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Effect of Hydraulic Loading Variations on the Performance of Decentralized Small Scale Activated Sludge Treatment Plant

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Abstract: A compact decentralized small scale activated sludge treatment plant receiving domestic wastewater was monitored over 12 month period. The plant was constructed, so that carbonaceous and nitrogenous bioreactions are to take place. The plant was operated at different hydraulic loadings (15, 20, 30 and 40 m^3/d) in order to investigate the plant performance at varying conditions and to check for its absorbance capacity for possible shock loadings as a result of fluctuating influent quality. Carbonaceous kinetic coefficients based on Monod kinetics were determined. It has been found, that the plant was operated properly under different hydraulic loadings and produced a water quality that complies with the lowest Jordanian Standard 893-2006, which set an allowable maximum level of 30 mg-BOD_5/L and 100 mg-COD/L for irrigating cooked vegetables, parks, playgrounds and sides of roads within city limits. The results showed clearly, that the plant is sufficiently capable to absorb the organic chock loadings, which is not unexpected in small treatment systems. Nutrient (nitrogen and phosphorous) removals were found to be very efficient, so that maximum ammonium and phosphorous removals were found to be 90 and 70 % respectively. The obtained kinetic coefficients showed clearly, that this treatment facility is able to biodegrade this type of wastewater with low excess sludge production.

Key words: Wastewater % Decentralized treatment % Hydraulic loading % Kinetic coefficients

INTRODUCTION

Water scarcity and contamination of soils, surface and groundwater are major problems in the Middle East and nearly all semi-arid and arid countries. Inadequate fresh and wastewater management has resulted in these problems, which are aggravated by rapid population increase combined with rising standard of life. It is widely recognized that increasing stresses on freshwater supplies will place further emphasis on the development of sustainable, reliable and cost-effective technologies capable of treatment and reclamation of wastewater for reuse [1].

In the context of integrated water resources management, centralized wastewater treatment plants have been proven to be an appropriate approach for large communities. The basic idea behind the use of centralized water treatment is that relatively high quality water from various natural sources can be treated to an even higher quality for distribution and use [2]. However, in small communities, costly centralized wastewater services are inappropriate because of their high costs and may result in severe operational problems [3, 4]. The use of decentralized approaches for the management of water and wastewater can play an important role in the future of water resources management.

The sustainable development of wastewater services to small communities should be based on decentralized wastewater treatment technologies. The approach should provide wastewater services that are robust, efficient, equally convenient, cost effective and environmentally responsible and responsive to the water scarcity. Accelerated extension of wastewater management services to small communities is essential to address serious concerns over water scarcity, pollution and protection of public health [5, 6].

Decentralized treatment plants can be used for wastewater treatment generated from an individual isolated house to a cluster of houses or to a subdivision. Decentralized systems may also be used for the treatment of wastewater generated at universities campuses, or by isolated commercial, industrial and agricultural facilities. In all the above cases, reclaimed water is utilized typically at the vicinity of wastewater generation. Decentralized

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wastewater treatment systems usually are not linked to a central sewer wastewater collection system network and to a centralized treatment plant, however, on some occasions they may be connected to a centralized plant.

Flasche [7] estimated that the 10% of the population connected to small-scale WWTPs in Lower Saxony (Germany) account for 20% of the organic and nitrogen loads in domestic wastewater, assuming that the plants are maintained and operated properly. In reality, this value is expected to be much higher. However, decentralized wastewater treatment systems usually lack solids processing facilities. Solids generated from these facilities are returned to the collection system for processing at a centralized treatment plant. Apart of the obvious utility for water reuse, the decentralized treatment systems may also be used to reduce wastewater flows to the centralized facilities, or as a means to eliminate or reduce discharges to impacted receiving water bodies [2]. Since decentralized wastewater treatment is seen as a possible future technology allowing the sanitation requirements to be met [8, 9], nutrient removal in small-scale plants should move into the focus of research interest.

In this work, a pilot treatment plant was constructed at the campus of the Mafraq domestic wastewater treatment plant and designed based on the activated sludge system proceeded by denitrification tank (Bardenpho Configuration). This pilot plant represents a modern small scale compact wastewater treatment plant operated at local Jordanian conditions. The main objective of this work is to monitor the performance of a small activated sludge treatment facility under different hydraulic loadings. The capability of the plant in producing wastewater suitable for different reuse applications according to the Jordanian standard 893-2006 was investigated. This work is also aimed to determine the carbonaceous kinetics coefficients based on Monod kinetics.

