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MANAGEMENT OPTIMISATION OF A LARGE WASTEWATER TREATMENT PLANT

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ABSTRACT

The present study gives a useful way to optimize the operating (i.e. improving efficiency and saving energy) of a large wastewater treatment plant. The methodology was developed at the nitrogen removing activated sludge plant of "Roma-Est" (800,000 p.e.). Once design and operating data had been collected, a five-month experimentation was conducted to characterise the influent wastewater substrate fractions and to calculate the main kinetic parameters of the biomass. All data were used as parameters for a modified version of the ASM n.1 mathematical model, simulating the biological process flow, organic load and temperature variations as well as plant scheme modifications. Simulations showed the possibility of shutting down one of the three treatment lines and overloading the other two, with great operating improvement. Besides, neither the use of primary sedimentation, nor the aerated sludge internal recycle seem to be convenient. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

COD fractionation; heterotrophic growth; model application; readily biodegradable substrate; respirometric measurements; wastewater characterisation.

NOMENCLATURE

b_H = heterotrophic endogenous decay coefficient (d^{-1})
OUR = oxygen uptake rate (mgO/l/h)
NUR = nitrate uptake rate (mgN/l/h)
RBCOD = readily biodegradable COD (mgCOD/l)
UPCOD = unbiodegradable particulate COD (mgCOD/l)
USCOD = unbiodegradable soluble COD (mgCOD/l)
$f_{S,bs}$ = RBCOD/total COD
$f_{S,us}$ = USCOD/total COD
$\hat{\mu}_A$ = maximum autotrophic growth rate (d^{-1})
$\hat{\mu}_H$ = maximum heterotrophic aerobic growth rate (d^{-1})
$\hat{\mu}_{HD}$ = maximum heterotrophic anoxic growth rate (d^{-1})
η_G = anoxic correction factor for growth
V_{ml} = volume of mixed liquor (l)
V_{ww} = volume of influent wastewater (l)
Y_H = heterotrophic yield coefficient (mgVSS/mgCOD)
Y_{HD} = anoxic yield coefficient (mgVSS/mgCOD)

INTRODUCTION

In this paper a useful way to optimise the operating practice (i.e. improving efficiency and saving energy) of a large wastewater treatment plant by a model application is presented. In fact, effluent standards are becoming more strict all over Europe and particularly in Italy where the CEE/91/271 concerning domestic wastewater treatment has not been enacted yet, but steps are being taken in that direction. Moreover, operating costs (particularly those related to energy consumption of the aeration system) are often higher than needed.

Models are widely used in full scale plants to understand the dynamics of the biological treatment processes. By means of a simulation model it is possible to investigate the cause-effect relationships in the plant, to forecast fluctuation effects, to choose the optimal control strategy and to study the most cost-saving solution.

The first objective of the study was to compare respirometric and physical-chemical methods for determining the readily biodegradable COD fraction of influent wastewater. The possibility of using batch tests with little amount of biomass and with wastewater only was also examined. At the same time, tests were used to calculate the maximum heterotrophic and autotrophic growth rate and to determine the correction factor that should be applied to the heterotrophic growth under anoxic conditions.

The second aim was to use all the parameters estimated in the previous experimental phase and calculated in the following calibration phase, as input to a mathematical model simulating the biological process flow, organic load and temperature variations as well as plant scheme modifications. Particularly, the possibility of: i) overloading a treatment line, ii) feeding settled or unsettled wastewater, iii) using or not internal recycle flow, was investigated by using the model.

MATERIALS AND METHODS

"Roma-Est" wastewater treatment plant

The methodology was developed at the "Roma-Est" activated sludge plant (800,000 p.e.) which is divided into two different sections treating 4.3 m^3/s in total. Influent wastewater is almost entirely domestic with a little industrial fraction, resulting in 41,500 kg COD/day of organic load.

The analysed section, designed for 1.5 m^3/s, consists of a preliminary treatment, a primary sedimentation, a nitrification/denitrification single-sludge treatment and a disinfection (Figure 1). In the primary and biological processes the flow is equally divided into three parallel lines such that no intermediate mixing of the activated sludge takes place: consequently, during any maintenance event one of the lines must be completely shut off overloading the other two.

