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Research paper



Optimum Design of Phosphorus and Nitrogen Removal from Domestic Wastewater Treatment Plant

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Abstract

In this study, a sewage treatment plant was designed for the city of Al-Nasiriyah in Dhi Qar governorate in southern Iraq serving 316083 inhabitants. The resulting treated water is suitable for agricultural irrigation and can be discharged to the Euphrates River when needed by adding nitrogen and phosphorus removal units to the wastewater treatment plant. The obtained plant design has been verified and optimized by implementing the proposed plant layout in the GPS-X 5.0 modeling and simulation software (Hydromantis). Where the results of the design showed that the total phosphorus flow is higher than the desired limit of 2 mg / L, due to the excessive release during anaerobic digestion. Control of phosphorus concentration can be controlled by adding chemicals (iron or aluminum salts) in different parts of the wastewater treatment plant. In this case, two different control strategies can be implemented: adding aluminum doses in both water and sludge lines (at Chem1 and Chem2 points) or adding aluminum doses in the water line only (at point Chem2). The second strategy showed that it is the most efficient in controlling the concentration of phosphorus and nitrogen produced, which meets the limits of the Iraqi standard of water used in irrigation.

Keywords: *Activated Sludge; Irrigation;Total Kjeldahl Nitrogen; Total Phosphorus Wastewater.*

1. Introduction

The crisis of water scarcity in Iraq is one of the most important problems facing the Iraqi economy, especially the agricultural sector, because Iraq was and is still an agricultural country. The size of the water problem is great and if it does not appear clear today it will be dangerous in the future. The flow of wastewater to surface water may expose it to the risk of contamination with pathogenic organisms and buoyant residues, as well as to sedimentation and thus the emergence of anaerobic conditions. It also affects the safety of aquatic life. However, the greatest concern has been the rapid emergence of algal growth in these surface waters (Tredici *et al*., 1992). The phenomenon of algae growth (Eutrophication) is a natural growth process within the water due to increased biological activity. Water with algal growth is characterized by the presence of water grasses and algal mosses in high concentrations. The death of these organisms leads to the deposition to the bottom and then decomposition and oxidation, which eventually lead to the consumption of dissolved oxygen available water and therefore the emergence of anaerobic conditions at the bottom accompanied by foul odors (Pasereh *et al*., 2017). Algal growth speed increase of nutrient loads associated with the final effluent resulting from the wastewater treatment plants (Amirhossein, 2017).

Phosphorus and nitrogen are the main nutrients that cause the growth of phytoplankton, and therefore their removal within wastewater treatment plants will reduce this phenomenon. Environmental engineers consider that the disposal of these nutrients within wastewater treatment plants is the most effective way to control this phenomenon (USEPA, 2008). But this is not the only problem these nutrients cause. Ammonia is toxic to some aquatic organisms, albeit with small concentrations. Ammonia oxidation to nitrite and nitrate can severely deplete dissolved oxygen concentrations (DO) within the water. Nitrite has been found to be more strongly linked to hemoglobin than oxygen and thus to be removed in the blood causing hemoglobinemia or blue baby disease in children. The presence of phosphates, albeit with small concentrations of 0.2 mg/l, is inconsistent with the chemical removal of turbidity in drinking water (Aslan and Kapdan, 2006). Faced with the increasing nutrient loading, coupled with the steady interest and successive demand to protect the world's water resources, research and development of phosphorus and nitrogen removals of wastewater have progressed significantly. Much attention has been paid to manipulating the surrounding conditions to strengthen the biological mechanisms responsible for nutrient removal (Martínez *et al*., 2000). The negative effects of nutrients (phosphorus-nitrogen) on the receiving water resources (rivers and lakes) have been shown and these effects have been covered by adequate scientific studies (Converti *et al*., 2009, Kong *et al*,. 2010, Mata *et al*., 2010, Bernard, 2011, Abdel-Raouf *et al*., 2012, Samorì *et al*., 2013, Kim *et al*., 2014, Mark and Robert, 2017, Ghawi, 2017 and Ghawi, 2018). Therefore, the legislations that define the specifications of treated water for water sources have been established, thus ensuring the safety and preservation of these sources.