MATERIALS AND METHODS

The pilot treatment plant was designed to receive an average wastewater flow of 15 m^3/d. Feed wastewater is diverted from the existing inlet manhole at Mafraq centralized domestic wastewater treatment. The influent wastewater is screened through a rotary screening and flows to the anoxic tank, where denitrification process should takes place. The denitrified mixed liquor flows into the aeration tank, where carbonaceous and nitrogenous biochemical reactions occur. Oxygen concentration in the aeration tank was measured online and set to remain continuously above 2 mg/L to ensure, that oxygen is not a limiting factor in the treatment process. The mixed liquor is then allowed to settle in the settling tank and the supernatant flows directly into the chlorination tank. Part of the settled sludge is returned to the first denitrification tank and the remainder is stored in the sludge holding tank. Chlorination of treated wastewater is carried out using automatic chlorine dosing pump and liquid sodium hypochlorite. The online measurement of the residual chlorine ensures that the residual chlorine concentrations at 30 min contact time will always remain above 0.2 mg/L to ensure a coliform free effluent [10]. The chlorinated water flows into the sand filter and eventually into the irrigation tank. The plant is equipped with several by-passes, fittings and valves, so that the mode of operation can be easily changed and adjusted. The schematic diagram of the treatment plant is shown in Figure 1.

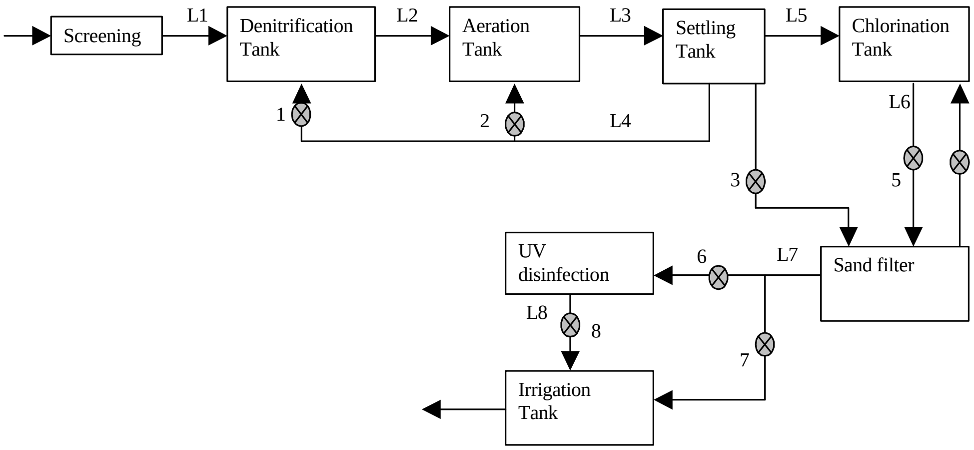

Fig. 1: Schematic diagram of the pilot plant operation

Table 1: Operated loading of the pilot plant

Loading phase (hydraulic loading)	HL1	HL2	HL3	HL4
Discharge, m^3/d	15	20	30	40
Organic loading, kg $BOD_5/m^3.d$	0.92	1.35	1.92	2.82
Standard deviation	0.13	0.08	0.09	0.17
Sludge loading (F/M), kg BOD_5/kg TSS.d	0.25	0.35	0.52	0.76
Standard deviation	0.02	0.01	0.09	0.12
Sludge age, d	14.18	11.48	5.04	4.44
Standard deviation	1.36	0.46	1.14	0.66
Excess sludge production, m^3/d	0.5	0.8	1.4	1.6

Table 2: Monod-kinetic Parameters to be determined at the Mafraq pilot plant

Parameter	Definition
Y	Growth yield coefficient
μ_{max}	Maximum specific growth rate, h^{-1}
K_s	Half velocity constant, mg/L
k_d	Endogenous decay coefficient, h^{-1}

The pilot plant was monitored over 12 months starting from March 2007. Wastewater samples at different time intervals were collected in sterilized BOD bottles from different unit operations and processes. Wastewater samples were transported to the laboratory and analyzed for different parameters (pH, dissolved oxygen DO, temperature, total suspended solids TSS, total dissolved solids TDS, electrical conductivity EC, biological oxygen demand BOD_5, chemical oxygen demand COD, ammonia NH_4^+, nitrate NO_3^-, orthophosphate PO_4^{3-}, total coliform). All these tests were carried out according to the Standard Methods for Examination of Water and Wastewater [11].

