Influence of primary sedimentation on pre-denitrification system performances

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Abstract The effects of suppressing primary sedimentation on nitrogen removal efficiency of a pre-denitrification system have been evaluated for a large municipal wastewater treatment plant. Simulations have been carried out using the STOAT model. For both the process schemes with and without primary sedimentation, nitrification efficiencies are calculated for increasing influent loads of COD, total N and suspended solids. The sensitivity analysis shows that for the usual carbon to nitrogen ratios in the raw influent both the process schemes allow the requested removal efficiencies, whereas for significantly high C/N ratios the scheme with primary sedimentation is preferable.

Keywords Activated sludge; primary sedimentation; nitrogen compound removal; nitrification; denitrification

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Introduction

The European Directive 91/271 established severe quality standards for the nutrient discharge in the so-called sensitive areas. In order to meet these standards, phosphorous and nitrogen have to be removed. For the removal of nitrogen compounds, municipal wastewater treatment plants (MWWTPs) utilize specific processes, often consisting of a biological single sludge system, alternating anoxic and oxic phases. Among the biological suspended growth systems, the most widely used is the "Ludzack-Ettinger" scheme, in which the oxidation-nitrification process follows a denitrification phase accomplished using carbon source from the influent (Figure 1).

There is not a general agreement about the opportunity of using primary sedimentation in the Ludzack–Ettinger configuration. In fact, the organic particulate removal in the primary sedimentation lowers the concentration of organic compounds available to allow high denitrification performances. On the other hand, without primary sedimentation the resulting organic overload composed of slowly biodegradable substances may negatively affect the oxidation-nitrification phase.

For small MWWTPs the choice of a simplified treatment scheme, without primary settling and also with the aerobic digestion of the excess sludge, appears definitely favourable.

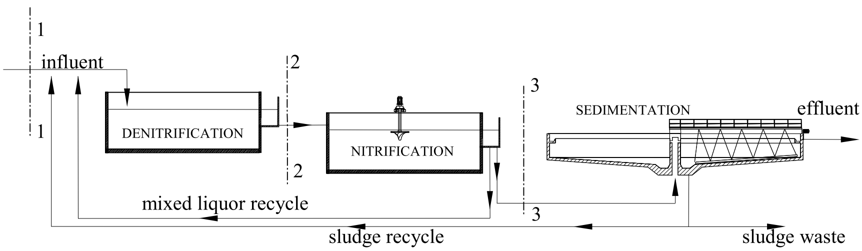

Figure 1 Ludzack–Ettinger system flow-sheet

As far as large treatment plants (more than 100,000 p.e.) are concerned, this choice proves to be quite innovative and it is not possible to carry out a systematic comparison between the two configurations, with and without primary settling, analysing a sufficient number of existing full scale plants. Therefore, the development, in the last years, of software tools able to simulate the physical, chemical and biological treatment processes has suggested to carry out a study with the aim to compare the two solutions in the case of a large MWWTP.

The study was conducted on a full scale treatment plant (about 200,000 p.e.) recently designed to be constructed in Naples, Italy. Plant performances were tested with and without primary sedimentation using the STOAT simulation model. The comparison was based on both technical and economical considerations and, in particular, a sensitivity analysis was carried out to evaluate the performances of the two configurations to face influent flow, organic carbon, and nitrogen compounds overloads.

Materials and methods

The simulations were carried out on a full scale MWWTP composed by the following processes:

Wastewater treatment. Preliminary treatment, primary sedimentation, denitrification, combined nitrification, secondary sedimentation, disinfection.

Sludge treatment. Gravity thickening of primary sludge, mechanical thickening of excess activated sludge, anaerobic digestion, mechanical sludge dewatering.