Phosphorus is one of the main nutrients and must be reduced to acceptable minimum levels before the treated water is discharged to the public water resources (lake-river). In general, the primary sedimentation ponds remove the phosphorus in contaminated water by 10-30% Secondary treatment is characterized by low effectiveness in the removal of phosphorus because it is found in the form of dissolved (Lee *et al*., 2013).

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The objective of this study is to design a sewage treatment plant with a concentration of phosphorus produced less than 2 mg/l and the concentration of total nitrogen within the permissible limits. Using a mathematical model (GPS-X 5.0 software (Hydromantis)) to achieve the optimal design of the wastewater treatment plant to ensure the reuse of water in the irrigation of gardens and agricultural land. To achieve this, the nitrogen and phosphorus removal unit was added to the design of the treatment unit.

Nutrient control design manual EPA 2009 indicates that wastewater treatment plants should include phosphorus and nitrogen removal units. The most important reasons for the inclusion of phosphorus and nitrogen units are to control the ratio of phosphorus and nitrogen in the water discharged from the sewage treatment plants, and thus the point of discharge of the treated water can be changed to public use for watering purposes. In this study, SERECO S.r.l. the technology was used in the design of nitrogen and phosphorus removal units. Also, The aim of this study is to optimum design a conventional sewage treatment plant using the GPS-X 5.0 program for the city of Al-Nasiriyah in Dhi Qar governorate in southern Iraq, serving 316083 people. So that the treated wastewater is suitable for agricultural irrigation or can be discharged to the Euphrates river by adding nitrogen and phosphorus removal units and the resulting water is in conformity with the river Protection Law. Also, the aim of this study is to describe the design and verification of the process adopted to achieve nitrogen and phosphorus removal from the treated wastewater.

The sewage treatment plant in the city of Al-Nasiriyah was designed to discharge the resulting water after the addition of nitrogen and phosphorus removal units for use in irrigation of domestic gardens and agricultural land near the project. That the parameters adopted in the addition of nitrogen and phosphorus removal units for the wastewater treatment plant in the city of Al-Nasiriyah are the specifications provided by the Directorate General of Iraqi Sewage (GDS) for the purpose of adding the system of removal of nitrogen and phosphorus. These limitations are the global specifications of the removal of nitrogen and phosphorus and must be adhered to as they preserve the environment from the pollutants of nitrogen and phosphorus and of great economic feasibility. That Iraq is experiencing the scarcity of fresh water and increased pollution in the rivers as well as the scarcity of water used in agriculture and combating drought and desertification and that the water produced from sewage treatment plants without adding the system of removal of nitrogen and phosphorus cannot be used in agriculture in the long term because the proportion of nitrogen and phosphorus high. Therefore, this is required in the law of the protection of rivers No. 25 of 1967 and the national determinants of the use of treated wastewater for agricultural irrigation No. (3) for the year 2012 to preserve the water and agricultural wealth.

2. Material and Methods

2.1. Description of Al-Nasiriyah Wastewater Treatment Plant (NWWTP)

The project of sewage treatment plant in the city of Al-Nasiriyah in the province of Dhi Qar of the strategic projects of the giant infrastructure, serving 316083 people. The city of Al-Nasiriyah to the southeast of the city of Baghdad, which is about 375 km. It processes wastewater to minimize its negative impacts and reused for irrigation. The area of wastewater treatment unit is (140x428) m. The station's location is within the limits of the city's basic design and is close to densely populated areas. Al-Nasiriyah Wastewater Treatment Plant (NWWTP) are 60000 m^3/day capacities. They are of conventional activated sludge process type as shown in Figure 1 in which the raw wastewater passes three stages of treatment; primary treatment where suspended solids settled or retained, secondary treatment where biological process is taken place to transform dissolved and suspended organics into simple compounds, then the third stage where sludge stabilization takes place in digestion systems.