The plant was first investigated based on its conventional mode of operation using the design hydraulic loading of 15 m^3/d. The plant was then run under other different hydraulic loadings of 20, 30 and 40 m^3/d. At each loading mode, the investigation was carried out for a complete period of 3 months. Table 1 shows the important loading parameters at different operated hydraulic loadings.

The results obtained at the different hydraulic loadings were utilized to determine the treatment plant specific carbonaceous kinetic coefficients. The results were compared with those obtained and published in other works. The parameter determination was based on Monod kinetics using the mathematical representation of mass balance for both microorganism and substrate. Table 2 shows these parameters and their definitions.

The method of kinetic parameter determination is based on linearization of mass balance equations with the assumption, that Monod kinetics is applicable for this type of wastewater and treatment technology. It is also assumed, that the plant is operated at a steady state conditions under all loadings modes. The linearized form of mass balance equations for substrate (BOD_5) and microorganisms at the aeration tank are presented in equations 1 and 2, respectively [10].

$$\frac{Xq}{So-S}=\frac{Ks}{k}\frac{1}{S}+\frac{1}{k} \qquad (1)$$

$$\frac{1}{qc}=-Y\frac{r_{su}}{X}-k_d \qquad (2)$$

Where:

r_{su} : rate of substrate utilization

X : microorganism concentration in the aeration tank (mg TSS/L)

S_0 : substrate concentration in the influent (mg BOD_5/L)

S : substrate concentration in the effluent (mg BOD_5/L)

θ : hydraulic detention time (day)

θ_c : sludge age (mean cell residence time in days)

k : maximum rate of substrate utilization per unit mass of microorganisms (μ_m/Y)

other parameters as described in Table 2.

The value of K_s and k can be determined by plotting the term $(X\theta/(S_0-S))$ versus (1/S) in equation 1. The values of Y and k_d can be determined by plotting $(1/\theta_c)$ versus $(-r_{su}/X)$ in Equation 2.

RESULTS AND DISCUSSION

The performance of the treatment plant under varying loadings was investigated. The organic matter concentrations, in form of BOD_5 and COD for both influent and effluent wastewater, are shown in Figure 2 and 3 respectively. Each point in the Figures represents the analysis result of three months sampling and the error bars indicate the corresponding standard deviation. The high values of COD compared to BOD_5 in the influent are attributed to the industrialization of the Mafraq area, where most of the industries are connected to the sewer system without pretreatment. This has also resulted in a significant fluctuation in the influent organic concentrations indicated by high values of standard deviation. However, in spite of these two major parameters (high COD values and fluctuating organic loading), the plant was found to operate satisfactorily under different hydraulic loadings and produced a water

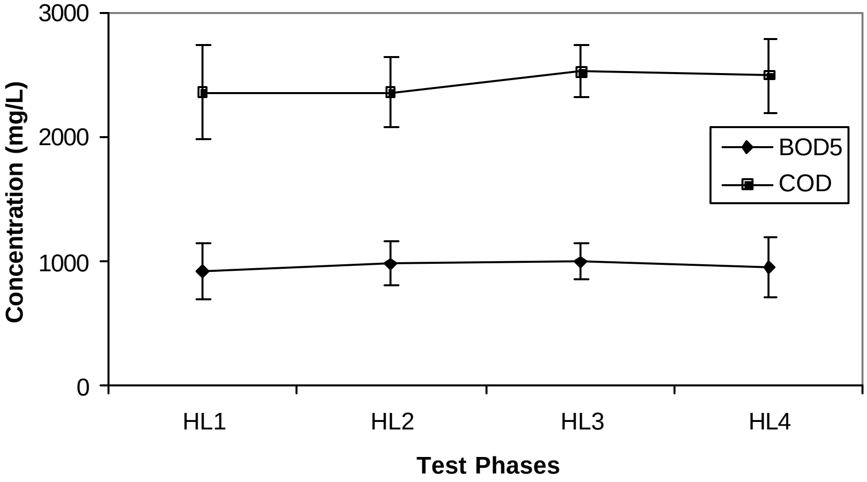

Fig. 2: Monitoring results of BOD_5 and COD concentrations in the pilot plant influent (L1)

