Editorial Manager(tm) for Water Science and Technology
Manuscript Draft

Manuscript Number:

Title: Technical-Economical Analysis of Selected Decentralized Technologies for Municipal Wastewater Treatment in the City of Rome

Article Type: Research Paper (Editorial Office Upload)

Section/Category: Biological Treatment Processes for Wastewater (inc Activated Sludge, Biofilms, Membrane Bioreactors)

Keywords: Constructed wetlands; deep shaft; filtration; membrane biological reactor; sequencing batch reactor; UV-disinfection

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After the analysis of the main technical features, an economical estimate was carried out taking into account the investment, operation and maintenance costs as a function of the plant's capacity. The analysis was based on real data provided by the Company who manages the entire water system of the City of Rome (Acea Ato 2 S.p.A.). A preliminary design of the treatment plants using some of the selected technologies was finally carried out.

Technical-Economical Analysis of Selected Decentralized Technologies for Municipal Wastewater Treatment in the City of Rome

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Abstract
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Keywords
Constructed wetlands; deep shaft; filtration; membrane biological reactor; sequencing batch reactor; UV-disinfection

INTRODUCTION

Traditional wastewater treatment technologies, such as those based on activated sludge, have been widely adopted in the last decades all over the world and also in Italy; therefore, their capabilities and operation are well known and offer high reliability. Nonetheless, they present some limitations which may reduce the advantages related to their adoption. For instance, continuous flow treatment systems usually do not represent the optimal solution for small urban centres. In these cases, the wide variability of the influent loadings and flowrates may negatively affect their treatment efficiency; besides, the construction, operation and maintenance costs may become remarkable.
For the existing wastewater treatment plants, depuration of increased volumes and/or compliance with more stringent effluent limits are often required. In these cases, the upgrading interventions on the traditional systems encounter difficulties due to their high footprint and the limited available spaces in the densely populated areas.
Furthermore, operation of the activated sludge systems is strongly conditioned by the management of the excess sludge, whose cost can account for about 50-60% of the total expenses of the plant. Along with economical issues, also final destination of the treated sludge poses serious problems which can be only partially overcame by their reuse in agriculture.
In the present study, a technical-economical analysis was carried out on several treatment

technologies selected as alternatives to the continuous flow activated sludge systems which are the most widely adopted in Italy. The final aim was to provide some guidelines to be used as a useful tool by the water management Company of the city of Rome (Acea Ato 2 S.p.A.) to afford and, possibly, solve the different issues it has to address. On the base of the real needs of the Company, the following technologies were selected:

- Constructed Wetlands (CW);
- Membrane Biological Reactor (MBR);
- Deep Shaft (DS);
- Sequencing Batch Reactor (SBR);
- Combined filtration and UVc-disinfection (F+UV).

According to the regional law (Piano di Tutela delle Acque della Regione Lazio, 2007), CWs is included within the class of the “appropriate” processes and is considered suitable to provide depuration to small and isolated urban areas. The MBR and SBR systems were chosen for either the upgrading of existing plants or the construction of new treatment plants in decentralized areas.

Due to the reduced footprint, the DS may be suitable in the cases of limited available spaces; besides, it can offer high treatment potentiality. Finally, the tertiary system made by filtration followed by UVc-disinfection, has recently received increasing attention in either new plants or when more stringent requirements are posed on the effluent.

The selected technologies were studied for their main technical and economical features, referring to real data and information provided by Acea Ato 2 S.p.A. and other specialized companies operating in the water sector. The economical evaluation referred to the main investment, and operation and maintenance (O&M) costs, and compared the data obtained for the selected technologies with the costs of the traditional treatment scheme. Besides, the technologies were distinguished based on the limits they are potentially capable of accomplishing on the effluent. Consequently, the MBR and tertiary system (F+UV) were considered together (Group 1) as they should be able to allow effluent discharge into soil (according to the Italian D.Lgs. 152/06, Table 4, All. 5) and/or reuse (according to the Italian D.M. 185/03), whereas the SBR and DS were grouped together (Group 2) for their capability to comply with the standards for the discharge into surface waters (according to the Italian D.Lgs. 152/06, Table 1, All. 5). The selected technologies were applied to some case-studies located in the Province of Rome and the preliminary design of two of them is presented at the end of the paper.