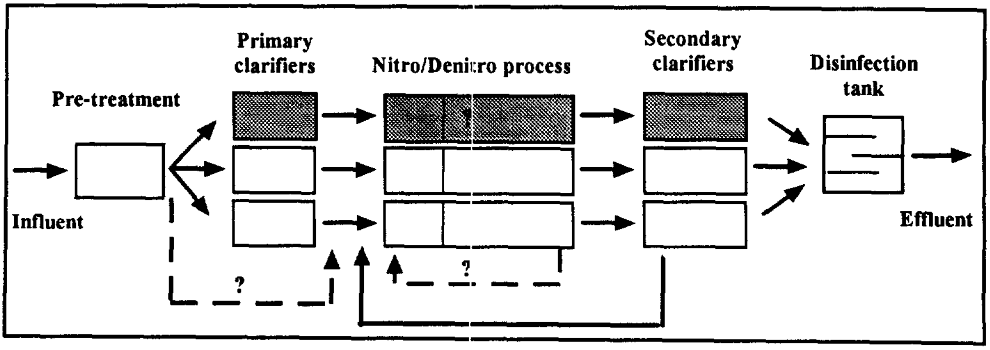

Figure 1. Flow sheet of "Roma-Est" WWTP section.

Moreover, the bioreactors can be fed with unsettled wastewater by-passing the primary sedimentation tanks while the internal recycle flow, even if provided, might be used or not. The flexibility of "Roma-Est" makes the model useful to forecast the effects of process scheme modifications.

Operating data were collected for a one year period in order to obtain average values to be used as input to the model. Unsettled, settled and effluent wastewater values are summarised in Table 1.

Table 1. Long period operating data of the full-scale plant

	Unsettled wastewater		**Settled wastewater**	**Effluent wastewater**	
Parameter	**Average concentration** (mg/l)	**Average load** (kg/d)	**Average concentration** (mg/l)	**Average concentration** (mg/l)	**Law limits** (mg/l)
TSS	210	27,200		10	80
COD	300	38,900	240	25	160
TKN	32	4,200	29	$2^{(*)}$	$15^{(*)}$
NO_3-N	-	-	-	6	20
total P	5	650		1	10

$^{(*)}$as NH_4^+

Characterisation methods

To characterise the influent wastewater and to calculate biomass kinetic parameters tests were conducted in laboratories. Simple and short-time requiring procedures were preferred to continuous flow methods which conversely require a longer time because of the biomass acclimation. Kind of tests used, parameters, literature notes about the procedures and references are summarised in Table 2.

In the aerobic and anoxic batch tests samples were collected from the influent wastewater and from the oxidation tank. Samples from the effluent were also required for the physical-chemical test. Average daily and instantaneous samples (collected particularly during the morning peak hour of load) were used. Standard Methods (APHA, 1995) were followed for the analytical procedures.

Table 2. Methods used during the experimentation

Kind of test	**Parameters**	**Notes**	**Reference**
Aerobic batch A	RBCOD, $\overline{\mu}_A$	ww/sludge ≅ 2/1	*Kappeler and Gujer*, 1992
Aerobic batch B	RBCOD, $\overline{\mu}_H$, $\overline{\mu}_A$	ww/sludge ≅ 5/1	*Ekama et al.*, 1986 *Dold et al.*, 1991
Aerobic batch C	$\overline{\mu}_H$, b_H	ww/sludge ≅ 20/1	*Kappeler and Gujer*, 1992
Aerobic batch D	RBCOD, active biomass, USCOD, UPCOD	wastewater only	*Wentzel et al.*, 1995
Anoxic batch	RBCOD, $\overline{\mu}_{HD}$	ww/sludge ≅ 5/1	*Ekama et al.*, 1986
Physical-chemical	RBCOD, USCOD	flocculation-fitration	*Mamais et al.*, 1993

The aerobic batch tests were performed with different proportions of wastewater and sludge, in order to determine the proper F/M (food to microorganisms) ratio to be used for the specific case studied. Among all the respirometric tests, the aerobic batch D should be the simplest (it requires influent wastewater only) and the most complete one in the COD characterisation. The physical-chemical test was performed through a previous flocculation with zinc sulfate ($ZnSO_4$) followed by a sedimentation and finally by a supernatant filtration on GF/C filters.

Mathematical model

The mathematical model used was a modified version of the IAWQ Activated Sludge Model no. 1 (ASM 1), which simulates the activated sludge process including organic carbon oxidation, nitrification and denitrification (Henze *et al.*, 1987).

The model includes two other processes besides those described in the ASM 1; it is considered that ammonia as well as nitrate can serve as nitrogen source for cell synthesis in both aerobic and anoxic growth: this is accomplished through the use of switching functions (Dold *et al.*, 1991). Basically, the same input parameters of the ASM 1 model have to be used with the addition of influent active biomass, and the same output parameters are obtained.