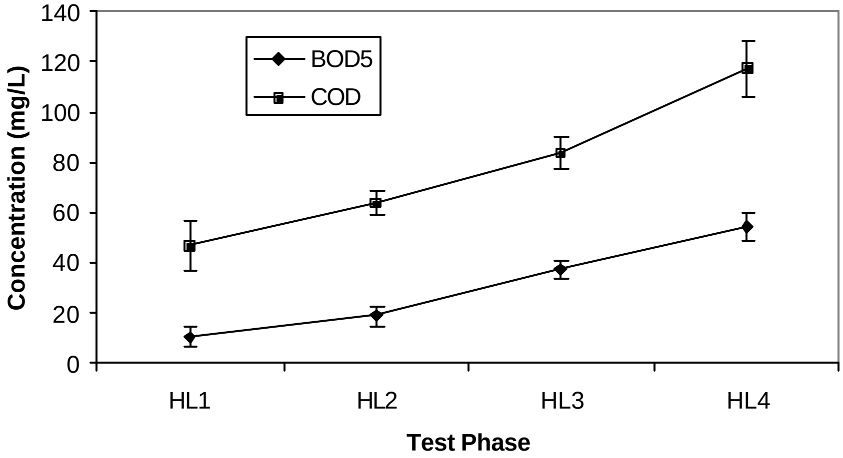

Fig. 3: Monitoring results of BOD_5 and COD concentrations in the pilot plant effluent (L7)

