp	stored poly-phosphate in PAO	gP/m3	0.0
- Influent Fractions			
ivsstotss	VSS/TSS ratio	gVSS/gTSS	0.75
- Organic Fractions			
frsi	soluble inert fraction of total ...	-	0.018
frss	readily biodegradable fractio...	-	0.02
frxi	particulate inert fraction of t...	-	0.01
frscol	colloidal fraction of slowly bi...	-	0.17
- Nitrogen Fractions			
frsnh	ammonium fraction of solub...	-	0.6
insi	N content of soluble inert m...	gN/gCOD	0.05
inxi	N content of inert particulate...	gN/gCOD	0.001
- Phosphorus Fractions			
ipsi	P content of soluble inert ma...	gP/gCOD	0.05
ipxi	P content of inert particulate...	gP/gCOD	0.05
- pH and Alkalinity			

State Variables			
- Soluble Gases			
so	dissolved oxygen	gO2/m3	0.0
+ Other Soluble Gases			
+ Other Soluble Organic Variables			
+ Other Particulate Organic Compounds			
- Nitrogen Variables			
snh	ammonia nitrogen	gN/m3	18.0
snoi	nitrite	gN/m3	0.0
snoa	nitrate	gN/m3	0.0
+ Other Nitrogen Variables			
- Phosphorus Variables			
sp	ortho-phosphate	gP/m3	4.5
+ Other Phosphorus Variables			
- Biomass Variables			
xbh	heterotrophic biomass	gCOD/m3	13.8
xbai	ammonia oxidizer biomass	gCOD/m3	12.5
xbaa	nitrite oxidixer biomass	gCOD/m3	116.8
xbp	phosphate accumulating bi...	gCOD/m3	6.75
xbf	fermenting biomass	gCOD/m3	32.8
xbpro	acetogenic biomass	gCOD/m3	0.25
xbacm	acetoclastic methanogenic ...	gCOD/m3	13.0
xbh2m	hydrogenotrophic methano...	gCOD/m3	0.0
xbmet	methylotrophic biomass	gCOD/m3	0.0
xbax	anammox biomass	gCOD/m3	0.0
- Carbon Variables			
stic	total soluble inorganic carbon	gC/m3	74.5

Composite Variables			
- Solids Variables			
x	total suspended solids	g/m3	195.4
vss	volatile suspended solids	g/m3	146.5
xiss	total inorganic suspended s...	g/m3	48.8
ivt	VSS/TSS ratio	gVSS/gTSS	0.75
- Organic Variables			
scod	soluble COD	gCOD/m3	31.8
cod	total COD	gCOD/m3	250.0
sbod	soluble cBOD5	gO2/m3	19.6
bod	total cBOD5	gO2/m3	141.8
stbod	soluble cnBOD5	gO2/m3	155.6
ttbod	total cnBOD5	gO2/m3	346.4
svfa	volatile fatty acids	g/m3	15.6
+ Other Organic Variables			
- Nitrogen Variables			
snox	nitrite and nitrate	gN/m3	0.0
tkn	total TKN	gN/m3	45.0
tn	total nitrogen	gN/m3	45.0
tninert	total inert organic nitrogen	gN/m3	0.228
+ Other Nitrogen Variables			
- Phosphorus Variables			
stp	soluble total phosphorus	gP/m3	4.73
tp	total phosphorus	gP/m3	9.0
tpinert	total inert organic phosphorus	gP/m3	0.35
+ Other Phosphorus Variables			
+ Other Biomass Variables			

Figure 3-17:influent advisor in GPS-X.

3.10 GPS-X ModeIling Approach

After collecting the laboratory test data and other necessary information, the modelling of the Karbala sewage treatment plant was done using the following procedure (Moghaddam and Pirali, 2021):

1. A maximum of actual Karbala WWTP information as applicable to GPS-X simulation was gathered.

2. Construction of Karbala sewage treatment plant using GPS-X Model was done according to the data obtained (see Figure 3-18).

3. Using the GPS-X influent advisor, the influent fractionation values of COD and nitrogen components were adjusted and set to an acceptable state, as these influent components are not simple to measure; the composite variables mass balance was also set.

4. The simulation was run and then calibrated by modifying varying stoichiometric, kinetic, and other relevant parameters to enable the simulation to obtain the best match between the simulation results and actual plant effluent values.

5. A different set of Karbala WWTP sewage quality data was used to validate the calibrated model.

6. Simulations were also run under various scenarios to investigate the impact of relevant operational conditions on the capacity of the plant and its performance in terms of final effluent quality.

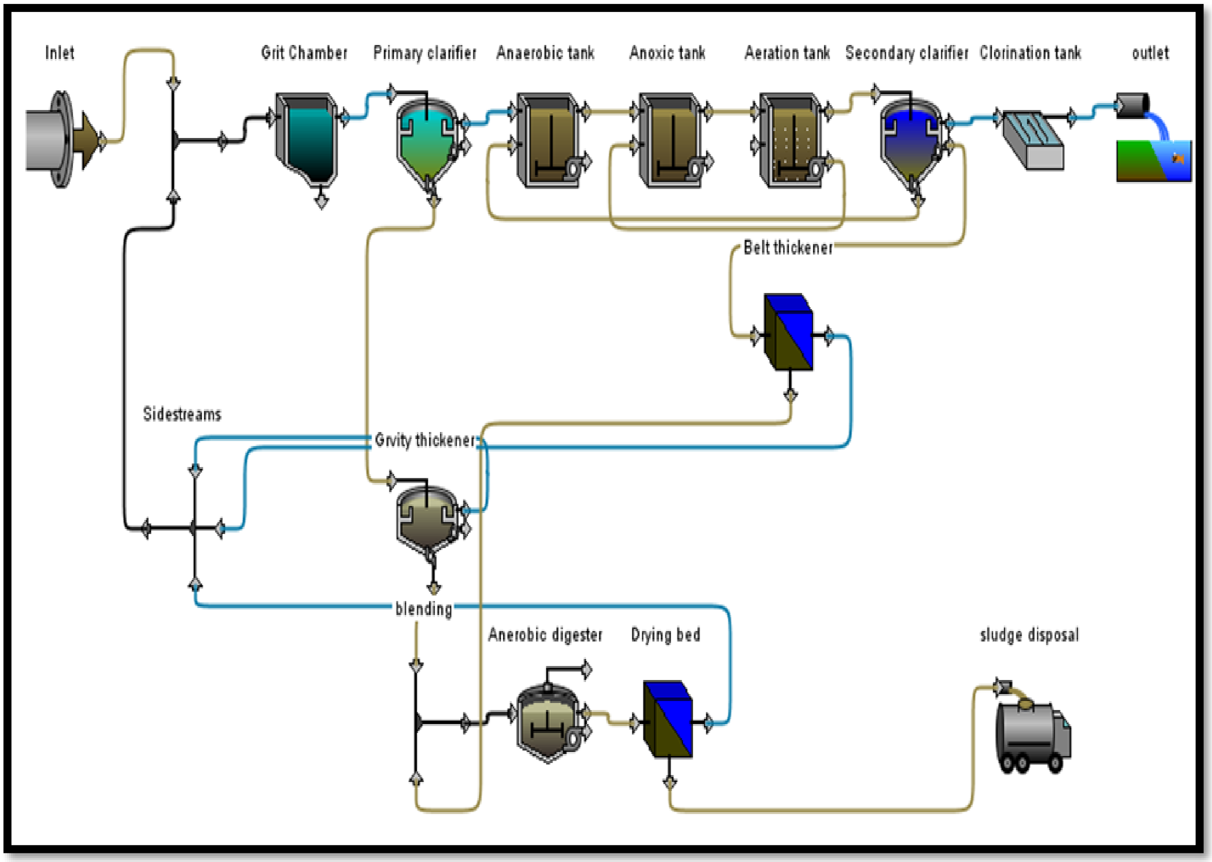


Figure 3-18:Layout of the Karbala WWTP in GPS-X model.

3.11 GPS-X Model Calibration and Validation

As most pollutants remain constant throughout the year, with only a slight discrepancy, the autumn and winter seasons were adopted as calibration data, and spring and summer sets were used as validation. The model was thus first calibrated, and then verified based on those results not entered during calibration. After obtaining a close match between the model's output and reality, the remaining disparity was statistically examined by means of the root mean square error (RMSE), and correlation coefficient (R), as shown in equations 1 and 2

$$\mathrm{R} = \frac{\sum[(Co - \overline{Co})(Cp - \overline{Cp})]}{\sigma co\ \sigma p} \qquad (1)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(Co - Cp)2}{N}} \qquad (2)$$

Where Co is the actual data in the modeled data, while the average of actual data is the average of modeled data, and σ is the standard deviation over the full dataset. These statistical criteria reasonable limits are $1 \geq \mathrm{R} > 0.8$ and $0 \leq \mathrm{RMSE} < 1.5$. Figure (3-19) depicts the schematic processes for systematic model calibration and validation as used in this investigation (Zwain, et al, 2020).

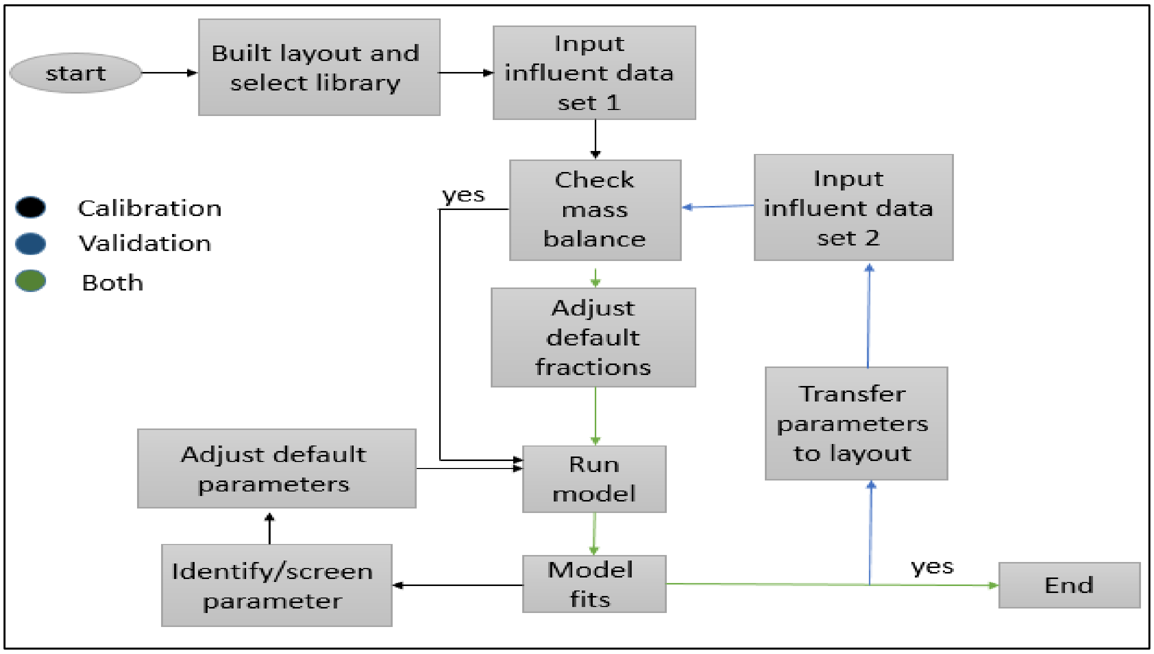


Figure 3-19:Procedure calibration and validation.