In order to calibrate the model, COD, ammonia, nitrate, MLVSS, pH and temperature data of one month were used. During the period considered the plant operation was regular and no particular problems were encountered. Data from average daily samples drawn from the influent, anoxic and aerobic tank and effluent were obtained. Calibration was conducted to determine all those parameters (influent active biomass, TKN fractions, model constants, switching functions, etc.) not calculated in the previous experimental phase and needed for using the model. Particularly, influent organic nitrogen fractionation was reached adjusting the ammonia and nitrate effluent concentration with a computational method (Henze *et al.*, 1995).

DISCUSSION

As far as RBCOD measurements are concerned, respirometric batch test results are represented in Table 3. The tests were carried out with different preselected initial substrate to biomass (COD/MLVSS) ratios in order to identify the suitable proportion for the specific wastewater. The OUR profile showed a clear pattern only when the F/M ratio was set around 0.6 mgCOD/mgVSS. Tests with lower ratios showed irregular OUR patterns (e.g. the aerobic batch 3, even if with a F/M ratio typical of the test of Kappeler and Gujer (1992), showed a pattern similar to that associated with Ekama's interpretation) and RBCOD results were not easily derived (unstable values).

Table 3. Respirometric batch test results

Tests	V_{ww} (l)	V_{ml} (l)	V_{ww}/V_{ml}	**total COD** (mg/l)	**MLVSS** (mgVSS/l)	**F/M** (mgCOD/mgVSS)	**RBCOD** (mg/l)	$f_{S,bs}$
AE1	2.4	0.6	4	385	3,134	0.49	42	**0.11**
AE2	3.4	0.6	5.7	314	3,992	0.45	16	**0.05**
AE3	3.5	0.5	7	322	5,084	0.44	20	**0.06**
AE4	3.5	0.5	7	335	4,214	0.56	30	**0.09**
AN1	3.2	0.8	4	451	3,127	0.58	39	**0.09**
AN2	3.5	0.5	7	344	3,896	0.62	26	**0.08**
MEAN				358	3,908		29	**0.08**

Finally, when the proper F/M ratio was utilised, no difference between the aerobic and the anoxic batch test for the RBCOD determination was noticed. The RBCOD average value calculated was 8% of the total COD. In the physical-chemical test a comparison between instantaneous and average daily samples was done, but the values obtained were nearly the same (Table 4). The RBCOD mean value was determined to be around 15% of the total COD, which is very much higher than the one calculated in the respirometric batch tests.

Table 4. Physical-chemical test results

Tests	**Sample type**	**total COD** (mg/l)	**RBCOD** (mg/l)	$f_{S,bs}$	**USCOD** (mg/l)	$f_{S,us}$
PC1	Average daily	417	52	**0.12**	34	**0.08**
PC2	Average daily	261	50	**0.19**	18	**0.07**
PC3	Average daily	332	43	**0.13**	13	**0.04**
PC4	Instantaneous	323	75	**0.23**	13	**0.04**
PC5	Instantaneous	451	68	**0.15**	15	**0.03**
PC6	Average daily	278	59	**0.21**	33	**0.12**
PC7	Average daily	277	42	**0.15**	15	**0.05**
PC8	Average daily	302	47	**0.16**	6	**0.02**
PC9	Average daily	241	35	**0.14**	21	**0.09**
PC10	Instantaneous	322	18	**0.06**	33	**0.10**
PC11	Average daily	277	37	**0.13**	10	**0.04**
PC12	Instantaneous	335	54	**0.16**	26	**0.08**
PC13	Average daily	228	38	**0.17**	15	**0.07**
PC14	Instantaneous	344	41	**0.12**	17	**0.05**
MEAN		313	47	**0.15**	19	**0.06**
Instantaneous samples		355	51	**0.14**	21	**0.06**
Average daily samples		290	45	**0.15**	18	**0.06**

This discrepancy could be due to a storage phenomenon during the OUR and NUR tests (Ubay Çokgör *et al.*, 1998), not included in the calculations, which causes an underestimation of the RBCOD fraction. Probably, there is also a concomitant error generated by the physical-chemical test, because not all the filtered COD can be accounted as readily biodegradable substrate, but it includes also a little portion of slowly biodegradable COD. The research is now investigating which is the reason inducing the biggest error.

Influent USCOD was determined by the physical-chemical method filtering the sample drawn from the plant effluent. As reported in Table 4 the values are stable with a mean value of 6% with respect to the total COD. In this case results obtained are more reliable because of the test simplicity, not suffering from misinterpretations.