The volumes of primary sedimentation, denitrification and combined nitrification phases are, respectively, equal to 3,538, 7,500 and 16,667 m^3. Influent wastewater characteristics, employed as input for running the simulations, are taken from the design project: the average flowrate is 1,529 $m^3\ h^{-1}$ and the average concentrations of COD, total nitrogen (Total N), and total suspended solids (TSS) are equal, respectively, to 625, 43 and 380 g m^{-3}; Total COD/N ratio is 14.53, higher than the usual values in a municipal raw wastewater. To carry out the simulations, these concentrations have been fractionated (Table 1), assuming the percentages suggested by the COST 682 Working Group No 2 (Alex *et al*., 1999). In particular, COD has been fractionated in four components: soluble biodegradable, soluble non biodegradable, particulate biodegradable, particulate non biodegradable. Total N components are ammonia, nitrates, organic soluble biodegradable and organic particulate biodegradable. TSS are constituted by volatile suspended solids (VSS) and non volatile suspended solids (NVSS).

The mathematical model used for primary sedimentation is the dynamic model developed by Lessard and Bech (1988). A modified version of the IAWQ Model n.1 (Henze *et al*., 1987) is implemented in the STOAT model (Water Research Centre, 1999) for the simulation of the biological process in which alkalinity effects are neglected. The dynamic model of Takács *et al*. (1991) is used for activated sludge settling and thickening, while a mathematical model based on the work of Mosey (1983, 1989, 1990) is used for anaerobic digestion.

Discussion

The results obtained applying the STOAT model to a MWWTP have been analysed in order to evaluate the technical efficiency and the economical convenience of primary sedimentation in the Ludzack–Ettinger configuration.

Computer simulations are applied both to treatment cycle with primary sedimentation (CPS) and to a modified treatment cycle without primary sedimentation (CWPS). For both

Table 1 Influent wastewater characteristics

Parameter	%	Average concentration (g m^{-3})	Average load (kg d^{-1})
Total COD	**100**	**625**	**22,935**
Soluble biodegradable COD	20	125	4,587
Soluble nondegradable COD	8	50	1,835
Particulate biodegradable COD	60	375	13,761
Particulate nondegradable COD	12	75	2,752
Total nitrogen	**100**	**43**	**1,578**
Ammonia	64	27.5	1,009
Nitrates	0	0	0
Organic soluble biodegradable nitrogen	14	6	220
Organic particulate biodegradable nitrogen	22	9,5	349
TSS	**100**	**380**	**13,944**
VSS	75	285	10,458
NVSS	25	95	3,486

configurations, steady-state feeding conditions have been considered, keeping influent flowrate and quality parameter concentrations constant in time. A sensitivity analysis has been performed to evaluate the capability of the two different configurations to face COD, suspended solids and nitrogen overloads. Before these operations, the calculus code had been repetitively applied on the CPS configuration for the model tuning. During these first calculations, the parameters values of the models describing the various treatment processes have been manipulated to best fit the software to the design removal efficiencies.

The effluent quality obtained from the simulations, after the parameter calibration phase, is reported in Table 2, row 1 (run 1). The calculus code was run, at exactly the same conditions, for the CWPS configuration, showing that autotrophic organisms cannot grow. The effluent concentrations obtained from this simulation are reported in Table 2, row 2 (run 2). This result, influenced by the high Total COD/N ratio in the influent wastewater is due to the organic substrate overload entering the biological process. In fact, the organic overload causes an increase of the heterotrophic biomass growth with a simultaneous decrease of the autotrophic growth. In order to meet the effluent standards, the volume of nitrification phase of the CWPS has been increased of about 20%, reaching a final volume of 20,510 m^3. With this modification TSS, COD, ammonia, nitrates and total nitrogen effluent concentrations reach the values reported in Table 2, row 3 (run 3). In both run 1 and run 3, denitrification process efficiencies resulted very high, with nitrate effluent concentrations of the anoxic phase very close to zero (0.1–0.2 g m^{-3}).

Oxygen demand in the oxidation-nitrification phase is different for the two cases, being equal to 448 kg h^{-1} in run 1 and 540 kg h^{-1} in run 3.