3.12 Sensitivity analysis

After the model was calibrated and validated, those sensitive parameters that had a positive or negative impact on the work of the plant were identified. To determine the most sensitive values with respect to the performance of the plant ,the simulation outputs were monitored while the values of various parameters were manipulated. The sensitivity of a plant’s work may also be affected by operational factors; thus, after the construction of the Karbala sewage treatment plant within the GPS-X model, the default values for kinetic and stoichiometric parameters were used. The results were outside the required limits, so all sensitive parameters were then modified, and sensitivity analysis was applied to develop an understanding of the extent to which these parameters affect the fate and behavior of pollutants inside the plant (Cao et al., 2021).

3.13 Process Optimization

In this study, several scenarios were implemented, the most important of which is the regulating of the work of the plant according to the quantity and quality of the mainstream. The second scenario is the manipulation of operational factors. The third was the upgrading of the station by adding and deleting units in the Karbala sewage treatment plant.

Chapter Four: RESULTS AND DISCUSSION

4.1 Karbala wastewater treatment plant performance

Evaluation of the performance efficiency of the Karbala wastewater treatment plant was done based on the percentage of pollutants removed from the plant. After reducing the plant's proportion of contaminants, the concentrations are within the required standards. After collecting samples and taking an average for the year 2021of the plant's wastewater influent and effluent, and using Equation 3-1 in Chapter 3, the removal efficiency for each parameter is shown in Table 4-1

Table 4-1:Removal Efficiency Summary of Karbala WWTP treatment efficiency.

Parameter	Influent, mg/l	Effluent, mg/l	Removal Efficiency (%)	Allowable limits (Mg/L)
COD	255	26	90	100
BOD_5	150	10	93	40
rbCOD	50	0	100	--
TSS	181	14	92	60
TN	45	34	24	--
NO_3	0	32	-	50
NH_4^+	18	0.2	98	10
TP	9	5.8	35	--
PO_4-P	4.5	3.5	22	3
H_2S	35	0.3	99	3
Oil & grease	45	3	93	10
DO	0	3.5	-	--
SO_4	850	860	-	400

From the above table, it is noted that the organic matter in terms of (COD and BOD_5) was removed excellently, as the efficiency of its removal reached about 90%and 93% respectively This is attributed to microorganisms, especially heterotrophic bacteria, contributed to the elimination of organic matter after the required dissolved oxygen concentrations were available and adequate mixing inside the reactor, which led to the decomposition of these compounds and their transformation into fixed substances (Bankston, et al.,2020). Good removal was seen by the secondary sedimentation basins in the removal of suspended solids (TSS), reaching about 92%. A very low concentration of rbCOD was observed in the wastewater of Karbala city, which affected the removal of nutrients (Khursheed et al., 2018), as the percentage of removal of nitrogen and phosphorous reached 24% and 35 %, respectively. The reason for this is due to the removal of nitrogen and phosphorous may also have affected the high dissolved oxygen concentrations that are returned with IR and RAS flow (Stewart et al., 2022). Because of the nature of the gypsum soil and the high levels of groundwater in Karbala city, large quantities of sulfate entered the network through percolation, which contributed to the increase of these concentrations. Karbala sewage treatment plant, being of an A_2/O system, cannot remove sulfates, but rather contributes to eliminating hydrogen sulfide gas. Aeration, mixing, and sorption are all factors that have affected the removal of hydrogen sulfide in the plant by about 99% (Zwain, et al., 2020). The nitrification process was observed in the Karbala wastewater treatment plant is working good, as ammonium was oxidized by about 98%. The denitrification process in the Karbala wastewater treatment plant is not working well due to a lack of suitable organic substrate. Fat removal is excellent because the gravel, sand, and fat removal unit works well.

4.2 Adjusting the mass balance of the Karbala WWTP (processes regulation).

One of the most important processes that must be controlled is the mass balance based on the quantity and quality of wastewater entering the plant. Adjusting the mass balance gives positive results by operating the plant with the best operation and the lowest cost, and ensuring that the operations are carried out within the international parameters (Gao et al., 2016). In this study, the determinants were compared with the specification. Based on the information obtained by the management of the plant, it was observed that the plant does not operate within the international parameters, despite the quality of the treated wastewater for the organic substrate and some problems in the treatment of nutrients. In this study, the mass balance processes were carrical out as follows:

1. Calculate the mass loadings in the primary clarifier influent.

The changes in volume and solids through screening and grit chamber units are relatively small. Both processes may be ignored in mass balance analysis.

Mass of BOD5, $W_{BOD5,1} = BOD_5Q_{in} = 150\ g/m^3 \times 60{,}000\ m^3/d \times 10^{-3}\ kg/g$

$= 9000\ kg/d$

Mass of TSS, $W_{TSS,1} = TSS_0Q_{in} = 181 g/m^3 \times 60{,}000\ m^3/d \times 10^{-3}\ kg/g$

$= 10860\ kg/d$

2. Calculate the primary sludge characteristics.

Based on the information obtained from the plant management staff, it was observed that the efficiency of the primary sedimentation basin was 55% of TSS removal and 35% of BOD5 removal. Also the solids content in the primary sludge is 4% and the specific gravity is 1.01 (Qasim & Zhu, 2017).

Mass of BOD5, $W_{BOD5,2} = 0.35 \times W_{BOD5,1} = 0.35 \times 9000\ kg/d$

= 3150 kg/d

Mass of TSS, $W_{TSS,2} = 0.55 \times W_{TSS,1} = 0.55 \times 10860$ kg/d = 5973 kg/d

$$sludge\ flowrate\ from\ primary\ clarifier = \frac{100\% \times W_{TSS,2}}{P_{s2} \times S_{s2} \times \rho_w}$$

$$= \frac{100\% \times 5973\ kg/d}{4\% \times 1.01 \times 1000\ kg/m3} \cong 148\ m^3/d$$

The flow of primary effluent= flowrate- sludge flowrate from the primary clarifier =60000-148 =59852 m^3/d

3. Calculate WAS flowrate

$$WAS\ flowrate = \frac{54054\ m^3 \quad \times \qquad 3500\,\frac{mg}{L}}{12\ d \times 10000\,\frac{mg}{L}}$$

$$= 1577\ m^3/d$$

4. Calculate RAS flowrate:

$$RAS\ flowrate = \frac{59852\ m^3 \quad /d \times \ 3500\ mg/L}{10000\,\frac{mg}{L} - 3500\ mg/L} \cong 32000\ m^3/d$$

5. Calculate belt thickener flowrate:

to calculate this discharge, solids content in thickened sludge is 6% and solids capture rate of 94% is taken into account.

$$\text{Belt thickener flowrate} = \frac{\frac{15770kg}{d} \times 94\%}{\frac{1000kg}{m3} \times 6\%} = 247\ m^3/d$$

6. Calculate HLR:

For primary clarifier

$$HLR = \frac{Q}{A} = \frac{59852\ m\text{^}3/d}{3216\ m^2} = 18.6\ m3/m2.d$$

The foregoing equation yielded the result that HLR is less than the needed determinant in the(Metcalf et al., 2014) , which is 40 m3/m2. d. As a result, certain units must be removed from the operation in order to get close to the required determinants. As a result, we can calculate the number of primary sedimentation basins that must be entered by using the equation below:

$$A = \frac{Q}{HLR} = \frac{59852\frac{m^3}{d}}{\frac{40m3}{m2}.d} = 1496\ m2$$

No of required basin= $\frac{1496}{804}$=2 basins

It was observed that the ratio of the second area to the first reached almost 0.5, which is half the number of basins, and since the number of operating basins is 4, it is necessary to reduce their number to become 2 at present.

- Calculations of secondary clarifier

$$HLR = \frac{Q}{A} = \frac{59852\frac{m^3}{d}}{6432\ m^2} = 9.3\,\frac{m3}{m2.d}$$

No of required basin= $\frac{2720}{804}$ =4 basin

The HLR was observed at a level lower than the required specification as shown in (Metcalf), so it requires to stop some basins from service to be closer to the required value of HLR, which is 22 m^3/m^2. d. To calculate the required number of tanks required to operate in the Karbala WWTP the following calculation is used:

$$A = \frac{Q}{HLR} = \frac{59852\,\frac{m^3}{d}}{\frac{22m3}{m2}.d} = 2720\ m2$$

No of required basin= $\frac{2720}{804}$ =4 basin

The second area ratio was observed to the first at 0.42, so it requires operating half of the tanks. Since the current number of operating basins is eight, but only four of them must be operated.

- For belt thickener, to calculate the number of units required to work, it is considered a value of 800 L/min per m belt width, and the number of basins is calculated based on the equation below:

$$HLR = \frac{Q}{width} = \frac{1577\ m3/d}{1} = 1095\ \text{L/min per m belt width}$$

When discharging WAS is equal to 1577m3/d, the number of thickener units decreases from 3 to 2. Thus, the amount of polymer added to secondary sludge is reduced by 82%.

7. Calculating the number of digesters

Through the management of the plant, it was noticed that the digester was fed with sludge at an amount of 1370 m^3/d, but after adjusting the flowrate entering this reactor, it became 400 m^3/d, where the discharge decreased by 71%, and therefore the number of digesters used is 1 or 2 instead of 4.

A summary of the results of the mass balance and the regulation of the operation of the plant is shown in Table 4.2.

Table 4-2:Summary of the results of the mass balance and the regulations for Karbala WWTP.