TECHNICAL AND ECONOMICAL ANALYSIS

The traditional treatment sequence made by the activated sludge tank (AS) followed by secondary settlement (SS) and chlorination (C) was used as a reference in the cost analysis of both groups, despite it is usually unable to comply with standards posed by D.M. 185/03.

Group 1: F+UV, MBR

In this case, the following alternative treatment schemes were evaluated: (1) filtration and UV disinfection in place of final chlorination, and (2) membrane bioreactor in place of the secondary treatment (AS+SS+C) (EPA, 1999; Gander et al., 2000; Côte et al., 2004; Melin, 2006; Yang et al., 2006; Wisniewski, 2007). The investment costs were estimated based on the construction costs of the following items: tanks of AS, SS and C in the traditional scheme; tanks of AS and SS, microfiltration unit and UV-disinfection unit in the F+UV system; bioreactor and membrane modules in the MBR plant. The items being common to all the three configurations (e.g. the pumping station) were neglected in the analysis as well as the costs of the structures.

Construction costs. The biological reactor volume was designed using the software ASCAM (Tomei and Ramadori, 1999), then increased to take into account the membrane volumes. For the chlorination stage in the traditional scheme, the following items were included in the analysis: chlorine-dosing pump, residual chlorine meter, flowrate ultrasound-meter, automatic sampling device, chlorine storage tank, mechanical flowrate controller. The analysis was carried out in terms of cost per inhabitant (€/EI) and the following regression equations were obtained, where *c* refers to the cost per inhabitant.

For the traditional scheme:

$$c = 503.8 \times EI^{-0.2406} \tag{1}$$

For the tertiary system (F+UV):

$$c = 1232.7 \times EI^{-0.3062} \tag{2}$$

For the MBR system:

$$c = 125.53 \times EI^{-0.0333} \tag{3}$$

Figure 1 shows the curves obtained by applying the above formulas; dots indicate the real data. It can be noted that for small treatment capacities, the costs of MBR and of the traditional scheme are comparables, whereas the costs of the tertiary system are appreciably above both solutions.

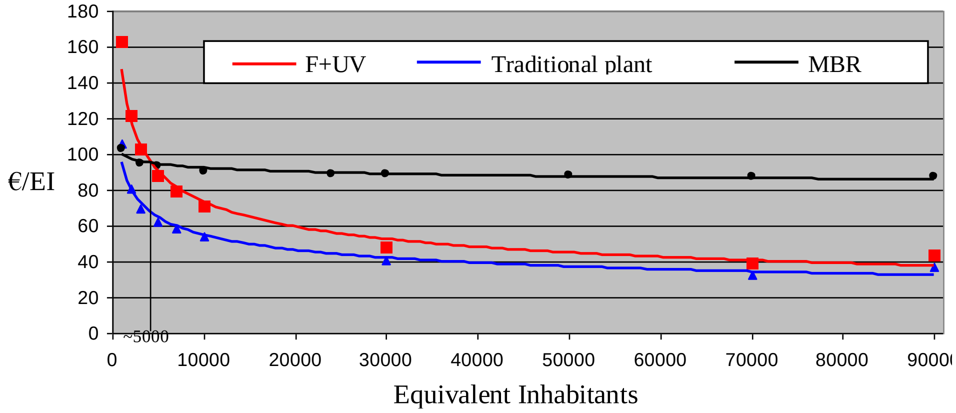

Figure 1. Construction costs of F+UV, traditional scheme and MBR.

At higher capacities, costs of the MBR plant increase mainly due to the purchase and installation costs of the membranes; at lower capacities, this effect is compensated by the saving arising from the elimination of both the secondary settlement and chlorination units. Due to the lower incidence of the installation costs, the tertiary system shows reducing overall construction costs as the treatment capacity increases. Similar pattern is observed for the traditional scheme. It is noteworthy that intersection among the three regression curves occurs at about 5000 EI. Therefore, this capacity can be assumed as the capacity limit below which MBR becomes more convenient than the tertiary system to ensure compliance with standards set by D.M. 185/03.