Further simulations have been performed to evaluate the capability of the plant to face some increasing hydraulic loads both in the CPS and in the CWPS configurations. Simulations have been set up using the same plant conditions of run 1 and run 3. In the CPS configuration, the wastewater treatment plant efficiency is tested considering influent wastewater flowrate increases from 10% to 80% whereas with CWPS the flowrate increase

Table 2 Biological process effluent characteristics in different operating conditions

Run	TSS (g m^{-3})	Total COD (g m^{-3})	Ammonia (g m^{-3})	Nitrate (g m^{-3})	Total N (g m^{-3})
1	34.4	88.0	1.0	4.4	7.7
2	32.6	86.3	25.3	0	27.8
3	32.5	84.7	2.2	3.7	8.3

is varied from 10% to 40%. In all cases, influent concentrations have not been modified but kept equal to the above values. Only the biomass concentration into the aerobic reactor was gradually increased in order to get a larger heterotrophic fraction to deal with the increasing organic load. However, in all the examined conditions, attention has been paid not to reach too high values of biomass concentration in oxidation-nitrification reactor, in order to avoid possible shortcomings related to poor oxygen solubilization and mixed liquor settling.

It can be noted that CPS scheme has a higher flexibility than the CWPS scheme (Figure 2). In both cases the nitrification process efficiencies tend to decrease gradually with increasing flowrate, but in CPS configuration efficiency becomes very low only for flowrate increases larger than 70%. Without primary sedimentation 30–40% hydraulic overloads are sufficient to reduce significantly the autotrophic biomass growth and consequently the nitrification efficiency. This is due to the higher organic suspended mass, which could inhibit the growth of autotrophic biomass.

Further simulations have been performed keeping constant the design value of influent flowrate and all the fractions of organic substrate and suspended solids and increasing the total nitrogen concentration. Total nitrogen increases from 10% to 50% are considered, corresponding to Total COD/N ratios from 14.53 to 9.69. Figure 3 shows, for both CPS and CWPS configurations, the concentration profiles of all nitrogen compounds in the final effluent and the concentration profile of nitrates in the effluent of the denitrification process. In CPS configuration the nitrogen removal efficiencies are always greater than in the case of CWPS. In both cases total nitrogen concentration profiles show an increasing trend, but the increase rate is slightly higher in CWPS; this is due to the higher concentration of organic particulate biodegradable nitrogen in the CWPS final effluent. More in details, in this case-study total nitrogen quality standards (10 g m^{-3}) are met with N overloads of 30% and 20%, respectively for CPS and CWPS. It can be noted that varying the total nitrogen concentrations in the influent, the ammonia concentration in the final effluent is maintained fairly constant. The effluent from the anoxic compartment shows a slow increase of nitrate concentration for both CPS and CWPS. However, the increase rate is lower for CWPS, as a consequence of the beneficial effect of primary settling absence on the denitrification process performances. It is expected that this result is amplified with Total COD/N ratio lower than 9.69. Nitrate concentration profiles of the final effluent present an increasing trend, but, differently from the anoxic compartment effluent, the increase rate is slightly higher in the CWPS scheme. This is probably due to the increase of the hydrolysis rate of organic particulate biodegradable nitrogen.

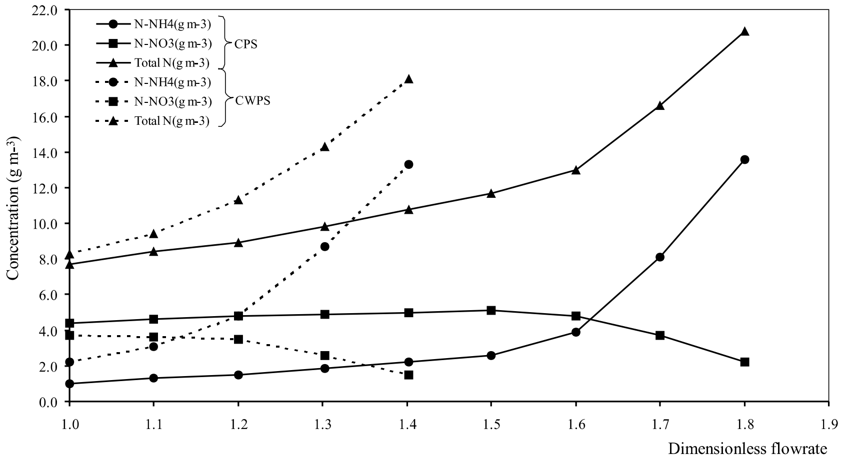

Figure 2 Nitrogen compounds concentration in the effluent versus dimensionless flowrate