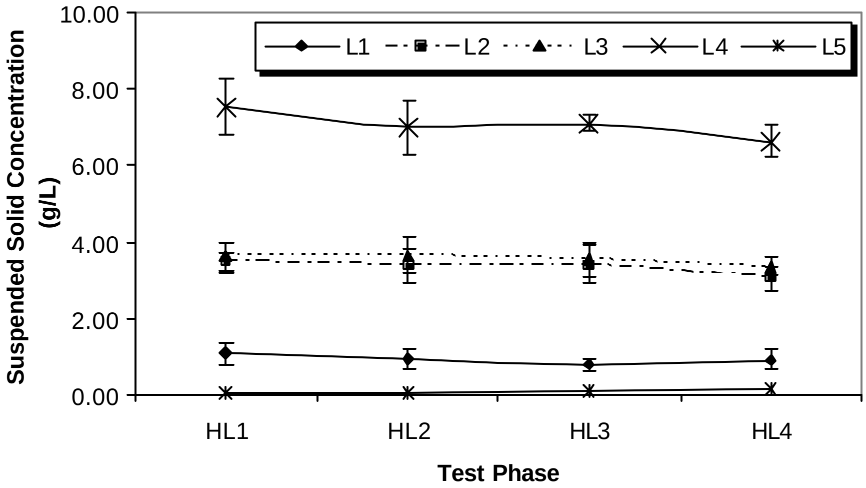

Fig. 4: Total solids concentration at different locations in the pilot plant

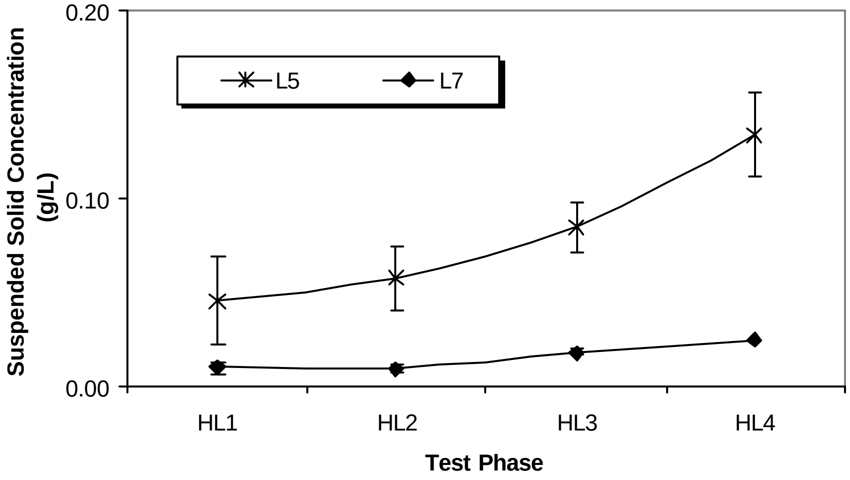

Fig. 5: Total suspended solids at locations L5 and L7

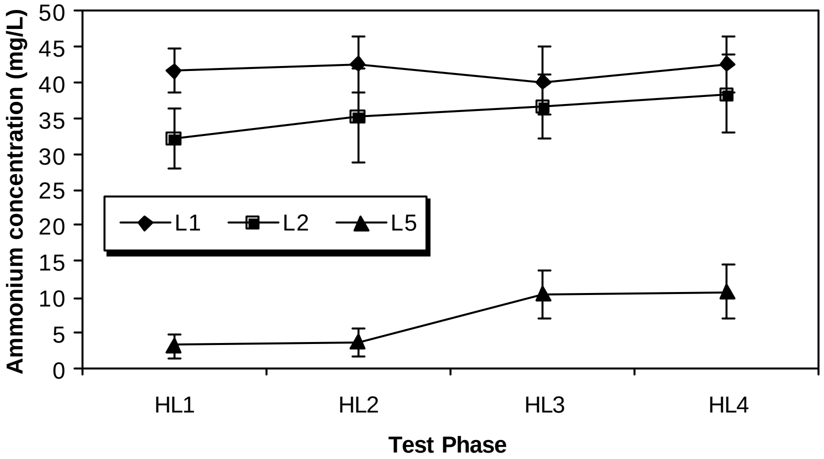

Fig. 6: Ammonium concentration at locations L1, L2 and L5

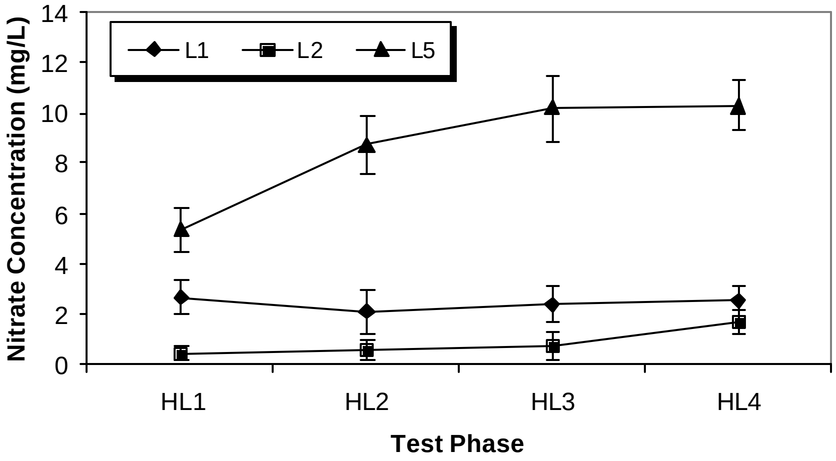

Fig. 7: Nitrate concentration at locations L1, L2 and L5

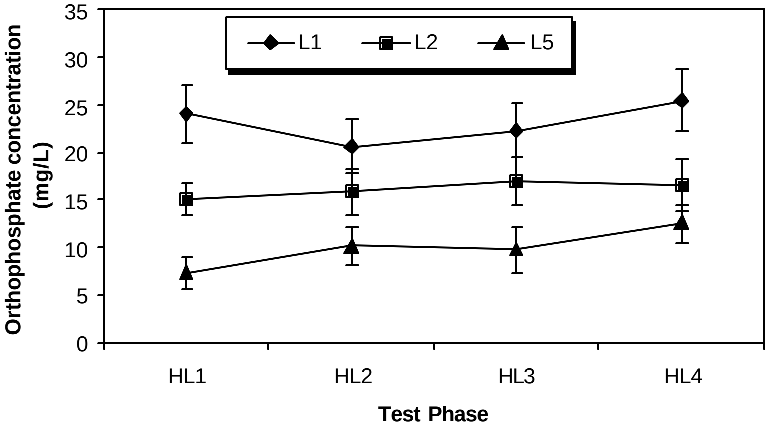

Fig. 8: Orthophosphate concentration at locations L1, L2 and L5

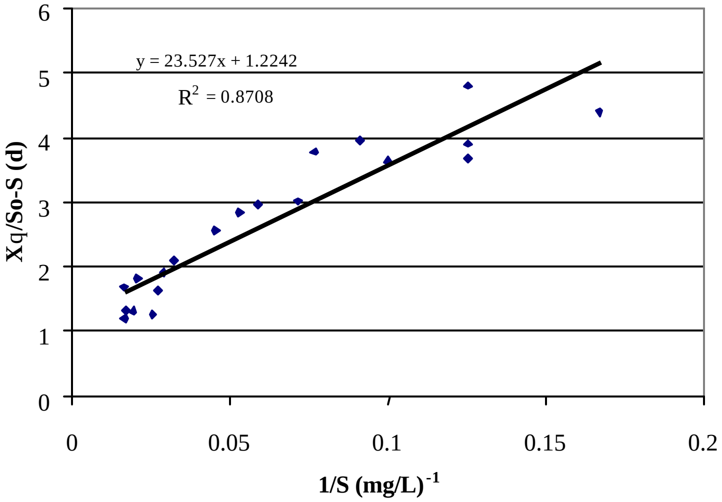

Fig. 9: Linearization of experimental data according to equation 1

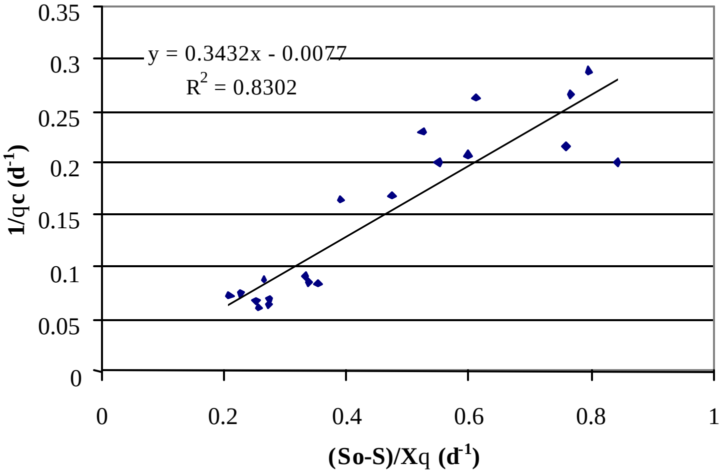

Fig. 10: Linearization of experimental data according to equation 2

quality that mostly complies with the lowest Jordanian Standard 893-2006, which set an allowable maximum level of 30 mg-BOD$_5$/L and 100 mg-COD/L for irrigating cooked vegetables, parks, playgrounds and sides of roads within city limits. The results showed clearly, that the fluctuations in the effluent concentrations are much lower than those in the influent concentrations. This indicates, that the plant is sufficiently capable to absorb the organic shock loadings, which is not unexpected in small treatment systems. However, the lower the shock loading the more absorbance was noticed.