Fig. 1: General layout of Al-Nasiriyah WWTP (Water line: Screening-Aerated grit chamber and inlet Parshall flume – Primary settling – Biological Treatment – Secondary Settling –Disinfection. Sludge line: Thickening – Blending – Anaerobic digestion – Drying beds).

2.2. Influent characteristics

The Iraqi National Standards set by the Regulation 25 of 1967 for the design and specifications of wastewater raw and treated sewage from a domestic wastewater treatment unit also the capacity and technological parameters of this study are shown in Table 1. The BOD5 loading is typically in the range of 40-80 gBOD5 per equivalent inhabitant (EI) per day. Based on the data of EI (316083), flow rate (69538 m3/d) and BOD5 (350 mg/L), a contribution of 77 g BOD5/EI.d can be estimated. Considering this BOD5 contribution, it is possible to check the average influent characteristics in proportion to this parameter. Table 1 compares the estimations obtained adopting different sets of load values or using the influent advisor tool provided with the modeling software GPS-X 5.0 (Hydromantis). The simulation program (GPS-X 5.0 (Hydromantis)) make the design of the wastewater facility more efficient and evaluate each option. Hydromantis is home to the GPS-X system, known as the simulation and improvement of the wastewater treatment plant. GPS-X is a multi-purpose computer program for the modeling and simulation of municipal and industrial wastewater treatment plants. Whether you're designing a new facility or simulating an existing station, GPS-X will help to improve design and efficiency. As noticeable from Table 1, the influent COD should be quite higher than the official data provided by GDS (460 mg/L). Therefore a prudential value of 670 mg/L has been assumed for plant design and verification purpose.

2.3. Process design for enhanced biological nutrient removal (EBNR)

The biological treatment of municipal wastewater is typically based on the so-called activated sludge process, i.e., on the use of suspended biomass capable of oxidizing organic compound (Bougaran *et al*., 2010).

Organic nitrogen and ammonium can also be oxidized to nitrate (nitrification process) by ensuring additional aeration capacity and the adequate sludge retention time for the selection of slow-growing nitrifying biomass.

In order to reduce the concentration of nitrogen in the treated effluent, it is possible to introduce an anoxic tank in which the nitrate will be used instead of oxygen for the oxidation of readily biodegradable organic matter (denitrification process) (Figure 2). The nitrate will be consequently converted to nitrogen gas and released to the atmosphere. For an optimal denitrification process, the presence of readily biodegradable COD is mandatory and can be satisfied by internal or external sources. For this project, the introduction of a pre-denitrification step has been adopted, which is based on the utilization of readily biodegradable matter coming with the influent.

During normal biological degradation processes marginal amounts of phosphorus are used for the biomass growth, however, a significant removal efficiency can be achieved by Enhanced

Biological Phosphorus Removal (EBPR). The latter process is based on the introduction of an anaerobic tank similar to a selector, i.e., a tank in which the growth of phosphorus accumulating organisms (PAO) is favored. These bacteria are able to store phosphates into the cell when a sequence of anaerobic and aerobic conditions is achieved: carbon storage and phosphorus release will happen in the anaerobic zone, while this carbon will subsequently be utilized in the anoxic and aerobic tanks and phosphorus uptake will take place. Phosphorus will be then discharged with the wasted biomass.

Table 1: Comparison the estimations obtained adopting different sets of load values or using the influent advisor tool provided with the modeling software GPS-X 5.0 (Hydromantis).

Parameter mg/l	A typical value in high strength wastewater[1]	Estimated value based on EI load (USA)[1]	Estimated value based on EI load (regional)[1]	GPS-X Influent Advisor (Hydromantis)	Official data provided by GDS	Assumed value	Treated effluent limits mg/L
BOD_5	350	360	180	350	350	350	20
COD	800	860	350	660÷740	460	670	100
TSS	400	410	250	400	400	400	30
TN	70	55	50		40	40	7
NH_4-N	45	32	45		20	20	30
TP	12	8	5		8	8	2

[1]Data from Metcalf and Eddy (2003)

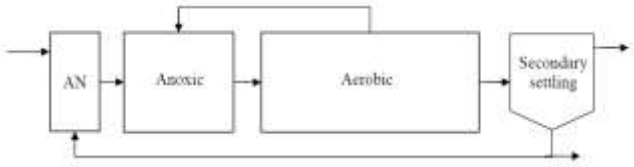


Fig. 2: The biological nutrient removal system.