Description	The value before mass balance adjustment	The value after mass balance adjustment	Standard value
Primary clarifier influent	60000 m^3/d	60000 m^3/d	-
Primary sludge	230 m^3/d	148 m^3/d	-
Primary clarifier effluent	59770 m^3/d	59852 m^3/d	-
Waste activated sludge (WAS)	3500 m^3/d	1577 m^3/d	-
Returned activated sludge (RAS)	36000 m^3/d	32000 m^3/d	25-100 (Metcalf et al., 2014)
Belt thickener flowrate	375 m^3/d	247 m^3/d	-
HLR: For primary clarifier	18.6 m3/m^2.d	40 m^3/m^2.d	40 m3/m2.d (Metcalf et al., 2014)
HLR: For secondary clarifier	9.3 m^3/m^2.d	22 m^3/m^2. d	22 m^3/m^2. d (Metcalf et al., 2014)

HLR: For Belt Thickener	800 L/min per m belt width	1095 L/min per m belt width	400-1000 L/min per m belt width (Qasim & Zhu, 2017)
Polymer dosage	63 kg/d	41.5 kg/d	1-7 kg/d (Qasim & Zhu, 2017)
Number of digesters	4	2	-

The process of regulating and adjusting the mass balance with the reality of the state of the specifications of the plant led to improvements in energy and cost, as shown in Table(4-3)

Table 4-3:Feasibility of regulating Karbala sewage treatment plant

Unit process	Improvement in energy and cost	Remark
Primary clarifier	50%	Reducing the number of primary sedimentation basins from 4 to 2, contributed to reducing energy to half, as well as maintenance and operating costs as well.
Secondary clarifier	50%	Reducing the number of secondary clarifiers from 8 to 4, contributed to reducing energy in half, as well as maintenance and operating costs as well.
Primary sludge pump	36 %	Reducing sludge pumping as a result of the new mass balance contributed to reducing energy and reducing operating time, which will reflect positively on the operating cost of the pump.
Return activated sludge pump	11%	Reducing sludge return contributed to reducing pump operation, which contributes to improving cost and energy
waste activated sludge pump	55%	Increasing the SRT contributed to reducing the excess output of the sludge to the sludge treatment line

Gravity thickener	50%	Reducing sludge pumping contributed to reducing the thickening tanks by half
Belt thickener	34%	Reducing WAS contributed to decreasing upper flow belt thickener.
Polymer dosage	34%	When reduced the discharge of the upper flow belt thickener, the costs of Polymer are reduced
Anaerobic digester	50%	When the primary and secondary sludge discharges were reduced, this contributed to reducing the size of the reactor to suit the new flowrate, and thus the reactor was improved well.
overall improve	37.3	-

4.3 Model Calibration for Karbala WWTP

When using simulation systems to benefit from them in shortening the time and compensating for some laboratory tests, calibration and verification must be carried out in a way that ensures that the model’s outputs are as close as possible to reality. In this study, the model was calibrated with the average results of the effluent of the Karbala sewage treatment plant for the autumn and winter seasons and validated for the spring and summer seasons. The model was run according to the default data inside it, so the results were very far from reality (Mu’azu, et al., 2020). Some of the necessary parameters that affected the change of results were modified. These changes were according to Tables 4-4 and 4-5. The results were good when compared with the predicted and actual ones, as shown in Figure 4-1. From Figure 4-1 it was observed that TSS default results were less than 5 mg/L and in this case, they were far from reality. Therefore, the sensitive parameters were modified in GPS-X Model about the secondary sedimentation basin. Some sensitive parameters such as (the feeding point from the bottom) have been modified from the default 1m to the real 4.3 m, and (the maximum Vesilind settling velocity) has been changed from 410 m/d to 358 m/d. These two parameters were more sensitive in addition to dimensional other operational parameters. It was also noticed that the concentrations of COD and BOD were higher than the reality, as some sensitive parameters were changed and presented in Tables 4.4 and 4.5, these concentrations were reduced to fit the reality. It was seen that the default nitrate concentrations were much lower than the reality, but after adjusting some sensitive parameters on the kinetics of ammonium and nitrates, where (Nitrogen Fractions) and (Active Heterotrophic Biomass) were modified, this modification led to fitting the predicted nitrate concentration with reality. Phosphates were the opposite of nitrate concentrations, where the default was higher than the real, and after adjusting for (Phosphorus Fractions), the predicted was fitted with the real one.

Table 4-4:GPS-X Input stoichiometry parameters (default & adjustment) based on GPS-X influent advisor.

Influent Stoichiometry Composition			GPS-X	Calibration	Validation
Classification Parameter	Parameter	Unit	Default	autumn and winter average	spring and summer average
Influent Fractions	i_{vt}	gVSS/gTSS	0.75	0.71	0.70
	i_{cv}	gCOD/gVSS	1.8	1.51	1.53
Organic Fractions	X_{BA}	-	0	0.051	0.048
	X_{BH}	-	0	0.054	0.055
	X_i	-	0.13	0.011	0.012
	S_i	-	0.05	0.017	0.018
	S_S	-	0.2	0.019	0.021
Nitrogen Fractions	S_{nh}	-	0.9	0.61	0.62
	nS_i	gN/gCOD	0.05	0.05	0.05
	nX_i	gN/gCOD	0.05	0.001	0.001
Phosphorus Fractions	pS_i	gP/gCOD	0.01	0.05	0.05
	pX_i	gP/gCOD	0.01	0.05	0.05

Table 4-5:The stoichiometry and kinetic parameters of the A2/O GPS-X default and adjusted models are similar for calibration and validation results.

Influent Stoichiometry Composition			GPS-X Default	Calibration	Validation		
Classification Parameter	Parameter	Unit		autumn and winter average			spring and summer average
Physical	V	m3	1000	54054			54054
	d	M	4	6			6
Model Stoichiometry Parameters							
Active Heterotrophic Biomass	Y_H	gCOD/gCOD	0.666	0.19			0.2
	U_H	gCOD/gCOD	0.08	0.08			0.08
Active Autotrophic Biomass	Y_H	gCOD/gCOD	0.18	0.21			0.21
	U_H	gCOD/gCOD	0.08	0.069			0.069
Kinetic Parameters							
Active Heterotrophic Biomass	$\mu_{max,H}$	1/d	3.2	0.76			0.78
	b_h	1/d	0.62	0.48			0.5
Active Autotrophic Biomass	$\mu_{max,A}$	1/d	0.9	0.95			0.95
	K_{NH}	mgN/L	0.7	0.5			0.5

Hydrolysis	k_h	1/d	3	5			5
	Kx	gCOD/gCOD	0.1	0.03			0.03

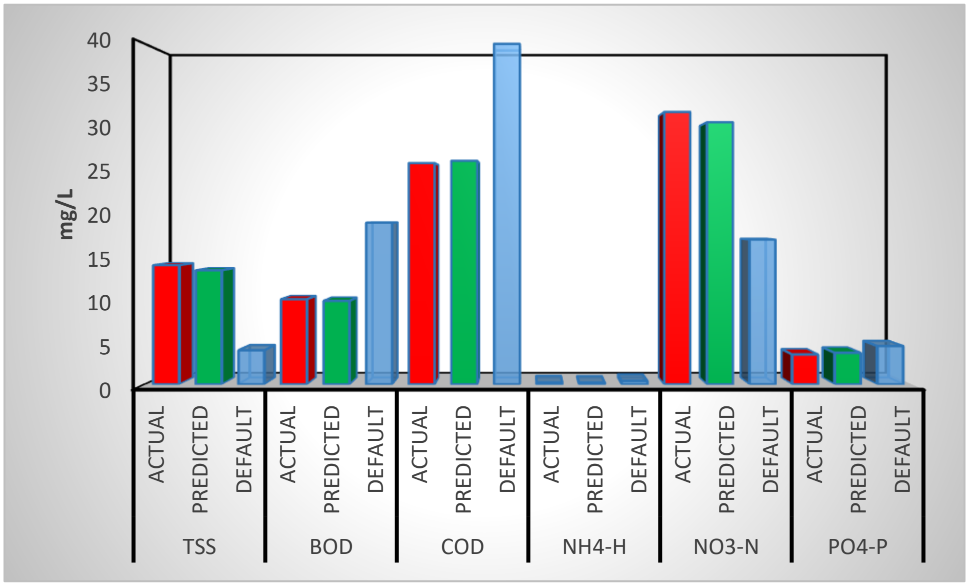


Figure 4-1:The calibration of actual, predicted and default values.

4.4 Model Validation for Karbala WWTP

The next task after the calibration process is the validation process,which is to reach results as close to the actual as possible for results that were not included in the calibration process. It was noticed that after changing some kinetic and stoichiometry parameters that did not significantly affect the results (see Figure 4-2). The small discrepancy between calibration and verification is due to the moderate concentration of pollutants throughout the year. The process of calibration and validation and after adjusting the sensitive parameters within the model gave results, all within RMSE and R and as shown in Table 4-6.

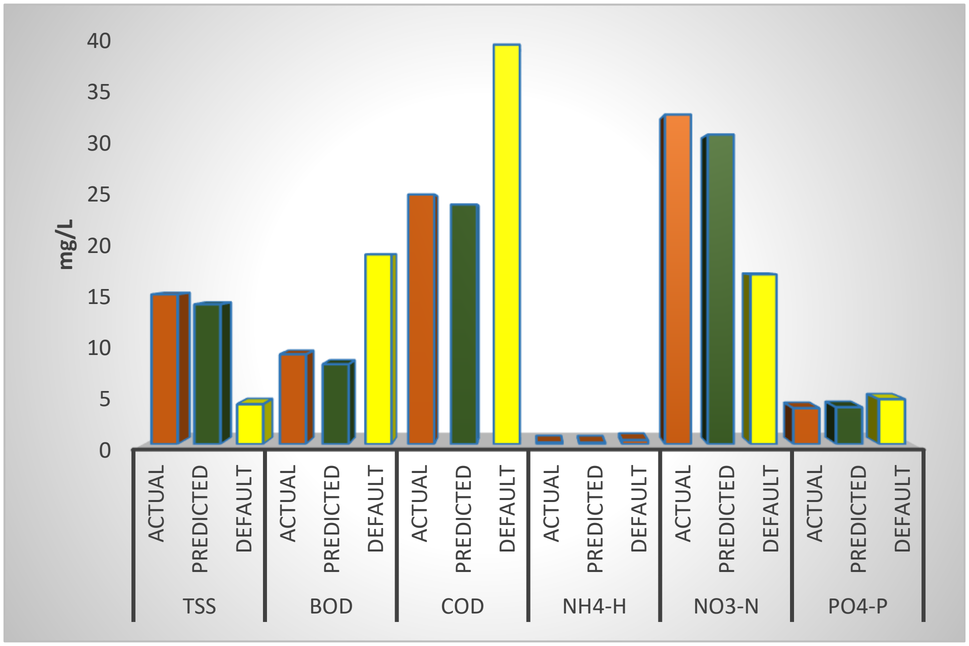


Figure 4-2:The validation of the actual, the predicted and default values

Table 4-6:R and RMSE values after adjustment for calibration and validation.