The unbiodegradable particulate (UPCOD) fraction was determined with the steady state model of Marais and Ekama (1976), fitting the amount of biomass theoretically found with that one present in the plant during the experimentation period. The fraction was set around 8% of the total influent COD. The remaining COD fractions (biodegradable particulate and that one associated with the active biomass) and all the organic TKN fractions were determined in the model calibration phase.

Biomass kinetic parameters obtained by respirometric tests are listed in Table 5. According to all the methods used, the aerobic batch test B seems to be the most suitable to determine the maximum specific growth rate of heterotrophs ($\bar{\mu}_H$) and autotrophs ($\bar{\mu}_A$). The average values calculated for $\bar{\mu}_H$ and $\bar{\mu}_A$ (3.1 and 0.21 d^{-1}, respectively) are among the lowest ones found in the literature. However, all the tests carried out with different F/M ratios showed very reproducible results both for the $\bar{\mu}_H$ and the $\bar{\mu}_A$.

Table 5. Respirometric batch test results

Tests	**F/M** (mgCOD/mgVSS)	$\overline{\mu}_H$ (d^{-1})	$\overline{\mu}_A$ (d^{-1})	$\overline{\mu}_{HD}$ (d^{-1})	η_G
AE1	0.49	**3.1**	**0.21**		
AE2	0.45	**3.0**	**0.19**		
AE3	0.44	-	**0.23**		
AE4	0.56	**3.1**	**0.22**		
AN1	0.58			**2.3**	**0.73**
AN2	0.62			**2.0**	**0.64**
MEAN		**3.1**	**0.21**	**2.1**	**0.68**

The maximum heterotrophic growth rate under anoxic conditions determined with the NUR test gave a mean value of 2.1 d^{-1}. Consequently, the correction factor for the anoxic growth (η_G) is 0.68. This value was calculated assuming an anoxic yield coefficient (Y_{HD}) equal to the heterotrophic yield coefficient under aerobic conditions (Y_H = 0.45 gVSS/gCOD): this assumption is supported by the previous RBCOD results obtained with $Y_{HD} = Y_H$. Calculations based on a lower value for Y_{HD} (0.37 gVSS/gCOD) as reported in Sözen *et al.* (1998) gave a mean η_G value of 0.42.

Finally, experimentation with other more recent respirometric methods did not give good results: for example, the aerobic batch tests C and D (those with a little amount or no biomass at all) did not show the expected OUR time profile. Further research is needed to test the methods with different types of wastewater.

Model simulations

Before simulating the plant by means of the model a calibration phase was conducted. First of all calibration showed that the plug-flow bioreactor of the plant has to be modelled as three completely mixed tanks in series: an anoxic reactor at the head end followed by two aerobic tanks. Moreover, calibration results could explain the low RBCOD fraction in the influent, probably induced by the high amount of biomass already present in the influent wastewater (15% of the total COD). Finally, except those parameters determined in the previous experimental phase, nearly all the other default values were not changed.

Once the model was calibrated, different hypotheses of plant scheme or operation changes were simulated according to the needs of the plant operators. The simulations allowed us to verify the possibility of excluding one of the three treatment lines from operation overloading the other two, with great management simplification and energy saving, without deteriorating the treatment efficiency. Of course biomass concentration increases but the secondary settling tanks of the two lines in operation are suitable to cope with the increased hydraulic and solid loading.

Organic carbon or nitrogen overload taken independently lead to different results: while the former causes an increase in biomass concentration and improves the denitrification process (because more substrate is available for the heterotrophic denitrifier biomass), the latter leads to high concentration of nitrate in the effluent, due to a low denitrification capacity.

Finally, neither the use of the primary sedimentation nor the use of mixed liquor internal recycle flow seem to be convenient for the case studied. In fact, settled wastewater would reduce the organic substrate available for the denitrification process (NUR in anoxic tank is reduced by 12%), so increasing the effluent nitrate concentration. Moreover, the use of primary sedimentation tanks leads to a greater sludge production (Table 6).

Table 6. Simulation 8: settled wastewater

INPUT PARAMETERS			
$Q = 0.33\ m^3/s$			
influent COD = 240 mg/l (– 20 %)			
influent TKN = 29 mg/l (– 10 %)			
T = 15°C			
OUTPUT PARAMETERS			
parameter	**reference value**	**simulation output**	**difference**
effluent NH_4-N	1.6 mg/l	1.6 mg/l	=
effluent NO_3-N	7.0 mg/l	7.5 mg/l	+ 0.5 mg/l
O_2 utilised	228 kg/h	191 kg/h	– 16 %
NUR in anoxic tank	3.4 mgN/l·h	3.0 mgN/l·h	– 12 %
Sludge production	9,450 kgSS/d	13,000 kgSS/d	+ 40 %

The use of mixed liquor internal recycle flow would not considerably improve nitrogen removal efficiency since the anoxic tank is already working at its maximum denitrification capacity (see Table 7). So it is not cost-effective unless the relative anoxic and aerobic tank volumes can be changed.