3. Results and Discussion

3.1. Basic plant design

For the purpose of this study, standard design procedure has been used for preliminary tank sizing and estimation of sludge production, once the influent characteristics and desired mixed liquor concentration have been fixed, the estimation of minimum SRT and sludge production (based on activated sludge model kinetics) lead to the definition of the aerated and anoxic tanks volume.
The obtained plant design has been verified and optimized by implementing the proposed plant layout in the GPS-X 5.0 modeling and simulation software (Hydromantis). The latter has been used for simulating and verify the process performances in conditions of minimum temperature, peak loading and typical fluctuations of these parameters. In Table 2, a summary of the main design results is presented for the proposed layout.

Table 2: A summary of the main design results is presented for the proposed layout.

Design Parameter	Unit	EBNR (design Metcalf)	EBNR (GPS-X 5.0)
Total tank volume Anaerobic tank Anoxic tank Aerated tank	m^3 m^3 m^3 m^3	42000 6000 9000 27000	
HRT_{tot}	h	14	
SRT_{tot}	d	17.5	17.7
SRT nitrification	d	12.5	11.3
MLSS	kg/m^3	4	3.9
Biomass loading (F/M)	kgBOD/kgvss d	0.13	
Volumetric loading	kgBOD/m^3 d	0.38	
Sludge recycle ratio		1	1
Nitrate recycle ratio		1.64	1.64
Sludge production	kg/d	9780	9300
Observed yield	kgTSS/kgBOD	0.62	0.6
Effluent TKN	mgN/L	4.0	2.0
Effluent NO_3	mgN/L	5.0	6.7
Effluent TP	mgP/L	1.7*	4.5
Oxygen required (avg)	kg/d	21200	21600
Peak oxygen demand	kg/h	1580	

3.2. Process verification and simulations with GPS-X

The plant layout as simulated in GPS-X (Hydromantis) is shown in Figure 3. However, as shown in Table 2, with this layout (Figure 3) the total effluent phosphorus is above the required limit of 2 mg/L, due to the excessive release during anaerobic digestion. For this reason, the addition of chemicals is required, as better explained in the following.

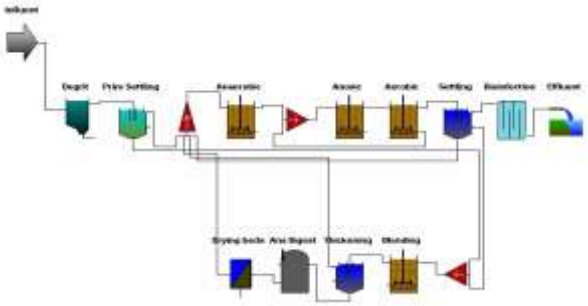


Fig. 3: The plant layout as simulated in GPS-X (Hydromantis).