Operation and maintenance costs. These costs were calculated taking into account the following items: chemicals, energy and disposal of screened and degritted material and of sludge, and ordinary and extraordinary maintenance interventions. The estimate was referred to a flowrate of 1,200,000 m^3/y, corresponding to a treatment capacity of about 16,000 IE. Table 1 lists and compares all the cost items for the MBR plant and the tertiary system. The expenses of operators were not taken into account in the evaluation since were considered to be comparables. As far as the ordinary and extraordinary maintenance costs of the MBR are concerned, they accounted for about 3% of the total costs of the mechanical components (about 262,000 € more than the cost of traditional scheme). Consequently, a value of 7860 € was obtained. For the tertiary system, maintenance of the filtration unit regarded replacement of filtering panels and nozzles, for a total cost of about 3700 €/y; for the UV-c disinfection unit, the replacement of the exhausted lamps accounted for about 600 €/y for. The total cost of the tertiary system was therefore determined to be about 4300 €/y.

Table 1. Estimate of the maintenance costs of the MBR and the filtration+UV-disinfection unit.

	Difference (€/y)	
	MBR	Tertiary system
Ordinary and extraordinary maintenance interventions	+7860	+4300
Electric energy	+50,400	+3250
Chemicals	-4420	-3200
Disposal of sludge, degritted and screened material	-30,300	
Total annual difference	+23,540	+3350

For the biological oxidation tank and the secondary settlement (including sludge returns) of the traditional scheme, the energy consumption was assumed to be about 0.35-0.40 kWh/m^3 of treated water. For the MBR the consumption was increased to about 0.65-0.70 kWh/ m^3 of treated water to take into account the enhanced energy consumption due to the constant operation of the aeration system to reduce membrane fouling. Consequently, based on an energy cost of 0.14 €/kWh, it was obtained a value of about 50,400 €/y as energy overall cost of the MBR. Similarly, the tertiary system also shows higher energy consumptions than the traditional scheme. Assuming 3.75 kW for UVc-disinfection (applied only from May to September) and 1.1 kW for the filtration unit, at the design flowrate, the energy cost results about 1900 €/y and 1350 €/y, respectively. Therefore, total expenses for energy in the tertiary system accounts for about 3250 €/y. About chemicals, differently from the traditional scheme, effluent disinfection is not needed in the MBR plants; sodium ipochlorine solution only is used for membrane washing with a cost of about 400 €/y. If the disinfection unit requires about 3200 €/y, therefore a total saving of about 2800 €/y is gained with the MBR. The tertiary system does not require chemicals for the disinfection. Dosages of polyelectrolytes for sludge dewatering can be assumed very similar in the three treatment alternatives (about 6 g/kgSS). However, the amount of sludge to be dewatered in the traditional scheme is higher than that of the MBR plant, and consequently the corresponding costs (about 535 kgSS/d and 4688 €/y, and 350 kgSS/d and 3068 €/y, respectively). A total saving of about 1620 €/y is therefore obtained for the polyelectrolyte usage with the MBR. By summing the above savings, it can be concluded that the MBR requires a lower expense for chemicals of about 4420 €/y with respect to the traditional scheme. For the tertiary system, the sludge dewatering cost is very similar to that of the traditional scheme. As far as the final sludge disposal is concerned, by assuming a 25% SS content and a cost of 100 €/Mg, due to the reduced sludge production, a lower expense of about 30,300 €/y is obtained with the MBR as compared to both the traditional scheme and the tertiary system. Table 1 highlights a significant increase of the maintenance costs of the MBR plant as compared to the tertiary system; nonetheless, the cost per inhabitant in both cases remains quite low (about 1.48 €/EI and 0.20 €/EI, respectively).

Group 2: SBR, DS

In this case the traditional scheme was compared to: (1) SBR plant followed by chlorination, and (2) DS (including the Verbit® reactor and the secondary settlement) followed by flotation (F) and then chlorination (EPA, 1982; Wilderer et al., 2001; Sirini, 2002; Tchobanoglous et al., 2003; Artan and Orhon, 2005).