	Model Calibration		Model Validation	
Parameter	R-value for autumn and winter average	RMSE value for autumn and winter average	R-value for spring and summer average	RMSE value for spring and summer average
TSS	0.84	0.011	0.87	0.011
BOD	0.87	0.082	0.88	0.072
COD	0.89	0.021	0.9	0.17
NH_4^+-N	0.9	0.022	0.86	0.021
NO_2^{-}N	0.84	0.027	0.85	0.026
NO_3^{-}N	0.83	0.138	0.82	0.136
PO_4-P	0.87	0.011	0.86	0.012

4.5 Sensitivity analysis

Conventional activated sludge systems are affected by several sensitive factors, the most important of which were identified using the calibration and validation process discussed. Some parameters in the GPS-X Model did not affect the results of calibration and validation, while other parameters affected these only slightly; the study thus focused on the most sensitive parameters for analysis, in order to determine the extent of their impact on improvement and upgrading processes.

Figure 4-3 shows the effect of dissolved oxygen concentration on the effluent of the plant. With an increase in the concentration of dissolved oxygen, the concentrations of COD and BOD decreased due to the oxidation of organic materials inside the cell and their transformation into stabilizers (Faris et al, 2022). However, when the dissolved oxygen increased, the production of nitrates increased due to the resulting nitrification process and endogenous respiration (Hocaoglu, et al, 2011). It was observed that when the dissolved oxygen concentration reached 1.5 mg/L, this offered effective treatment for the given organic substrate and ammonia levels. It was also observed, based on analyzing the sensitivity of the model with respect to dissolved oxygen, that after a concentration of 2 mg/L is reached, no benefit accrues from increasing the concentration.

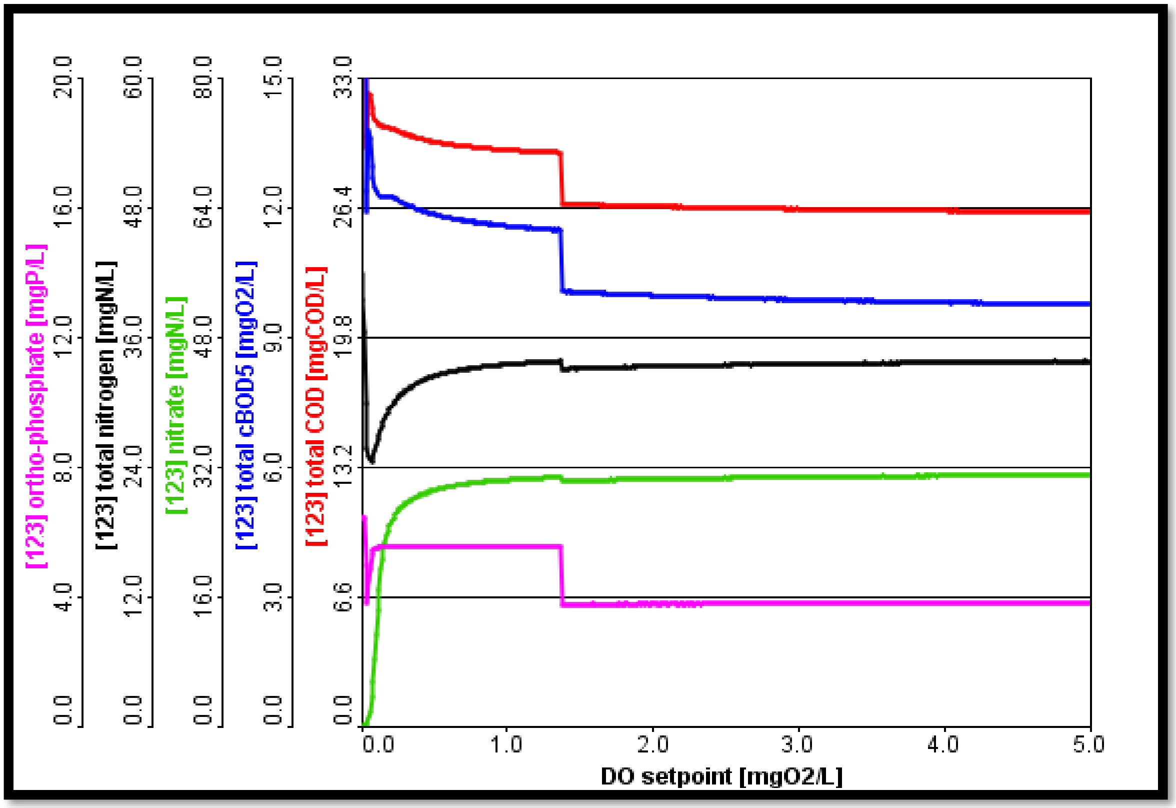


Figure 4-3:Effect of dissolved oxygen concentration on pollutants at the plant sewage effluent.

The main food source for phosphorous bacteria is rbCOD, which is also a food source and an electron donor for nitrate reduction. The effects of removing phosphates and nitrates with respect to this compound may lead to an imbalance in the removal of these nutrients, and this parameter is very sensitive to the removal of nutrients(Figdore, et al , 2018). In the sewage water of Karbala, the levels of this pollutant are low, and it may thus not help remove nutrients. Adding or increasing rbCOD concentrations may affect BOD and COD concentrations at the outlet of the plant. Figure 4-4 shows that the higher the rbCOD concentration, the greater the efficiency of phosphate removal and the more extensive the improvement of the nitrification and denitrification processes. Where natural concentrations of rbCOD are very low; however, an external carbon source must be added to improve the nutrient removal processes, as in the Karbala sewage treatment plant.

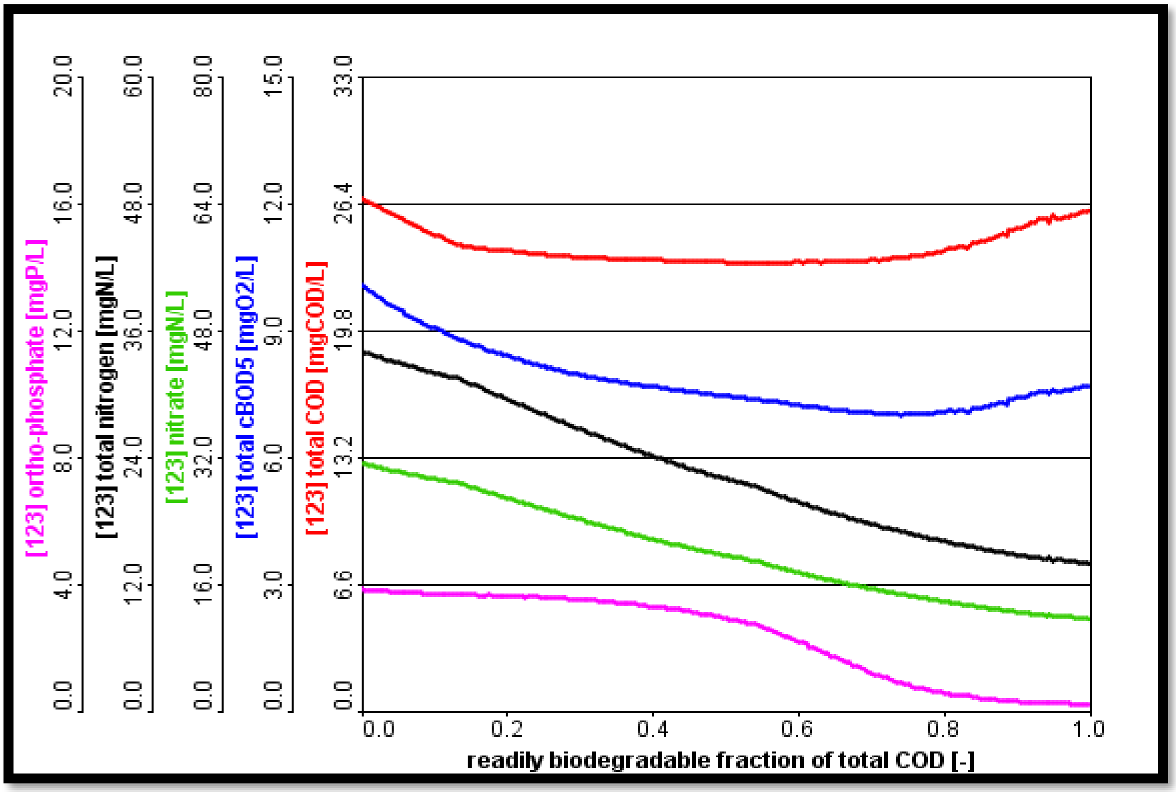


Figure 4-4:Effect of the readily biodegradable fraction on pollutants at the effluent plant.

Predicting sewage influent flow is critical from many perspectives, including the economic, environmental, and social standpoints. Forecasting influent flow at sewage treatment plants (WWTPs) is beneficial to the development of both the operators and the facility itself. Operators can run the plant more efficiently based on reliable forecasts projected in advance, which could allow them to improve sewage planning and management at various levels within the watershed (Boyd et al., 2019). Figure 4-5 shows the effect of discharge on the output of the plant. As discharge increases, the hydraulic load and the organic load on the reactors of the plant both increase, which negatively affects the treatment processes and thus increases concentrations of BOD, COD, and TSS in the treated wastewater. For the Karbala sewage treatment plant, however, even if discharge reaches 150,000 m3/d, the BOD, COD, and TSS concentrations do not exceed the Iraqi limits. It may, however, be possible to adjust the mass balance promptly based on observed discharge quantity and quality, which may reduce the concentrations of pollutants in the treated wastewater. It was further observed an increase in discharge increased the efficiency of phosphate removal, which depends on the acetate presence of rbCOD fermentation, and for such fermentation, retention times of 0.25 to 1.0 h are generally sufficient. (Metcalf et al., 2014) warned against employing excessive anaerobic contact times due to the risk of secondary phosphorus release, that is, phosphorus release unrelated to acetate uptake. Bacteria do not store polyhydroxybutyrate (PHB) for further oxidation in the aerobic zone when such secondary releases occur, and phosphorus uptake and storage both require energy, as provided by polyhydroxybutyrate. In the Karbala sewage treatment plant, the contact time in the anaerobic basin is currently in excess of 3 hours, which allows secondary release of phosphorous to occur, decreasing the efficiency of phosphate removal. However, nitrates are affected only very slightly when the discharge increases.

