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Assessment of wastewater treatment plant design for small communities: Environmental and economic aspects

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ABSTRACT

The preliminary design and economic assessment of small wastewater treatment plants (less than 2000 population equivalent) are issues of particular interest since wastewaters from most of these agglomerations are not covered yet. This work aims to assess nine different technologies set-up for the secondary treatment in such type of facilities embracing both economic and environmental parameters. The main novelty of this work is the combination of an innovative environmental decision support system (EDSS) with a pioneer approach based on the inclusion of the environmental benefits derived from wastewater treatment. The integration of methodologies based on cost–benefit analysis tools with the vast amount of knowledge from treatment technologies contained in the EDSS was applied in nine scenarios comprising different wastewater characteristics and reuse options. Hence, a useful economic feasibility indicator is obtained for each technology including internal and external costs and, for the first time, benefits associated with the environmental damage avoided. This new methodology proved to be crucial for supporting the decision process, contributing to improve the sustainability of new treatment facilities and allows the selection of the most feasible technologies of a wide set of possibilities.

1. Introduction

Many countries are facing important challenges in the field of water management. Satisfying an increasing demand of water resources while avoiding the degradation of ecosystems constitutes a complex challenge that requires viable answers following economic, social and environmental criteria (Macleod and Haygarth, 2010). Although the level of knowledge available to decision-makers to cope with drought and quality degradation is becoming increasingly sophisticated, water scarcity is being intensified in a parallel manner in nearly all basins and water policies have necessarily to be improved.

The European Directive 91/271/EEC (UWWTD) states that all generated wastewater agglomerations of between 2000 and 10000 people equivalent (p.e.) must set up collection and treatment systems by December 2005. Therefore, one of the main challenges for European authorities for the achievement of the good ecological status of water bodies[1] is to implement the appropriate treatment of wastewater in small agglomerations.

For example, Spain is characterized by the existence of a huge amount of low-populated locations. In fact, more of 73% of the municipalities have less than 2000 inhabitants, stating for almost 7% of the population of the country (INE, 2011) and the non-treated load of sewage originated in such small agglomerations is about 3–4 million p.e. (Salas et al., 2011). According to the Spanish National Plan for Water Quality (NPQW), which devotes special attention to the treatment of wastewater in such agglomerations, 100% of treated sewage must be achieved by 2015 (Aragón et al., 2011).

In addition, EU Commission has to come to the conclusion that additional sensitive areas and their related catchments should be designated. This fact entails the need of upgrading the treatment applied for a significant number of discharges and the development of new facilities in the near future. In this context, it is crucial to find out the most feasible technologies from an integrative point of view to tackle with new wastewater management projects, depending on each specific scenario.

The selection of the most suitable process involves many possible options and elements which are all linked, giving multiple interactions and a very large number of design and operation combinations. The accomplishment of a variety of objectives (such as effluent requirements, local conditions, investment costs, environmental issues, operational costs, etc.) and multiple criteria also increases the complexity of the problem, such that selection of the most appropriate plant design becomes a very difficult task (Flores-Alsina et al., 2010; Poch et al., 2004).

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[1] The Directive 2000/60/EC (Water Framework Directive) states to achieve the good ecological status of water bodies by December 2015.

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In that sense, recent years have seen the arising of promising tools able to cope with that level of complexity, the so called Environmental Decision Support Systems (EDSS). EDSS are tools designed to confront with this multidisciplinary nature and therefore to deal with complex environmental problems. They are inherently integrated (statistical/ numerical methods, environmental ontologies, etc.), and consist of various coupled models, databases, and assessment tools capable of supporting complex decision making processes (Shim et al., 2002; Matthies et al., 2007; Huang et al., 2010). Therefore, EDSS are gaining interest within the wastewater management sector. They can be used to justify multi-criteria decisions of policy-makers (transparency) more than making real decisions, and provide to end-users a tool to play with "what-if" scenarios, to explore the response surface and the stability of the solution in order to improve the consistency and quality of decisions (McIntosh et al., 2011).