Construction costs. Similarly to the analysis performed for Group 1, the investment costs were estimated based on the construction costs of the following units: tanks of AS and SS in the traditional scheme; reactor in the SBR; reactor, flotation and SS tanks in the DS. The following regression equations were obtained, where *c* refers to the cost per inhabitant.

For the traditional scheme:

$$c = 343.98 \times EI^{-0.2107} \tag{4}$$

For the SBR:

$$c = 4469.1 \times EI^{-0.4284} \tag{5}$$

For the DS:

$$c = 886.53 \times EI^{-0.2980} \tag{6}$$

Equation (5) was obtained by considering a cost of 90 €/m^3 for the reactor and also data from the literature. Figure 2 shows the regression curves obtained by applying the above equations; dots represent the real data. It can be noted that, for capacities below 5000 EI, costs of the SBR enhance due to the purchase and installation of the control instrumentation. At increasing capacities, the SBR rapidly becomes more convenient than the traditional scheme and the DS technology.

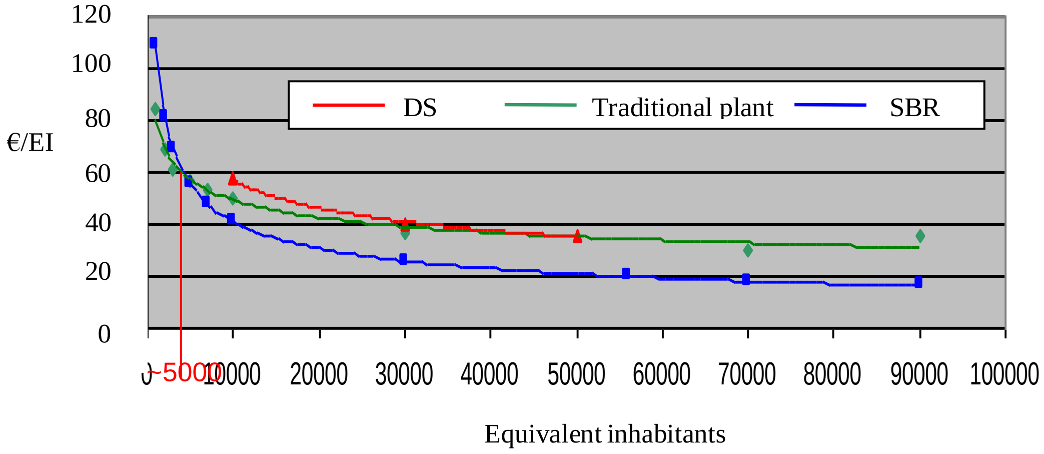

Figure 2. Construction costs of DS, traditional scheme and SBR.

Operation and maintenance costs. In this case, the difference among the three options was negligible.

Constructed wetlands

Wetlands were considered separately from the other technologies since are suitable to satisfy only limited applications, such as small communities or isolated houses (EPA, 2000).

The total costs are mainly due to construction since maintenance is very low as compared to the traditional plants. Among the construction costs, the main items are represented by geomembranes and filling material, which can account for up to 40% of the total costs. Based on literature data, it was assumed a cost per inhabitant of about 160 €/EI.

UVc-disinfection

An economical comparison was carried out between UVc and chlorine as disinfecting agents for the effluent from the secondary treatment.

Construction costs. For both chlorination and UVc-disinfection, the estimate was carried out by taking into account the cost of the disinfection reactor and the channel, respectively, and of the required electromechanical equipments (e.g. the chlorine dosage pump, the residual chlorine meter, a flowrate-meter, an automatic sampler, the chemical storage tanks). The following regression equations were obtained.

For chlorine disinfection:

$$c = 595.25 \times EI^{-0.5218} \tag{7}$$

For UVc-disinfection:

$$c = 1019.9 \times EI^{-0.5246} \quad (8)$$

Figure 3 shows the curves obtained by applying equations (7) and (8) and the real data.