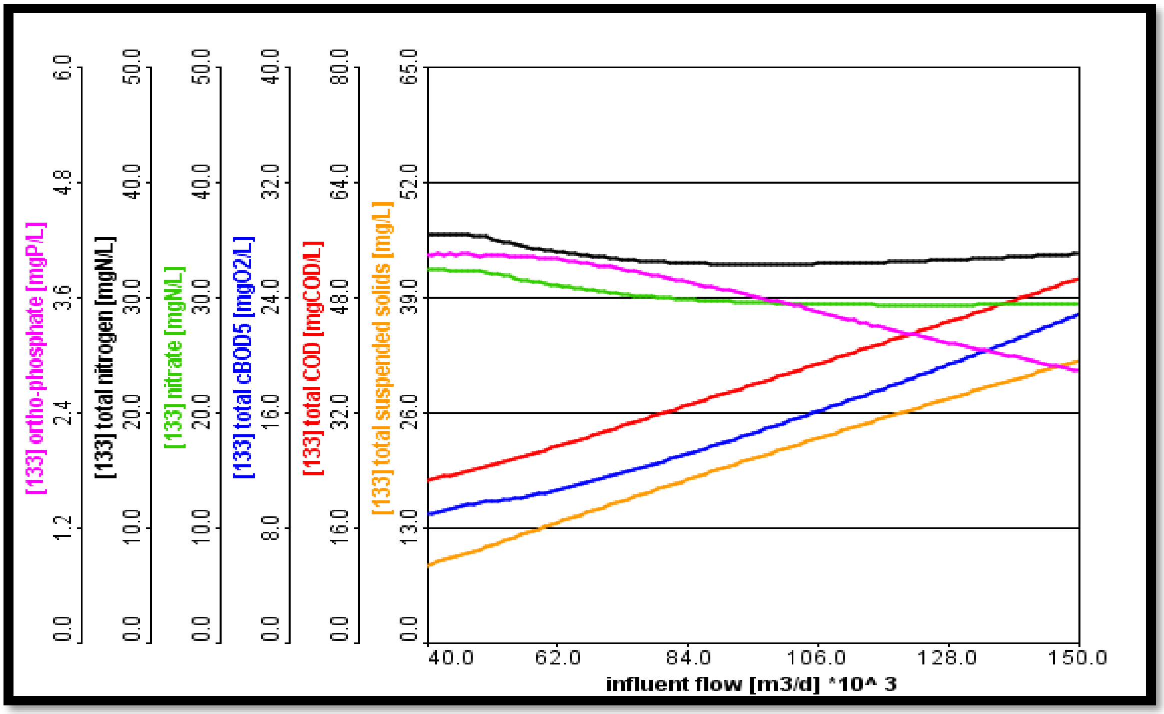


Figure 4-5:Effect of flowrate on pollutants at the effluent plant.

Figure 4-6 shows the effect of RAS on the concentration of pollutants in the treated wastewater. A very slight effect was observed in pollutant concentrations even when the RAS ratio ranged from 20 % to 100%. This makes it preferable to use the lowest percentage possible, so as not to waste energy and to increase MLSS concentrations in the aeration tank. Phosphates are affected by the return of sludge, however, as this flow may contain concentrations of dissolved oxygen and nitrates that affect phosphate removal efficiency (Chen, et al ,2015). The concentrations of TSS increase very slightly with an increase of RAS, due to the increase of SLR in the secondary sedimentation basin, while the concentrations of COD, BOD, and TN in the treated water improve when the percentage of RAS increases.

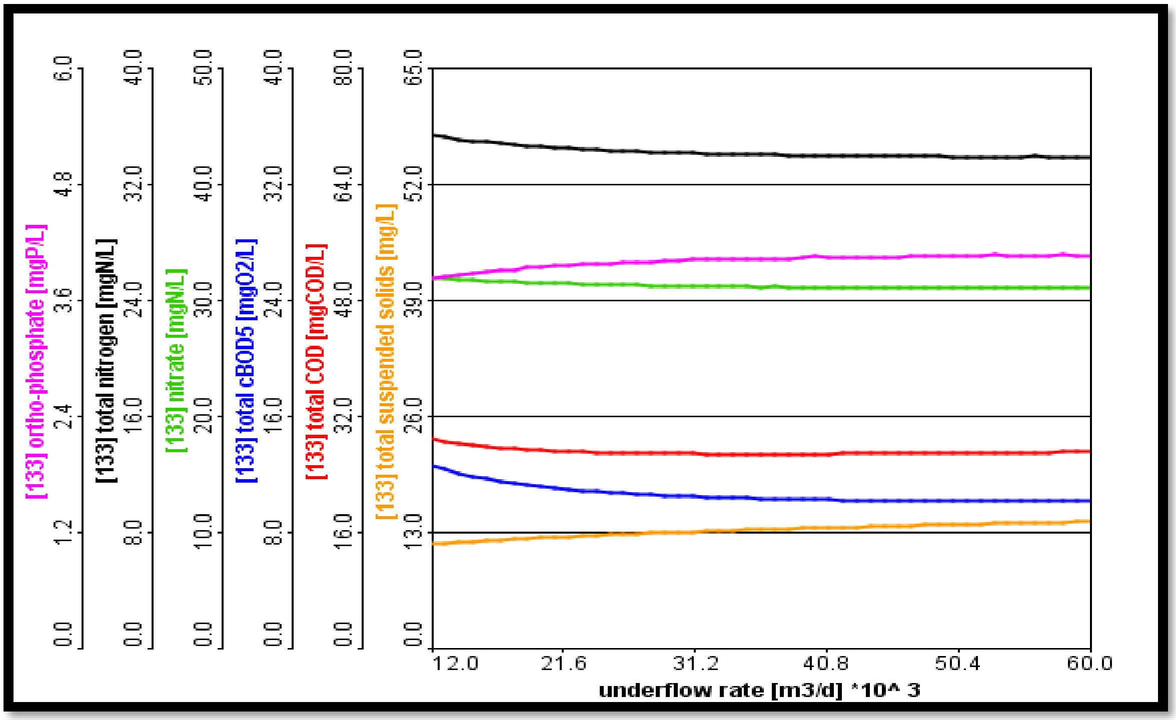


Figure 4-6:Effect of RAS on pollutants at the effluent plant.

Examining the internal recycling process involved assessing the nitrogen mass balance in the plant. Every biochemical process in the plant requires a donor electron and an acceptor electron. In the process of denitrification, rbCOD is the donor electron and nitrate is the acceptor electron (Y. Wang et al., 2019). Due to the lack of rbCOD in the sewage of the city of Karbala, however, it is useless to return large quantities from the aeration basin to the anoxic basin. ln Figure 4-7, pollutants are not affected even by IRs three times greater than the influent discharge to the plant, though these pumps consume very high rates of energy and require maintenance. In addition to the large accumulation of nitrates in the anoxic basin, when nitrate concentrations increase in the system, three negative effects occur. The first effect is that when the wastewater exits with WAS into the anaerobic digester basin, it transforms the treatment system from anaerobic conditions to anoxic conditions. In terms of the second effect, when the nitrates are returned to the phosphorous removal basin with RAS, anoxic conditions thus also occur in this basin. Finally, the third effect is the excess accumulation of nitrates in the anoxic basin, which may cause inhibition of nitrate-reducing bacteria.

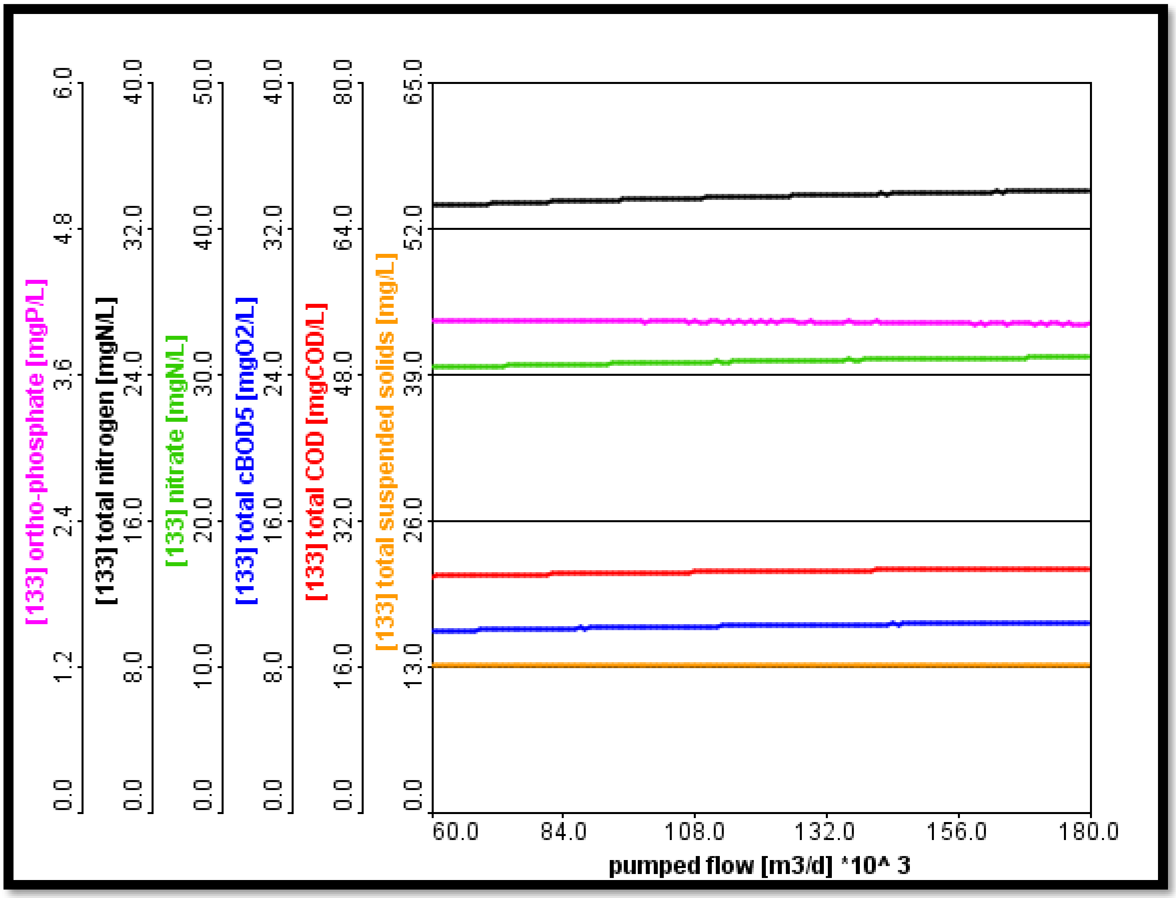


Figure 4-7:Effect of IR on pollutants at the effluent plant.