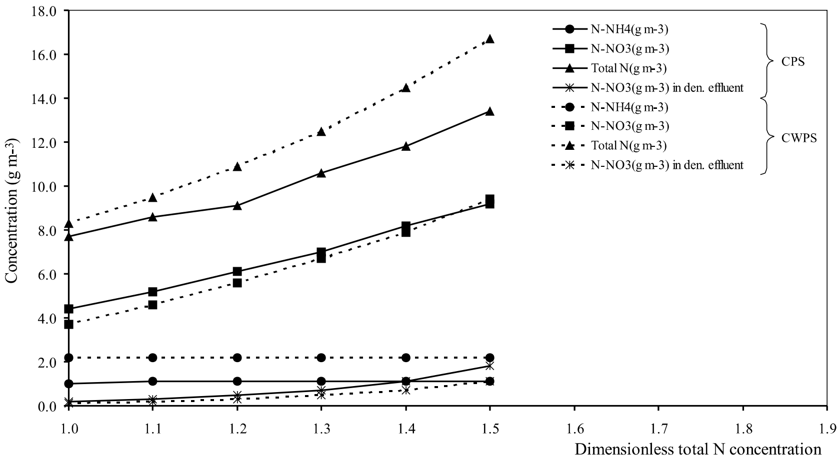

Figure 3 Nitrogen compounds concentration in the effluent versus dimensionless total N

Simulations have been also carried out to assess the plant response to organic and suspended solids overloads. This is done using constant flowrate and nitrogen concentration while increasing influent COD and TSS concentrations in the range of 10% to 50%. In order to face these COD and TSS overloads, the operating conditions of the plant have been modified gradually increasing the activated sludge recycle flowrate, which allows the presence of sufficient heterotrophic biomass within the activated sludge reactor. Simulations results show the effects of varying COD and TSS influent loads on the effluent nitrogen concentrations (Figure 4). It can be noted that increasing organic load with both CPS and CWPS schemes, results in constant ammonia concentration, equal to the value of the rows 1 and 3 of Table 2 respectively. Nitrate concentration decreases almost linearly, being always higher in the CPS configuration. Therefore, in general terms, there is a decrease of total nitrogen in the plant effluent for both CPS and CWPS. This result is due to the increase of nitrogen assimilation for cell synthesis as a result of the extra sludge production (van Loosdrecht *et al*., 1997). This assumption is demonstrated by a higher decrease rate of nitrate concentration in the final effluent for CWPS case compared to the CPS profile.

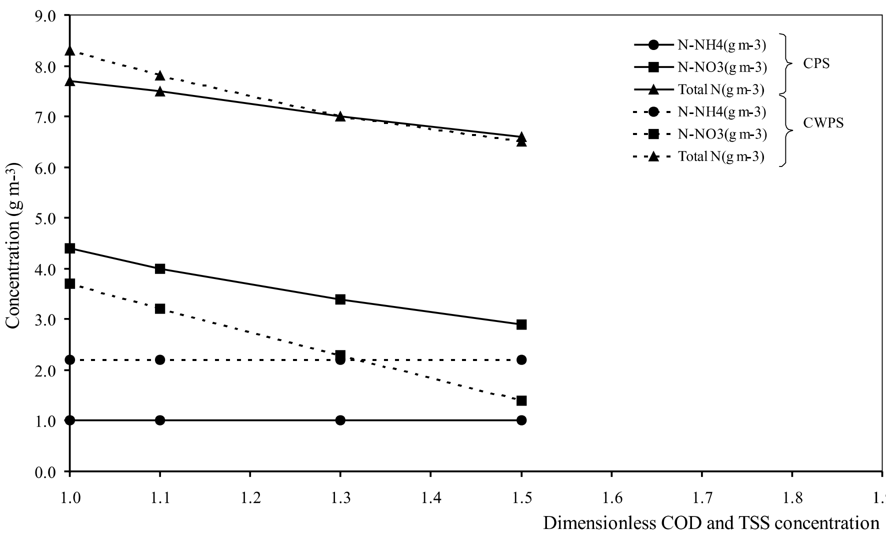

Figure 4 Nitrogen compounds concentration in the effluent versus dimensionless COD and TSS