Previous experiences successfully applied EDSS tools to identify adequate wastewater treatment technologies for small communities (Alemany et al., 2005; Comas et al., 2004). However, taken into account the role assigned by the Water Framework Directive (WFD) to water planning, suitable methodological approaches regarding the economic valuation of the different proposed alternatives by the EDSS were not sufficiently addressed. In this context, among the number of methodologies available which can be used as support instruments for the decision makers, cost–benefit analysis (CBA) is nowadays between the most accepted (Molinos-Senante et al., 2011a). In this sense, according to WFD, the environmental benefits derived from implementing measures or projects should be included in feasibility studies. Because these benefits are difficult to calculate since they are not determined by the market, economics have made important efforts in order to estimate the monetary value of them (Garrod and Willis, 1999; Glover, 2010). In the specific context of wastewater treatment, Hernández-Sancho et al. (2010) have adapted the pioneering methodology developed by Färe et al. (1993) in order to quantify in economic terms the environmental benefits derived from wastewater treatment (Table 1).

The EDSS presented in this paper (NOVEDAR_EDSS) constitutes a pioneer approach for implementing efficient and effective policies and strategies for wastewater treatment since it integrates not only the traditional methodology for the economic assessment of the technologies based on investment and operating costs but also environmental benefits from wastewater treatment are included. Hence, a useful economic feasibility indicator is obtained for each technology including internal and external costs and, for the first time, benefits associated with the environmental damage avoided. This new methodology proved to be crucial for supporting the decision process, contributing to improve the sustainability of new treatment facilities and allows the selection of the most feasible technologies of a wide set of possibilities.

The aim of the study presented here is assess nine different technologies (Table 2) set-up for the secondary or main treatment step in small wastewater treatment plants (WWTPs), in order to establish which ones might be more suitable from an integrative point of view embracing economical and environmental issues. In doing so, nine scenarios regarding influent load and water reuse options are evaluated. The most relevant factors contributing to the overall plant feasibility and environmental impact will be identified and discussed.

Table 1
Shadow prices for pollutants removed from wastewater (€/kg).
Source: Hernández-Sancho et al. (2010).

Destination	Shadow prices of undesirable outputs (€/kg)			
	N	P	SS	COD
River	16.353	30.944	0.005	0.098
Sea	4.612	7.533	0.001	0.010
Wetlands	65.209	103.424	0.010	0.122
Reuse	26.182	79.268	0.010	0.140

Note that shadow prices are interpreted positively because they represent the environmental benefits obtained by treating wastewater.

2. Materials and methods

2.1. The NOVEDAR_EDSS program

The development of the NOVEDAR_EDSS to systematize the design of wastewater treatment plants is performed under the project "NOVEDAR: Conception of the WWTP of the XXI century". NOVEDAR_ EDSS is innovative software for WWTP design which includes environmental, economic and social issues and operation analysis. The software includes several extensive databases (legislation, fully characterization of WWTP-related technologies, etc.) and methodologies such as Multi-Criteria Decision Methods (MCDM), Life Cycle Analysis (LCA), Cost–Benefit Analysis (CBA), Carbon Footprint Analysis (CFA), etc.

A variety of sources were used for the development of the different data bases which comprise knowledge extracted from interviews with experts and bibliography within the NOVEDAR Project (which accounts with the cooperation of 11 research groups, 29 relevant water companies and 14 public entities related to the water management, as well as project related engineers, companies and wastewater treatment authorities). Conventional knowledge acquisition methods (scientific and technical literature, conferences, etc.) were also used.

The proposed model for the EDSS is based on a hierarchical decision approach that breaks down a complex design problem (WWTP conceptual design) into a series of issues easier to analyze and to evaluate. The generation of WWTP alternatives is carried out by means of the interaction of different main knowledge bases (KBs). However, the most remarkable is the Specifications Knowledge Bases (S-KB) that collects a complete characterization of the wide range of unit process existing in WWTP. At this moment 274 unit processes are thoroughly characterized by a whole range of parameters encompassed in five main topics: technical, influent and effluent characteristics, costs and environmental impacts.

All technologies proposed by the NOVEDAR_EDSS can be divided into primary and main (secondary or advanced) treatments, according to the level of purification they can achieve.

2.1.1. Primary treatment

These technologies are designed to remove coarse solids, grit and therefore the associated fraction in terms of nitrogen, phosphorus and organic matter, but to a limited extent. The NOVEDAR_EDSS proposes two options for pre-treatment: a) coarse and fine screens and Imhoff Tank (functioning as primary sedimentation) and b) coarse and fine screens, degritting and cylindroconical settler. The guidelines used to select one of these configurations are based on the size of the community and according to bibliographic references and heuristic knowledge (Comas et al., 2004; Ortega de Ferrer et al., 2011).