Solid determination is considered to be essential in evaluating the performance of wastewater treatment plants. For this purpose, solid are measured in most of the pilot plant sampling's locations. The results of TSS monitoring at different locations and hydraulic loadings are shown in Figure 4, where the error bars indicate the corresponding standard deviation.

Figure 4 shows clearly, that the influent wastewater (location L1) contains high TSS concentration. This is attributed to the original water quality and to the industries which are directly connected to the sewer system. The TSS values in the aeration tank and the other unit processes were found to be within the typical range of similar systems [6]. The increase in the TSS concentration in the aeration tank (L3) over the denitrification tank (L2) is due to the higher rate of aerobic bioreaction in the aeration tank over the anoxic bioreaction in the denitrification tank. Settling tank was found to operate properly under all hydraulic loadings, as the TSS concentrations in the settling tank effluents (L5) were tremendously reduced comparing to the tank influents (L3). For more visible results, the TSS values in the locations L5 and L7 are plotted separately in Figure 5. The difference in the TSS concentrations between these two locations showed clearly, that under all hydraulic loadings, the sand filter is capable to improve the water quality, that complies with the lowest Jordanian Standard 893-2006, which set an allowable maximum TSS level of 50 mg/L for irrigating cooked vegetables, parks, playgrounds and sides of roads within city limits.