The economical comparison between the two plant configurations has been performed considering both capital and operating costs. For capital costs of the CWPS scheme the elimination of primary settling results in the absence of primary sludge, and thus no gravity thickener is necessary and the anaerobic digester requires a smaller volume. On the other hand, this process scheme requires a larger volume of the oxidation-nitrification reactor. In this evaluation the capital costs for the mechanical thickening of secondary sludge and for the mechanical dewatering of digested sludge are considered equal in both cases. Assuming the unitary costs of the design project, the elimination of primary settling produces an overall saving of €1,863,000. Assuming a system design period (n) equal to 20 years and an interest rate (i) of 5%, the following annual cost saving is evaluated: $\Delta C_1 = \{[(i + 1)^n i]/[(i + 1)^n - 1]\} \times 1{,}863{,}000 \cong 149{,}000$ €/year.

Operating costs of the air injection into the nitrification reactor and of the dewatered sludge final disposal, as well as the return related to the biogas production into the anaerobic digester process, are taken in account. As already seen, simulations have shown that, in order to maintain a D.O. level of 2 g m^{-3} in the aerobic compartment, the oxygen demand is 448 kg h^{-1} and 540 kg h^{-1}, respectively for CPS and CWPS configurations. Assuming a consumption rate of 1 kWh per kg of oxygen transferred, the higher energetic consumption of CWPS configuration has been evaluated equal to $(540 - 448) \times 1 \times 24 \times 365 = 805{,}920$ kWh $year^{-1}$. Assuming a unit energy cost of 0.075 €/kWh, the yearly cost increase is $\Delta C_2 = 0.075 \times 805{,}920 \cong 60{,}500$ €/year. Simulations have also provided the amount of dewatered sludge yearly disposed, which is 13,324,000 and 12,961,000 kg $year^{-1}$ for CPS and CWPS schemes, respectively. Assuming a disposal unit cost of 0.05 €/kg, the cost difference between the two configurations is: $\Delta C_3 = 0.05 \times (13{,}324{,}000 - 12{,}961{,}000) \cong 18{,}000$ €/year.

Biogas production results higher with CPS configuration, because of the presence of the primary sludge, which is more suitable for gasification process rather than secondary sludge. In fact, secondary sludge, due to the very long cell retention time required by nitrification process, is already partially stabilised in the wastewater processes (van Loosdrecht *et al.*, 1997). The STOAT model does not provide biogas production, which is evaluated, for both CPS and CWPS configurations, using the formula $g_s = 1.866 \times (1 - a)(1 - b)$, where g_s = biogas specific production, expressed as Nm^3 per kg of carbon into the sludge entering the digestion phase, a = fraction of carbon used for cell synthesis, b = fraction of carbon not involved in the biological reactions. Fraction a is evaluated using the experimental relation: $a = 0.775 \times 10^{-\delta T}$, where T (°C) is the operational temperature of the digestion basins. The parameter δ (°C^{-1}) depends on nitrogen/carbon ratio in the digester influent and is determined using the experimental relation $\delta = 0.00144/[(N/C)^{1.204} + (0.1094/10^3)\,(N/C)^{-2.11}]$. The parameter b, which is related to the quality of the digester influent sludge and to the digester hydraulic retention time, is evaluated using the experimental data reported in the *Design of Municipal Wastewater Treatment Plants* edited by WEF (1992). The results are shown in Table 3. After having estimated g_s, the overall biogas production is calculated using the relation: $G = g_s\,C$, where C is the carbon load (kg d^{-1}) of the digester influent sludge and it is directly provided by simulation results. Assuming a biogas heat value of 6.25 kWh Nm^{-3} and that the cogeneration plant has an efficiency of 28%, the amount of electric energy recovered from biogas is evaluated. Using the values of Table 3 and assum-