3.3. Proposed options for effluent phosphorus control

The control of effluent phosphorus concentration can be achieved by dosing chemicals (iron or aluminum salts) in various sections of the plant.
It is well known that the occurrence of anaerobic conditions in the sludge treatment line can turn in the considerable release of soluble orthophosphate into supernatants and drainage water. If these streams have to be returned to the water line without any further treatment, they can strongly contribute to increasing the P load to the water line. In this case, the dosage of chemicals in all liquid flows to be returned to the water line can be the cheapest option, especially if considering the recovery of a phosphate-rich chemical sludge that can be dried separately and sold as fertilizer.
On the other hand, it is known that high summer temperature results in instability of the biological P removal process also in case of separate treatment of liquid streams returned from the sludge line (as shown with GPS-X simulations). In this case, in-line chemical dosing just before the secondary settling tank would allow controlling the effluent phosphorus while keeping the costs for the chemicals as low as possible (indeed chemical dosage will be operated only if biological removal would be not sufficient).
In order to ensure the maximum flexibility in future plant operation, in-line chemical dosage on both water and sludge lines is strongly advisable. As for the sludge line at Al-Nasiriyah Wastewater Treatment Plant, the dosage of chemicals can be done into the blending tank or in the supernatant and drainage streams. Based on the above considerations the two following treatment schemes are proposed in Figures 4 and 5.

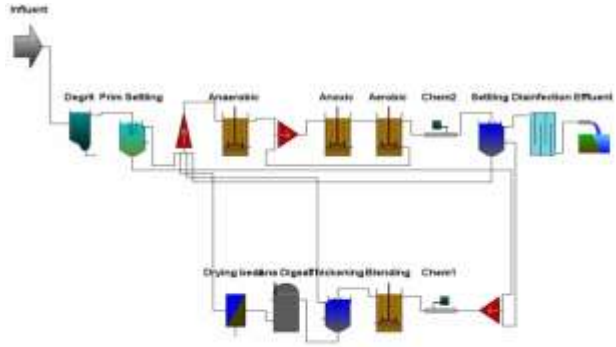


Fig. 4: Treatment schemes at Dosage in blending tank**.**

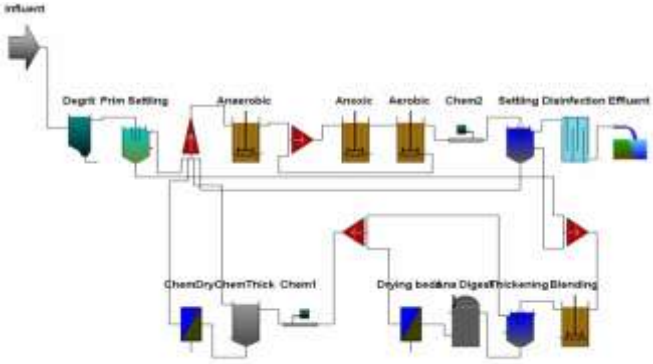


Fig. 5: Treatment schemes at Supernatant treatment and P recover**.**

These layouts (Figures 4, and 5) have been used to simulate the plant steady state operation in average conditions of influent flow, load and temperature. Moreover, the plant operation has been simulated in dynamic conditions:

- Daily variation of the influent flow rate (average temperature and optimized chemical dosage);
- Yearly variation of liquid temperature (at an average influent flow rate). In this case, 2 different control strategies can be implemented:
  - Dosing at both water and sludge lines (at points Chem1 and Chem2)
  - Water line dosing only (at point Chem2)

The results of this simulation are shown and discussed in the following.

3.3.1. Simulation of daily variations of influent flow and load

Daily flow variations have been simulated according to typical flow rate profiles for municipal sewers (Metcalf 2003), and Figure 6 shows the assumed variations for 3 days of operation.

Under the above daily variations and a liquid temperature of 20°C, the chemical dosing on the sludge line has been optimized to ensure less than 20% of returned phosphorus, while the chemical dosing on the water line was not required at the adopted temperature.

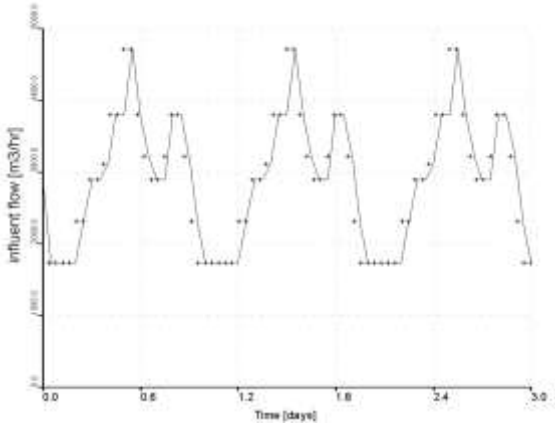


Fig. 6: Daily flow variations**.**

Simulation under the optimized conditions resulted in the following trends for the effluent quality. It can be seen that all parameter are below the requested limit.