Removing the excess sludge is necessary to reduce the concentrations of MLSS in the aeration tank in such a way as to ensure that the pollutants are treated effectively. The removal of sludge from the system affects the removal of nitrogen while improving the phosphate removal process, in addition to affecting the organic substrate (see Figure 4-8). With an increase in WAS, the concentrations of COD, BOD, and TN increased slightly in the treated wastewater, due to the decrease in biomass concentrations that contribute to the decomposition of organic matter and nutrients. An increase in discharge brought on a slight decrease in the TSS concentration, due to the decrease in solid loading rate in the sedimentation basin, and a slight decrease was also observed in phosphate concentrations, as phosphates are biologically removed alongside sludge that might be used in building the metabolic processes of cells.

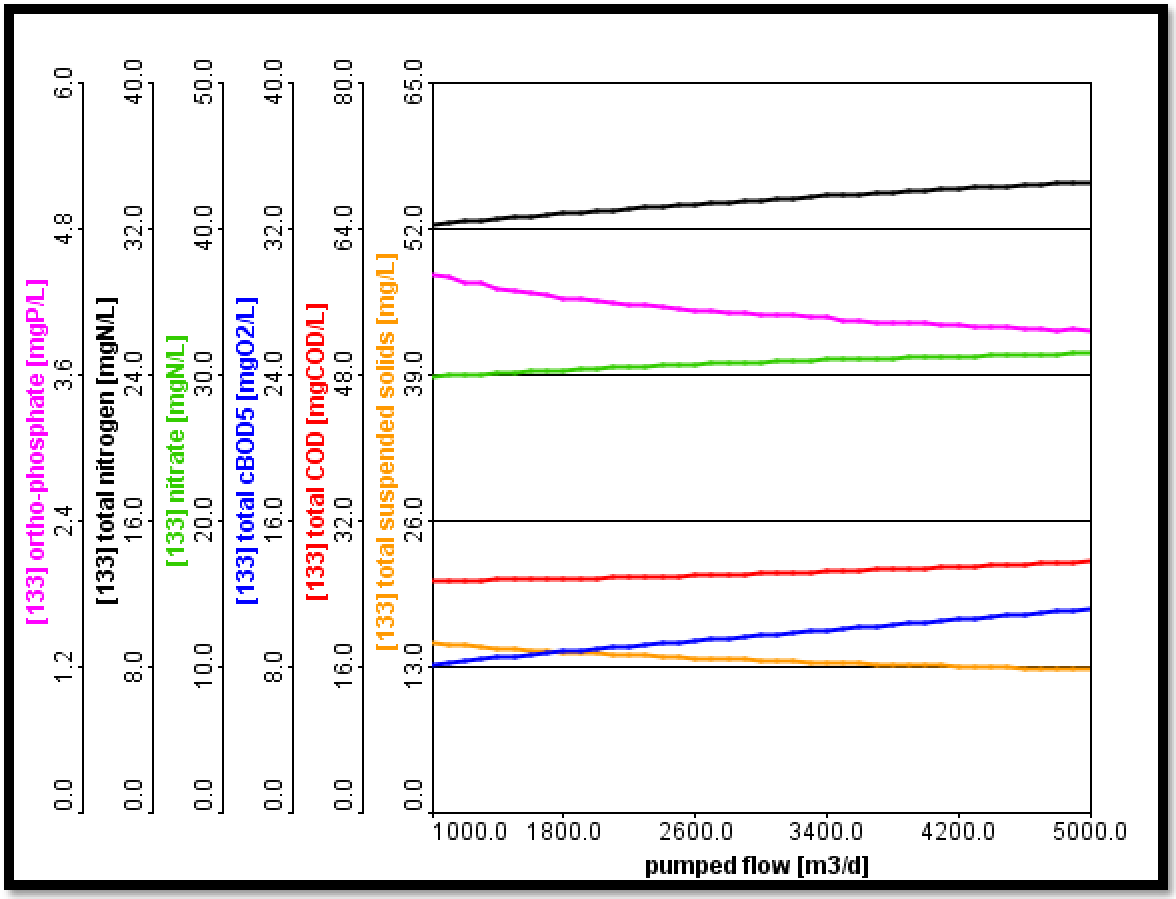


Figure 4-8:Effect of WAS on pollutants at the effluent plant

4.6 Upgrade the Karbala WWTP

Through the process of initial regulation of the plant and a mass balance procedure according to the reality of the plant's condition and after sensitivity analysis, the plant will be upgraded in the form of two stages of upgrades, the first stages is (physical and operational) and the other one is chemical. Table

4.7 shows the results obtained after operating the plant according to the new mass balance calculated in section 4.2.

Table 4-7:Plant results according to the new adjustment and mass balance by GPS-X.

Parameter	Actual Outlet, mg/L	Model GPS-X. results mg/L
COD	26	37
BOD_5	10	13
TSS	14	27
NO_3	32	27
NH_4^+	0.2	0.11
PO_4	3.5	3.4
Sludge product	3400 (kg/d)	2316 (kg/d)

The results shown in table are in conformity with the Iraqi Specifications No. 25 of 1967 (Jawad & Alrufaye, 2021), but it does not conform to the design parameters of the plant, so it requires physical and chemical upgrading, although the process of regulating and adjusting the mass balance has contributed to reducing the cost and energy to more than 40%. The regulating process reduced sludge production by 32%.

4.6.1 Physical and Operational Optimisation

Through sensitivity analysis, dissolved oxygen was approved at a level of 2 mg/L and the system was operated, as the same results that are shown in Table 4-7 were obtained, but the electrical energy in the aeration tank was reduced by 42%. The new regulating process led to an increase in TSS concentrations, so it is necessary to improve and reduce these concentrations by adding a sand filter to remove suspended solids. A sand filter is always followed by a physical disinfection process with ultraviolet rays and no need for chlorination. Chlorination has dangerous effects on the environment and plant workers, in addition to maintenance and operating costs (Wang et al., 2020). The Karbala sewage treatment plant was upgraded by removing chlorination, adding a sand filter, and a disinfection process by ultraviolet rays using GPS-X Model, as shown in Figure 4-9. Upgrade results are shown in Table 4-8.

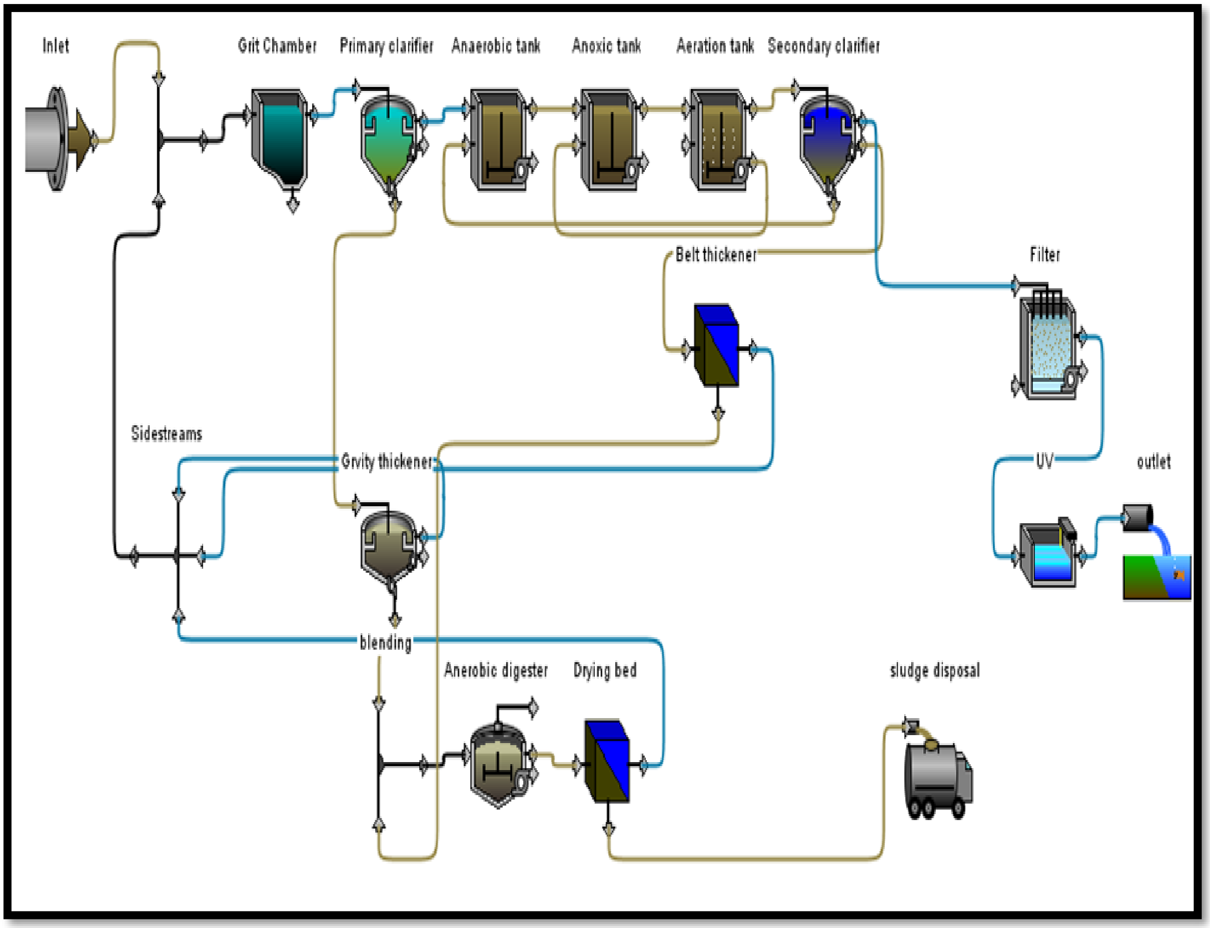


Figure 4-9:Upgrading Karbala sewage treatment plant wing sand filter and ultraviolet rays.