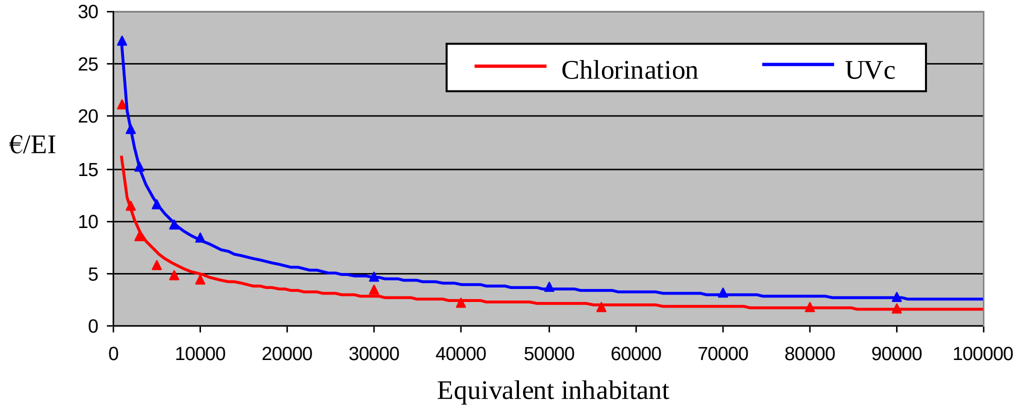

Figure 3. Construction costs for chlorination and UVc-disinfection.

It can be noted that UVc-disinfection costs are always higher than those calculated for chlorination; however, the difference among the curves is not significant and tends to reduce with EI increasing. At high capacities, it is about 1 €/EI.

Operation and maintenance costs. Determination of the maintenance costs was carried out by taking into account chemicals for chlorination and electric energy for UV-c-disinfection. The cost of operation was assumed to be the same in both cases; besides, it was considered that disinfection is applied only from May to September, for about 3672 h/y. Figure 4 shows the regression curves along with the real data obtained for both disinfection systems, expressed as €/EI (per year).

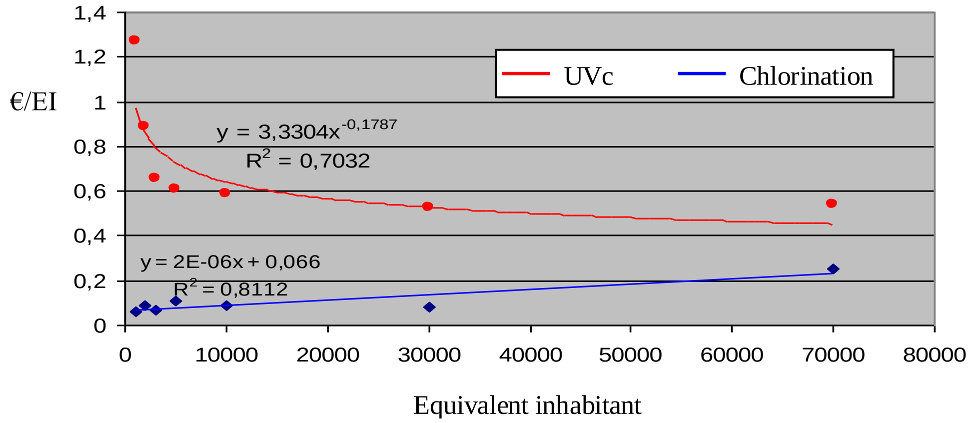

Figure 4. O&M costs for chlorination and UVc-disinfection.

At increasing capacities, UVc-disinfection requires reducing expenses, whereas maintenance costs of chlorination do not vary appreciably. Nonetheless, difference between the two systems tends to diminish and becomes very low at high capacities.

CASE-STUDIES

Application of some of the selected technologies to two case-studies is described below.

Constructed wetlands in Fonte Nuova

The site of Fonte Nuova is located close to a natural reserve; however, it hosts two illegal discharges. In the meanwhile a pumping station was built to deliver the discharges to the existing wastewater treatment plant, it was decided to build a wetland system as a temporary solution. The CW system was designed for a total capacity of about 600 EI and an average flowrate of 60 m^3/d. The effluent must comply with standards set by D.M. 185/2003. The complete flow sheet included: pre-treatment by screening, primary settlement and Imhoff tank followed by a sub-surface horizontal flow wetland plant. A final UV-disinfection was also envisaged, to respect microbiological standards. Besides, part of the effluent was collected from the well following CWs and returned to the Imhoff, to increase treatment efficiency. Design of the CWs was carried out based on the model of Kadlec and Knight (1996), and referring to three different temperature values (12, 16 and 20°C). The results of the design step are shown in Table 2, where C_{IN}, $C_{OUT,CW}$ and $C_{OUT,f}$ indicate concentrations in the influent, the effluent from CWs and the final effluent from the plant, respectively. These data where obtained considering a total surface plant of about 1200 m^2, divided into two identical lines.