Table 3 Energy profit due to biogas production

Configuration	*a*	*b*	g_S ($Nm^3\ Kg^{-1}$)	*C* ($Kg\ d^{-1}$)	*G* ($Nm^3\ d^{-1}$)	*E* (kWh $anno^{-1}$)
CPS	0.19	0.60	0.605	4,119	2,492	1,591,765
CWPS	0.30	0.75	0.327	3,101	1,014	647,693

ing a specific return from electric energy sale of 0.075 €/kWh, the profits related to CPS and CWPS configurations are evaluated and their difference is found to be equal to $\Delta P = 0.075 \times (1{,}591{,}765 - 647{,}693) \cong 71{,}000$ €/year.

The difference in operating costs of the two configurations is also due to: (1) energy consumption of the equipments for the centrifugation and pumping of excess sludge (which are higher for CWPS configuration); (2) pumping and pre-thickening of primary sludge; (3) pumping of recycled sludge and (4) dewatering process (which are higher for CPS configuration). These costs are significantly lower than the ones analysed above, and thus have been neglected.

In conclusion, the performed cost-benefit analysis provides an overall difference $\Delta C_1 + \Delta C_2 + \Delta C_3 - \Delta R = 149{,}000 - 60{,}500 + 18{,}000 - 71{,}000 = 35.500$ €/year, favouring CWPS configuration. This value represents a small percentage of the overall yearly cost of the plant. Therefore, for this particular case, the economical comparison cannot be used to evaluate the opportunity of using the primary sedimentation.

Conclusions

The influence of primary sedimentation on biological nitrogen removal was investigated in a full scale MWWTP with a pre-denitrification type configuration. The influence was evaluated using the STOAT simulation model for testing the plant performances with and without primary sedimentation. Both CPS and CWPS configurations allow the requested efficiency if the biological processes are well designed. In other words, the need of a high efficiency to respect the regulations on nitrogen standards, does not bring to univocal conclusions about the opportunity to include primary sedimentation, also because the two solutions are very similar in terms of costs. The lower capital and operating costs due to the absence of primary sedimentation and sludge thickening are balanced by the higher oxygen consumption in the oxidation phase, the lower biogas production and the higher capital costs for the oxidation reactor. However, in the case examined a slight preference is given to the scheme with primary sedimentation which, besides its proved efficiency in existing plants, allows a greater managing flexibility. In fact, the sedimentation phase ensures a reduction of both flowrate and pollution overloads, being useful primarily to weaken load fluctuations. Therefore, the primary settling phase should be adopted for those plants presenting a remarkable uncertainty and variableness of feeding conditions.

With reducing Total COD/N ratios in the influent, organic substrates are no more in excess in comparison with nitrates to be eliminated. Therefore, the elimination of primary sedimentation treatment may improve the denitrification efficiency. Furthermore, the partial degradation of the organic surplus in the anoxic section also improves the successive oxidation-nitrification phase. On the other hand, oxidation-nitrification reactor volume has to be larger in comparison with the scheme with primary sedimentation, although low influent Total COD/N ratios result in low volume increases. It is expected that in case of very low Total COD/N ratio plants the absence of primary sedimentation would enhance significantly the denitrification process.

Conversely, for high Total COD/N ratios the scheme with primary settling works more efficiently. In fact, under such conditions the influent organic load is very high in comparison with nitrate concentration to be eliminated. For this reason a further excess of organic substance would not result in improvements of the denitrification phase performance, while carbon overloading could influence the nitrification process. Carbon load, which is only partially degraded in the denitrification, would reach the oxidation tank, affecting negatively the growth of autotrophic organisms. In this case, a significant increase of the aerobic reactor volume is necessary, with a consequent increase of both capital costs and operating costs for air supply.

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