The pilot plant was designed and operated, so that nitrification as well as denitrification processes are to take place. Figure 6 shows the analytical results of the ammonium concentrations at different locations and hydraulic loadings. Ammonium concentration in the influent (L1) was found to range from 35 to 48 mg/L. The decrease in the ammonium concentration in the denitrification tank (L2) is attributed to the dilution occurred due to the return sludge from the settling tank (L4). The high drop in the ammonium concentration in the aerobic tank effluent (L3) is attributed to the effective nitrification process, where oxygen in the aeration tank is abundantly available. It is clearly seen from the Figure, that ammonium concentration was reduced about 90 % at the hydraulic loadings HL1 and HL2 and about 75 % at the hydraulic loadings HL3 and HL4.

To evaluate the denitrification process, nitrate concentration was also monitored. Figure 7 shows the nitrate concentrations at different locations and hydraulic loadings. It is clearly seen from the Figure, that nitrate concentrations in the aeration tank were increased compared to the influent nitrate concentration. It has been noticed, that this increase matches, to an acceptable extent, with the nitrification stoichiometry, where 3.44 g of nitrate is generated for each gram of nitrified ammonium [10]. The tremendous reduction in the nitrate concentration in the denitrification tank (L2) indicates efficient plant performance of denitrification. All nitrate concentrations in the plant effluent at different hydraulic loadings were found to comply with the lowest Jordanian standard 893-2006, which states an allowable maximum nitrate level of 30 mg/L for irrigating cooked vegetables, parks, playgrounds and sides of roads within city limits.

Phosphorus (as orthophosphate, PO_4^{3-}) was also determined to investigate the incorporated amount in the biological degradation at different hydraulic loadings. The results of the monitored orthophosphate concentrations are shown in Figure 8. It is clearly seen, that orthophosphate concentration is decreased between the locations L1 and L5 at the investigated hydraulic loadings. This indicates a biological incorporation of phosphorous in the degradation process. The average reduction of orthophosphate was found to be about 70, 60, 55 and 50 % for the hydraulic loadings HL1, HL2, HL3 and HL4 respectively. This is nearly similar to the reported values for similar small scale wastewater treatment treatment plants [12].

As previously discussed, kinetic coefficients describe the dynamic operation of wastewater treatment for particular wastewater type and treatment technology. The different hydraulic loadings investigated were utilized to determine the governing treatment plant specific carbonaceous kinetic coefficients for this particular wastewater type. The results of linearization of equations 1 and 2 using the experimental data achieved are shown in Figures 9 and 10, respectively.

The kinetic coefficients were determined according to the calculation discussed before. The results are shown in Table 3 and indicated that the yield coefficient (Y) was

Table 3: Kinetic coefficients based on Monod kinetics

Parameter	Value
Ymg TSS/mg BOD_5	0.343
μ_{max}, d^{-1}	0.28
K_s, mg/L	28.8
k_d, d^{-1}	0.0077

found to be 0.343, which is considered to be significantly low for aerobic processes. This result shows clearly, that excess sludge production is considerably low. This can be attributed to the high detention time in both anoxic and aeration tank, which contributes greatly in sludge stabilization within the secondary treatment unit process facilities. This can be also noticed by the low endogenous decay coefficient (k_d), which was found to be 0.0077 d^{-1}. Such finding is very important to consider in the system evaluation, especially recently, where the decentralized small scale treatment plants are globally favored over the conventional centralized large scale treatment facilities. The low value of half-velocity constant (K_s) shows clearly, that this type of treatment processes is very much suitable for the treatment of this type of wastewater. Similarly for the maximum specific growth rate (μ_{max}), where the result shows clearly, that the wastewater is easily degradable and the small scale activated sludge system is very efficient in treating this type of wastewater of dominating domestic origin. Generally, the determined carbonaceous kinetics coefficients were found to be lower than those reported by different studies for domestic wastewater treatment and reviewed by Vallejos [13].

CONCLUSION

The decentralized small scale wastewater treatment plant was found to operate properly and produced treated wastewaters, which comply with the Jordanian standard for wastewater reuse. The plant showed acceptable shock absorbance capacity and nutrient removal. The determined specific kinetic coefficients support the global transformation of favoring decentralized wastewater treatment plant over centralized large scale facilities.

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