Table 2. Design influent and effluent concentrations from the CWs plant in Fonte Nuova.

	C_{IN}	$C_{OUT,CW}$			$C_{OUT,f}$		
		12°C	16°C	20°C	12°C	16°C	20°C
BOD_5 (mg/L)	300	12.8	7.0	3.3	9.6	5.3	2.5
NH_4^+-N (mg/L)	50	11.2	8.9	6.9	10.0	8.0	6.2
NO_3^--N (mg/L)	0	12.0	5.3	1.3	12.0	5.3	1.3
SST (mg/L)	400	10.8	10.8	10.8	4.9	4.9	4.9
Ptot (mg/L)	15	8.1	8.1	8.1	7.7	7.7	7.7

According to the results obtained, the final effluent concentrations should comply with standards for 5-day Biochemical Oxygen Demand (BOD_5) and Total Suspended Solids (SST); by contrast, it should exceed limits of D.M. 185/03 for ammonia and phosphorous but only at lower temperatures. Nonetheless, it could be discharged into surface waters according to D.Lgs. 152/06.

SBR in Casal Monastero

The project regarded the replacement of one of the treatment lines of the AS continuous flow plant in Casal Monastero with a SBR. The existing plant needed to be upgraded in order to increase its capacity and also to solve the bulking problems. The conversion of one of the lines into a SBR allows also to compare performance of a continuous with a discontinuous flow process for prospective future applications. The design of the new plant was carried out based on an average flowrate of 1200 m^3/d and a temperature of 12°C. The existing secondary settlement tank will be converted into the equalization tank, whereas the biological reactor (including denitrification and oxidation) was demonstrated to have a volume large enough (about 1000 m^3) to be used as the SBR. The reactor should work through 4 daily cycles, consisting of: mixed fill (1h), aerated react (2h), mixed react (1h), settle (1h) and draw (1h). The calculated total hydraulic residence time (Θ_H) and the sludge retention time (Θ_c) were 20h and 17d, respectively.

CONCLUSIONS

A technical and economical evaluation of selected treatment technologies was carried out with the purpose to provide a list of alternatives to be used to either upgrade the existing plants or build new plants. These technologies must be capable of either increasing the treatment capacities or complying with more stringent requirements set by the law in force.

For each technology, investment, operation and maintenance costs were determined as a function of the plant's capacity (in terms of EI). Besides, a comparison was always carried out with the more common scheme consisting of a centralized continuous flow plant made by the activated sludge reactor followed by secondary settlement and chlorination.

Both the tertiary system and the MBR are capable of producing an effluent quality suitable to be reused according to the Italian D.M. 185/03. However, the investment costs of the MBR are higher than those of the traditional scheme, particularly at high capacities. The significant energy consumption makes O&M costs also to be remarkable. The tertiary treatment made by filtration and UVc-disinfection showed to become more convenient than chlorination above 5000 EI. The O&M costs are higher as compared to the traditional scheme, but lower than those of the MBR.

The second group of selected technologies included the SBR and Deep Shaft. The former is more convenient than the traditional scheme for capacities above 5000 EI, whereas the costs of the DS do not differ appreciably. Both systems can produce an effluent which can be discharged into surface waters, according to the Italian D.Lgs. 152/06.

The CWs confirmed to be the appropriate system for small communities or as a temporary treatment solution.

The present paper can be seen as a preliminary database comprising information useful for the water managing Company to individuate the proper alternatives to address the different treatment issues. The economical analysis must be properly adjusted and integrated to fit the specific cases, since it lacks of important components, such as the cost of pumps, tubes, dig, etc., which may deeply affect the overall cost estimate and even drive to choose a different alternative. From this point of view, operation of the plants designed with the selected technologies will provide important data to implement the technical and economical analysis presented in this paper.

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