Table 7. Simulation 12: internal recycle flow at 50 % of Q

INPUT PARAMETERS			
$Q = 0.33\ m^3/s$; $Q_{int} = 0.16\ m^3/s$			
influent COD = 300 mg/l			
influent TKN = 32 mg/l			
T = 15°C			
OUTPUT PARAMETERS			
parameter	**reference value**	**simulation output**	**difference**
effluent NH_4-N	1.6 mg/l	1.7 mg/l	+ 0.1 mg/l
NO_3-N in anoxic tank	2.3 mg/l	2.9 mg/l	+ 0.6 mg/l
effluent NO_3-N	7.0 mg/l	6.6 mg/l	– 0.4 mg/l
O_2 utilised	228 kg/h	227 kg/h	≅
NUR in anoxic tank	3.4 mgN/l·h	3.6 mgN/l·h	+ 6 %

CONCLUSIONS

The results obtained indicate the importance of introducing the use of mathematical models into the operation of full scale wastewater treatment plants in order to better sustain management and operating choices aimed at improving the plant efficiency from both an environmental point of view and an economical one. The best cost-effective solution can be derived from the simulation results.

Of course attention must be given to the experimental methods for the determination of model parameters for the specific case under study. In this sense a deep analysis has been conducted on the different methods derived from the literature in order to define the best ones or to point out some aspects which could in some way lead to unreliable results.

Particularly the interpretation of batch tests with wastewater and biomass was complicated by the choice of the right F/M ratio and by the occurrence of storage phenomena which are difficult to evaluate.

Finally, it is important that data from the plant be reliable and the operation be stable in order to get significant mean values to calibrate the model and to test the different solutions. A particular aspect coming out from this and other experimental works on full-scale plants in Italy is the difficulty in obtaining reliable data as to the plant sludge age which is conversely the most important operating parameter for a good simulation.

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REFERENCES

APHA (1995). Standard Methods for the Examination of Water and Wastewater. *19th edn. American Public Health Association*, Washington D.C.

Dold, P. L., Wentzel, M. C., Billing, A. E., Ekama, G. A. and Marais, G. v. R. (1991). Activated sludge system simulation programs. Published by Water Research Commission, Pretoria.

Ekama, G. A., Dold, P. L. and Marais, G. v. R. (1986). Procedures for determining influent COD fractions and the maximum specific growth rate of heterotrophs in activated sludge systems. *Wat. Sci. Tech.*, **18**(6), 91-114.

Henze, M., Grady, C. P. L. Jr., Gujer, W., Marais, G. v. R. and Matsuo, T. (1987). Activated Sludge Model No. 1: *IAWPRC Science and Technology Report No. 1*, IAWPRC, London.

Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, M. C. and Marais, G. v. R. (1995). Wastewater and biomass characterization for the Activated Sludge Model No. 2: biological phosphorus removal. *Wat. Sci. Tech.*, **31**(2), 13-23.

Kappeler, J. and Gujer, W. (1992). Estimation of kinetic parameters of heterotrophic biomass under aerobic conditions and characterization of wastewater for activated sludge modelling. *Wat. Sci. Tech.*, **25**(6), 125-139.

Mamais, D., Jenkins, D. and Pitt, P. (1993). A rapid physical-chemical method for the determination of readily biodegradable soluble COD in municipal wastewater. *Wat. Res.*, **27**(1), 195-197.

Marais, G. v. R. and Ekama, G. A. (1976). The activated sludge process Part 1 - Steady state behaviour. *Water SA*, **2**(4), 163-200.

Sözen, S., Ubay Çokgör, E., Orhon, D. and Henze, M. (1998). Respirometric analysis of activated sludge behaviour - II. Heterotrophic growth under aerobic and anoxic conditions. *Wat. Res.*, **32**(2), 476-488.

Ubay Çokgör, E., Sözen, S., Orhon, D. and Henze, M. (1998). Respirometric analysis of activated sludge behaviour - I. Assessment of the readily biodegradable substrate. *Wat. Res.*, **32**(2), 461-475.

Wentzel, M. C., Mbewe, A. and Ekama, G. A. (1995). Batch test for measurement of readily biodegradable COD and active organism concentrations in municipal waste waters. *Water SA*, **21**(2).