Table 4-8:Model results after upgrading with sand filter

Parameter	Actual Outlet, mg/L	Optimized system effluent mg/L	Improvement ratio %
COD	26	16.5	36
BOD_5	10	3.4	66
TSS	14	1.4	90
TP	5.8	4	31
CL_2 consumption Ton/year	110	0	100
Power consumption KW	137[a]	31[b]	77
Chlorine cost per year	90000$	0	100
Construction cost	2600000$	1000000$	61

a: The energy consumed by chlorination

b: Energy Consumed for Filter 28 and UV 3Kw.

Based on results analysis of Table (4-8) it was observed that the process of upgrading led to good improvement processes, as the process of upgrading led to an improvement of 90% in the removal of suspended solids, in addition to an improvement in the disposal of COD and BOD concentrations. The process of upgrading contributed to reducing energy consumption by 77% and saving an annual cost to a value of $90,000 for the value of eliminating chlorine.

4.6.2 Chemical upgrades

4.6.2.1 System Upgrade using Pre-denitrification

Many external carbon sources were used in this study to see how they affected nutrient removal from wastewater. To optimize the denitrification process and lower phosphate concentrations in the present system, four external carbon sources were chosen. Acetic acid, propionic acid, methanol, and glycerol are examples of these molecules. These materials were applied following the original sedimentation basin but prior to the phosphorous removal basin (see Figure 4-10). Nitrate and ammonium are the two most important nitrogen types associated with human consequences. The major nitrogen forms connected with human impacts are nitrate and ammonium. in light of the current eutrophication crisis. Therefore, reducing these concentrations will contribute to reducing harmful plants and algae in water sources

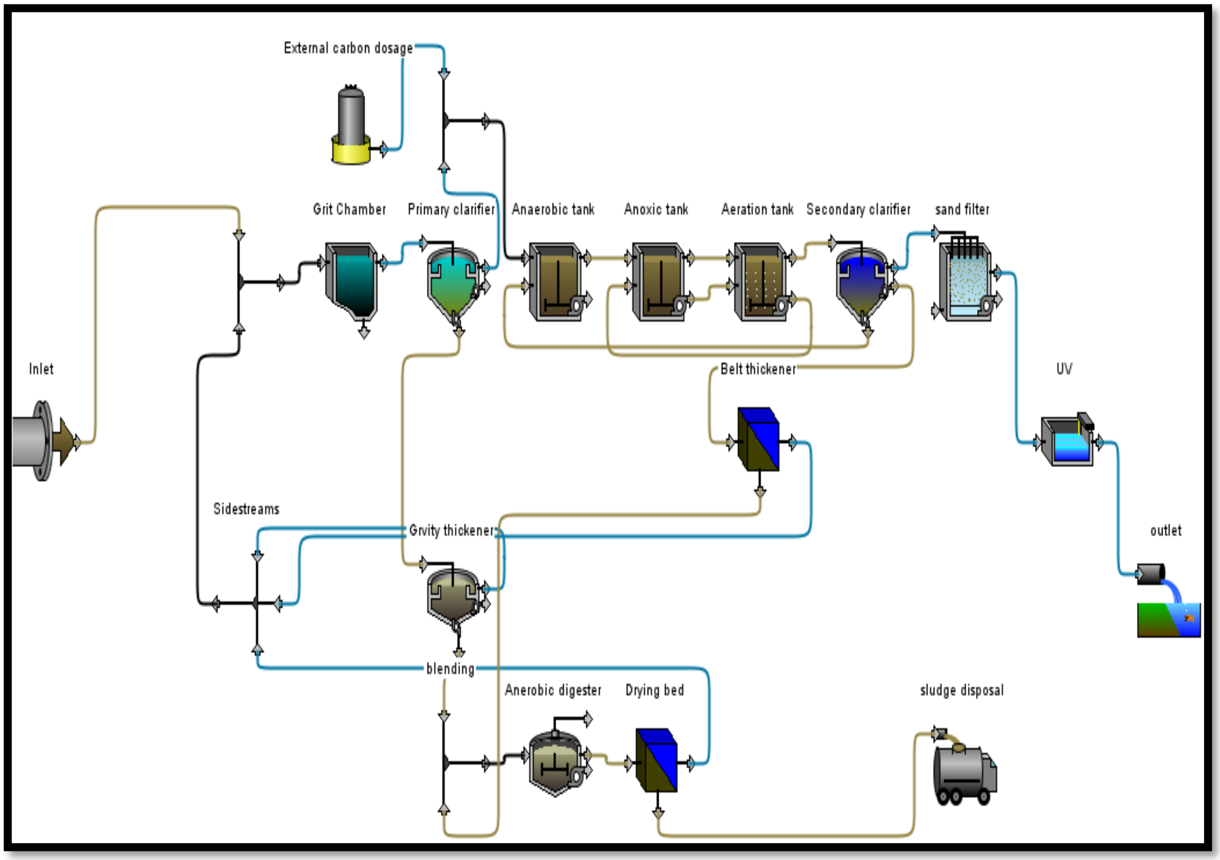


Figure 4-10:Upgrading Karbala sewage treatment plant by adding an external carbon source

The results shown in Table 4-9 were obtained. From the examination of results presented in Table (4-9), the best removal of nitrates and total nitrogen were observed when methanol was added. The total nitrogen concentrations reached to less than of 10 mg/L when methanol was added. While the best removal of phosphate was when adding propionic acid .Also, it was concluded that the achieved glycerol was the weakest external carbon source by removing nutrients. But glycerin did not raise the concentrations of BOD and COD when added compared to the rest.

Table 4-9:Simulation results after adding an external carbon source

Parameter	Actual Outlet, mg/L	Acetic acid mg/L	Propionic acid mg/L	Methanol mg/L	Glycerol mg/L
COD	26	23	27	28	16
BOD_5	10	4.7	6	8	3
TSS	14	1.7	1.8	1.7	1.4
TP	5.8	1.3	1.2	1.33	3.6
NO3	32	11.5	9	7.8	23
TN	34	13.56	11	9.7	24
PO4-P	3.5	0.33	0.11	0.33	2.8

4.6.2.2 System Upgrade using post-denitrification

Biological nutrient removal (BNR) is a term that refers to the removal of both P and N. The majority of BNR WWTPs use a pre-anoxic layout, in which the anoxic zone is positioned with regard to the flowrate of the aeration basin. As denitrification depends on ammonia oxidation in the aerobic zone, substantial mixed liquor recycle (MLR) rates are required in the anoxic zone to provide a suitable nitrate source. While high specific denitrification rates (SDNRs) can be achieved using this arrangement, MLR pumping has several drawbacks, including greater energy costs, the return of dissolved oxygen (DO) from aerobic processes, and dilution of influent carbon. The most important issue is that the pre-denitrification process cannot reach the required nitrate reduction levels, never taking concentrations below 5 mg/L. (Winkler, et al., 2011). As the anoxic tank positioned downstream of the aerobic nitrifying tank can produce an effluent with less than 3 mg/L, post-anoxic denitrification eliminates the need for MLR pumping as illustrated in Figure 4-11, the Karbala sewage treatment facility was updated by inserting the post-anoxic basin after the aeration basin.

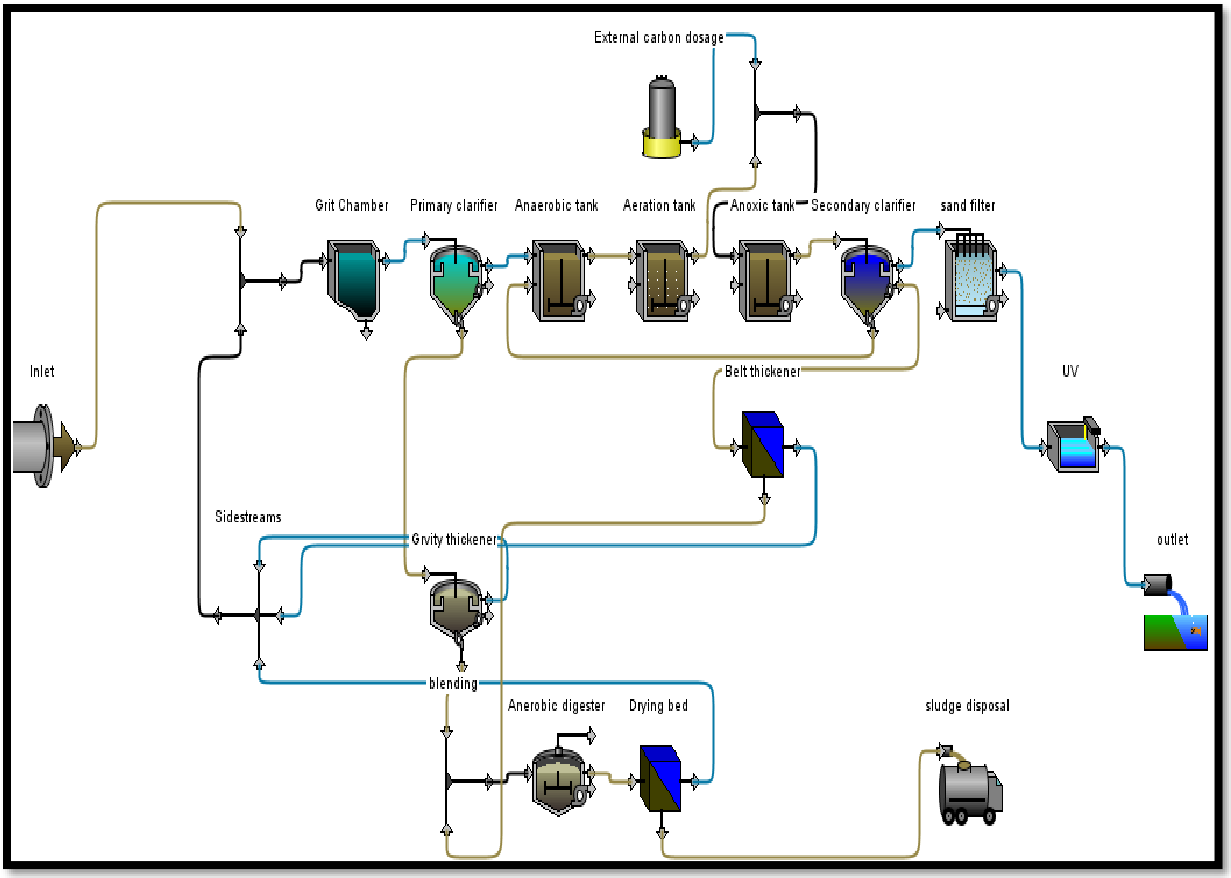


Figure 4-11:Upgrading Karbala sewage treatment plant by adding an external carbon source

In the case of operating the system in the post- denitrification process and adding methanol as the best external carbon source, the results were shown in Table 4-10.