As shown in Table 3, the optimal chemical dosage is higher when dosing into the blending tank. Table 3 also reports for both options the estimated daily and annual consumption of chemicals, either in terms of metal (Aluminium) or commercial salt (Alum, Al2[SO4]3 18H2O, conversion factor 12.35 kgAlum/kgAl).

Moreover, the sludge production due to the chemical dosing has been estimated, assuming that at the low metal dosage (i.e., molar ratio Me/P close or less than 1) most of the dosed metal will precipitate as aluminum phosphate leading to the production of 4.5 kgsludge/kgAl. In both cases, the increase of sludge production due to the chemical dosage is below 10% and can be considered not significant for the sludge treatment operation (Figures 7 and 8).

Table 3: The sludge line at an optimal chemical dosage in blending tank and supernatant treatment and P recover**.**

Parameter	Unit	1. Dosage in blending tank	2.Supernatant treatment and P recover
Optimal chemical dosage	kg_{Al}/d ton_{Alum}/d ton_{Alum}/y	530 6.55 2400	380 4.7 1700
Specific consumption	$kg_{Al}/kg_{Pinfluent}$ $kg_{Alum}/kg_{Pinfluent}$	0.95 11.8	0.68 8.45
Molar ratio		1.09	0.78
Sludge Production	kg/d	2400	1700
Chemical/(Primary+Bio)		9.4%	6.7%

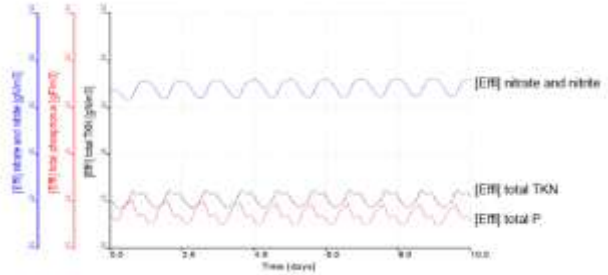


Fig. 7: The TP, TKN, and nitrate and nitrite effluent at a liquid temperature of 20°C.

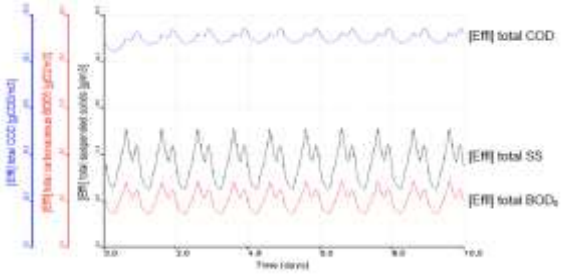


Fig. 8: The TSS, BOD, and COD effluent at a liquid temperature of 20°C.

3.3.2. Simulation of yearly variations of influent temperature

The liquid temperature variation during the year has been simulated according to the provided design temperature (Figure 9), and the assumed trend is shown below:

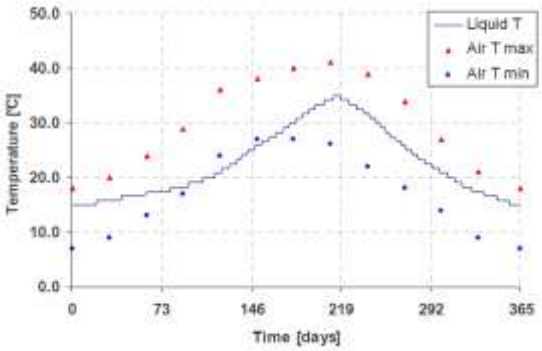


Fig. 9: The liquid temperature variation during the year.

3.3.2.1. Chemical dosage into both sludge and water lines (at points Chem1 and Chem2).

In case of chemical dosage to both sludge and water lines Figures 10, and 11, different chemical dosages are required. The consumption of the water lines are related to a few months (during summer), and in Table 4 separate evaluation, as well as maximum daily consumption and total annual consumption, have been reported. The sludge production due to the chemical dosing has also been estimated. From the data resumed in Table 4, it can be concluded that the dosage of chemicals in the supernatants line lead to a lower chemical consumption (about 20%), in comparison with the dosage to the blending tank. In both cases, the increased sludge production due to the chemical dosage is compensated by the reduction of biological sludge production due to the higher temperature, with no overloads to secondary settling and sludge treatment.

However, as shown in the graphs above, for most of the year the effluent phosphorus is far below the requested limit in both the previous options, i.e., the biological P removal is not completely exploited. For this reason, the chemical dosage to the water line only can result in the lowest chemical consumption, although the recovery of phosphorus-rich sludge would be not possible in this case.

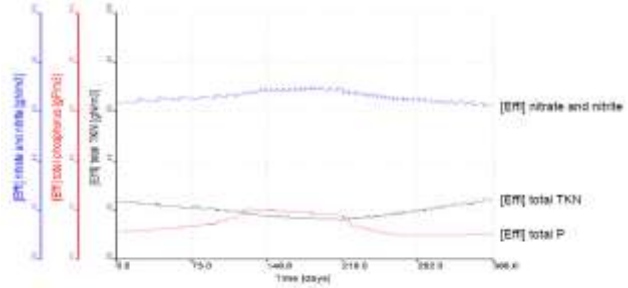


Fig. 10: The TP, TKN, and nitrate and nitrite effluent at chemical dosage into both sludge and water lines (at points Chem1 and Chem2)

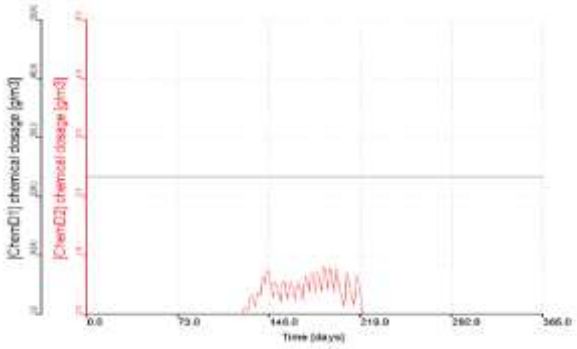


Fig. 11: Optimum chemical dosage into both sludge and water lines (at points Chem1 and Chem 2.

Table 4: The sludge line and water line at an optimal chemical dosage in blending tank and supernatant treatment and P recover.

Parameter	Unit	1. Dosage in blending tank	2.Supernatant treatment and P recover
Chem. dosage (water-line) Max daily dosage Duration	kg_{Al}/d kg_{Al}/d ton_{Alum}/d months	63 104 1.3 3	120 195 2.4 4
Chem. dosage (sludge line)	kg_{Al}/d ton_{Alum}/d	530 6.5	380 4.7
Total annual consumption	ton_{Alum}/y	2440	1900
Specific cons. (summer)	kg_{Al}/kgPinfluent kg_{Alum}/kgPinfluent	1.07 13.2	0.9 11.1
The molar ratio (summer)		1.22	1.0
Max sludge prod (water line) Chemical/Bio	kg/d	470 4.8%	880 9%
Sludge Prod. (sludge line) Chemical/(Primary+Bio)	kg/d	2400 9.4%	1700 6.7%

3.3.2.2. Chemical dosage into the water line only (at point Chem2).

Figures 12 and 13 show the effluent nutrients for the dosage of aluminum to the water line, controlled in order to obtain the required effluent quality (i.e., total P < 2 mg/L). In this option, 400 kgAl/d are required in summer time (for about 90 days), while a dosage of 270 kgAl/d is enough to control the P release during the rest of the year. These values correspond to max daily consumption of 4.9 tonnes of Alum, with a total annual consumption of about 1360 tonAlum/year. Compared to the options previously described, the dosage to the water line results in the lowest consumption of chemicals both as average and maximum daily dosage.