Table 4-10:Comparing the results of the model when adding methanol to the post and pre- denitrification process.

Parameter	Actual Outlet, mg/L	Pre-denitrification by Methanol addition mg/L	Post-denitrification by Methanol addition mg/L
COD	26	28	65
BOD_5	10	8	35
TSS	14	1.7	1.6
TP	5.8	1.33	2
NO3	32	7.8	4.7
TN	34	9.7	7
PO4-P	3.5	0.33	1

From the above table, it is observed that nitrogen removal is excellent when the denitrification processes are post-anoxic. The improvement ratio of nitrate for pre- denitrification and post-denitrification was 75% and 85 %, respectively.

4.7 Summary of improvement and upgrading of Karbala WWTP

Karbala wastewater treatment plant works with good efficiency according to the Iraqi standard specificarion parameters, but the nutrients do not match the design parameters of the plant. The basic parameters of the Karbala wastewater treatment plant were modified and adjusted according to the international parameters. All results were good and within the Ireqi standard specificarion Iraqi parameters. Table 4-11 shows the summary of the overall improvement and upgrading of the Karbala sewage treatment plant. The new mass balance led to an increase in some concentrations, but this increase did not exceed the of poullutant determinants. The adjustment in the mass balance significantly reduced energy and costs. During sensitivity analysis, the best-dissolved oxygen concentration was observed, which is 2 mg/L. The system was modified according to this new concentration, which contributed to a good reduction in energy and cost. To eliminate the increasing of some specificarion as a result of the new modification and to obtain high efficiency, a sand filter and physical disinfection were added and chemical disinfection was deleted, which contributed to a good economic, technical and environmental feasibility. The process of physical regulation, modification, and upgrading was not able to reduce the nutrient concentrations due to the lack of the donor electron represented by rbCOD. But the chemical upgrade represented by the addition of an external carbon source contributed significantly to reduc the nutrients to the required design determinants. But one of the disadvantages to adding an external carbon source is that it contributes to raising the operational cost and raising some concentrations at the outlet of the plant.

Table 4-11:Summary of the overall improvement and upgrading of the Karbala WWTP.

Parameter	current system	System improvement after modification (mass balance)	The system after adjusting DO to 2 mg/L	Optimization after adding the filter	Improvement after adding an external carbon source
COD mg/L	26	Not good	-	Very good	Not good
BOD mg/L	10	Not good	-	Very good	Not good
TSS mg/L	14	Not good	-	Very good	Not good
TN mg/L	34	Poor	-	Poor	Very good
TP mg/L	5.8	Poor	-	Poor	Very good
NO3 mg/L	32	Poor	-	-	Very good
PO4-P mg/L	3.5	Poor	-	-	Very good

Energy consumed KW	860	Good	Good	Good	Not good
Conception energy in a month ($)	190750	Good	Good	Good	Not good
The expected annual cost of operation and maintenance of the chlorinator($)	150000	-	-	Good	-
Disinfection effect	very high	-	-	Ineffective	-
External carbon source cost	-	-	-	-	High cost
Sludge product kg/d	3400	Good	-	-	Not good

Chapter Five: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. The new mass balance has reduced costs and energy by more than 47%,and reduced sludge production by more than 30%.
2. The Karbala sewage treatment plant was calibrated and validated within GPS-X Model, and all results were within the required parameters for R and RMSE.
3. The effect of rbCOD on the removal of nitrates and phosphates.
4. The increase in the discharge affected the concentrations of COD, BOD, and TSS at the outlet of the plant, but the increase in the discharge contributed to the reduction of phosphate.
5. The increase in RAS and IR flow did not affect the output of the plant much.
6. An increase in WAS led to a deterioration in the results of COD, BOD, and TN but a slight improvement contributed to reducing TSS and PO4-P concentrations.
7. The operation of the Karbala sewage treatment plant at a concentration of dissolved oxygen of 2 mg/L contributed to saving energy consumed by more than 40% in the aeration basin.
8. Physical upgrading by sand filter contributed to a significant improvement in TSS concentrations by 90%.
9. The removal of chlorination and the use of ultraviolet rays in the disinfection process also Implementation of physical disinfection instead of chemical disinfection contributes to reducing the cost to more than 60% and eliminating the risks resulting from that disinfection and reducing energy to more than 70% in this stage and saving more than 150000$ per year.
10. Chemical upgrading is very costly and COD and BOD concentrations may be adversely affected at the outlet of the plant.

11. The best external carbon source that contributed to reducing nutrients was methanol.

12. Upgrading the Karbala sewage treatment plant by pre-denitrification in reducing nutrients is better than post-denitrification.

5.2 Recommendations of Karbala Sewage Directorate

1. Due to the increase in the contact time (HRT) currently in the phosphorous removal basin, it is important to suggest using alum for reduction to reduce phosphate concentrations and make them within the allowable specifications.
2. It is suggested to optimize the denitrification process by producing an internal carbon source instead of an external carbon source.
3. It is suggested to find solutions to reduce phosphate concentrations by physical, chemical, or biological methods.
4. It is necessary to adopt the new mass balance which was obtained from the present study to effectively contribute to reducing energy consumption and cost.
5. The GPS-X Model has good ability to predict most proper of current and future operation processes.
6. It is good to tun off the operation of some aerators in the aeration basin when the dissolved oxygen concentration reaches 2 mg/L to contribute to reducing the energy consumed.
7. Use of sand filter at the outlet of the plant to contribute in further reducing the concentrations of suspended solids and organic materials.
8. Adoption of physical disinfection instead of chemical disinfection

5.3 Recommendations for future studies

1- Study of new variables such as a change in the percentage of discharges entering the plant to evaluate and model the performance of the wastewater treatment plant in Karbala by using the GPS-X program.

2- Using software or concluding mathematical models to describe the current and future operational performance of the plant.

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الخلاصة

محطات معالجة مياه الصرف الصحي التقليدية وخصوصا التي تحتوي على مراحل ثلاثية وإزالة المغذيات تكون لها حركيات كيميائية وبيولوجية معقدة للغاية. بسبب خصائص وطبيعة مياه الصرف الصحي دائما ما يحتاج الى تحسينات مستمرة وهذه التحسينات لابد ان تدرس بعناية قبل اجرائها. نظام التشغيل الأمثل يزيد من كفاءة المحطة وتقليل الطاقة المستهلكة وتحقيق الحدود البيئية لمخرجات المحطة. في الدراسة الحالية، تمت دراسة إستراتيجية جديدة لتقليل تركيزات المغذيات وتقليل الطاقة وتحسين مخرجات المحطة في مصنع واسع النطاق بواسطة نموذج GPS-X .تم جمع البيانات بكل دقة من إدارة المحطة مثل خصائص مياه الصرف الصحي لمدة سنة كاملة وكمية المياه المعالجة بالإضافة الى جمع البيانات الفيزيائية والتشغيلية لكافة احواض المحطة.

تم إجراء المعايرة والتحقق من صحة النموذج، وتم تعديل بعض المعلومات الحساسة، وكانت النتائج ضمن قيم R وRMSE. أوضح تحليل الحساسية أن العامل الأكثر أهمية لتقليل تركيزات النيتروجين والفوسفور هو الجزء القابل للتحلل الحيوي(rbCOD). تم تخفيض تدفقات IR وRAS وDO وWAS من 3٪ إلى 1٪، ومن 100 إلى 20٪، ومن 3.5 إلى 2 مجم / لتر، ومن 3500 إلى 1000 متر مكعب / يوم، على التوالي، وتم توفير نتائج لتحسين الطاقة 688.4 كيلوواط ساعة وتقليل الحمأة بنسبة 32٪.

أظهرت النتائج أنه من غير المجدي الحصول على نسبة من IR 3٪ بسبب نقص rbCOD بتركيزات كافية للمساهمة في تقليل النترات. انخفاض تراكيز rbCOD في مياه الصرف الصحي لمدينة كربلاء يتطلب ترقية كيميائية.

تمت الترقية الكيميائية بإضافة مصدر خارجي للكربون يتمثل بحمض الخليك، وحمض البروبيونيك، والميثانول، والجلسرين، وكانت النتائج جيدة، وأدى ذلك إلى تحسن من خلال تقليل TN وTP بنسبة (60 و77٪)، (68 و79٪) و (71 و77٪) و (29 و38٪) على التوالي. كان أفضل مصدر خارجي للكربون هو الميثانول، بينما كان الجلسرين أقل فعالية من البقية. تمت مقارنة عملية نزع النتروجين المسبق مع عملية ما بعد نزع النتروجين عن طريق إضافة الميثانول كمصدر خارجي للكربون. كانت النتائج جيدة لتقليل TN في عملية ما بعد نزع النتروجين، والتي وصلت إلى 80٪، بينما كان التأثير سلبياً على باقي الملوثات. تم الاستنتاج من خلال الدراسة ان عملية التنظيم لمحطة المعالجة واجراء توازن الكتلة بشكل صحيح يساهم بخفض الطاقة ويحسن العمليات البيولوجية للمحطة. ساهم برنامج GPS-X بإعطاء رؤية كاملة وفعالة وقريبة جدا من الواقع وننصح باستخدام من قبل دوائر مديريات المجاري والمهندسين العاملين في هذا المجال.

جمهورية العراق

وزارة التعليم العالي و البحث العلمي

جامعة كربلاء

كلية الهندسة

قسم الهندسة المدنية

تحسين أداء محطة معالجة مياه الصرف الصحي في كربلاء من خلال التغير في العوامل التشغيلية المؤثرة للمحطة باستخدام نموذج GPS-X

رسالة مقدمة الى مجلس كلية الهندسة / جامعة كربلاء وهي جزء من متطلبات نيل درجة الماجستير في علوم الهندسة المدنية

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