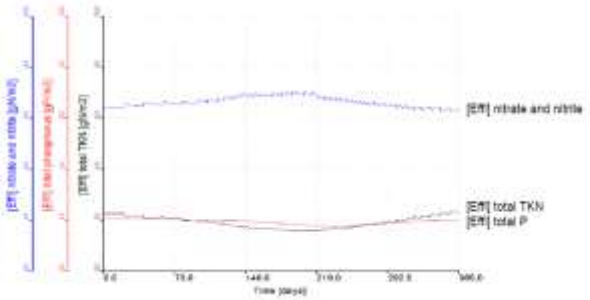


Fig. 12: The TP, TKN, and nitrate and nitrite effluent at chemical dosage into the water line only (at point Chem2)- the dosage of aluminum.

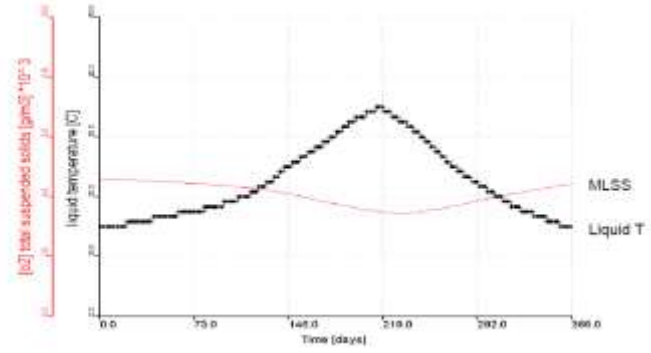


Fig. 13: The TSS effluent at chemical dosage into the water line only (at point Chem2) at the variation of liquid temperature- the dosage of aluminum.

Moreover, taking into account that the phosphorus load to the plant is 556 kg/d, a max specific consumption of 0.72

kgAl/kgPinfluent (i.e. 8.9 kgAlum/kgPinfluent) and a molar ratio of 0.83 can be estimated. This value is lower than the typical values of 1.25-1.50 adopted to obtain 75% of P removal with a pre-precipitation scheme (i.e., without biological removal, Metcalf 2003), and the difference can be attributed to the biological phosphorus removal.

Table 5: The effluent quality data estimated with the adopted design procedure and simulated by the GPS-X software.

Parameter (mg/l)	Treated effluent limits	Design estimation at 20°C	GPS-X simulation at 20°C	GPS-X simulation at 20°C + dosage	GPS-X simulation at 15°C + dosage	GPS-X simulation at 35°C + dosage
TSS	30		11	12	11	11
COD	100	84	90	88	89	87
BOD_5	20	1	3.8	3.6	4.2	2.1
TN	12	9	8.7	8.6	8.7	8.6
TKN	7	4	2	1.9	2.3	1.8
Ammonium		0.5	0.7	0.7	1	0.4
Nitrate		5	6.7	6.7	6.4	6.8
TP	2	1.7	4.5	2	2	1.8

4. Conclusion

In this work, the removal of TN and TP from Al-Nasiriyah Wastewater Treatment Plant in different operating conditions are evaluated. The obtained plant design has been verified and optimized by implementing the proposed plant layout in the GPS-X 5.0 modeling and simulation software (Hydromantis). The latter has been used for simulating and verify the process performances in conditions of minimum temperature, peak loading and typical fluctuations of these parameters. Results show that the effluent of TSS, COD, BOD, TN, TKN, Ammonium, Nitrate, and TP are approximately 11 mg/l, 87 mg/l, 2.1 mg/l, 8.6 mg/l, 1.8 mg/l, 0.4 mg/l, 6.8 mg/l, and 1.8 mg/l, respectively. This study proofed the conformity of this water to the law of the protection of rivers No. 25 of 1967 and the system of national determinants of the use of treated wastewater for irrigation or to discharge into fresh rivers No. (3) for the year 2012.

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