2.1.2. Secondary or main treatment

These technologies are applied to eliminate chemical oxygen demand (COD), suspended solids (SS), and depending on the treatment, reduce nitrogen (N) and/or phosphorus (P). More than 40 technologies for secondary treatment are included in the NOVEDAR_EDSS. However, taking into account the scope of the study only those more representative of the small agglomerations are considered.

2.2. Cost–benefit analysis methodology

Because the economic assessment through a CBA is one of the novel aspects of the NOVEDAR_EDSS, we will describe the basics of this methodology, including an innovative approach based on the economic valuation of non-market services.

The CBA is made to compare the economic feasibility associated with the implementation of different proposals. CBA main premise

Table 2
Secondary treatment technologies under study.
Source: Ortega de Ferrer et al. (2011); Tchobanoglous et al. (2003); Comas et al. (2004).

Secondary technology	Definition	Contaminants removal performance (%)	Associated costs (€/p.e.)
Pond System (PS)	Artificial man-made lagoons in which wastewater is treated by natural occurring processes and the influence of solar light, wind, microorganisms and algae.	N: 20–40 P: 60–70 COD: 60–96 SS: 50–90	IC: $y=3897.7x^{-0.407}$ ($R^2=0.998$) O&MC: $y=5.543x+3127.5$ ($R^2=0.991$)
Intermittent Sand Filter (ISF)	Wastewater treated with a well developed aerobic biological community attached to the surface of filter media.	N: 65–95 P: 75–99 COD: 75–90 SS: 85–95	IC: $y=2115.5x^{-0.399}$ ($R^2=0.992$) O&MC: $y=12.026x+3518.9$ ($R^2=0.992$)
Wetlands (CWS)	Pretreatment of wastewater by filtration and settling, followed by bacterial decomposition in a natural-looking lined marsh.	N: 30–70 P: 20–60 COD: 55–80 SS: 60–98	IC: $y=947.3x^{-0.188}$ ($R^2=0.991$) O&MC: $y=14.749x+3645.1$ ($R^2=0.994$)
Trickling Filter (TF)	A fixed bed over which sewage flows downward developing a layer of microbial slime (biofilm), covering the bed of media.	N: 35–50 P: 35–55 COD: 75–90 SS: 50–90	IC: $y=12{,}237.0x^{-0.487}$ ($R^2=0.993$) O&MC: $y=13.504x+6030.0$ ($R^2=0.998$)
Moving Bed Biofilm Reactor (MBBR)	Based on the aerobic biofilm principle. Carriers made from polyethylene provide large surface and optimal conditions for the bacteria culture to develop.	N: 10–20 P: 30–40 COD: 20–40 SS: 60–80	IC: $y=1187.0x^{-0.165}$ ($R^2=0.991$) O&MC: $y=12.794x+6031.0$ ($R^2=0.985$)
Rotating Biological Contactors (RBC)	Large disk with radial and concentric passages slowly rotating. The alternate exposure to oxygen/sewage promotes the development of a thin layer of biomass.	N: 20–80 P: 10–30 COD: 70–93 SS: 75–98	IC: $y=6931.4x^{-0.383}$ ($R^2=0.998$) O&MC: $y=313.4x^{-0.435}$ ($R^2=0.994$)
Membrane Bioreactor (MBR)	Combination of the conventional activated sludge process with a membrane filtration step.	N: 50–90 P: 20–70 COD: 70–90 SS: 85–99	IC: $y=5635.3x^{-0.352}$ ($R^2=0.992$) O&MC: $y=30.150x+13{,}542.0$ ($R^2=0.985$)
Extended Aeration (EA)	Modification of the activated sludge process preferred for small loads, where lower operating efficiency is offset by mechanical simplicity.	N: 50–90 P: 15–70 COD: 70–90 SS: 85–99	IC: $y=7946.0x^{-0.460}$ ($R^2=0.997$) O&MC: $y=30.150x+13{,}542.0$ ($R^2=0.985$)
Sequencing Batch Reactor (SBR)	Fill-and-draw activated sludge system where all the operations (fill, react, settle and draw) are achieved in a single batch reactor.	N: 55–90 P: 25–70 COD: 70–90 SS: 85–99	IC: $y=8258.9x^{-0.407}$ ($R^2=0.970$) O&MC: $y=309.4x^{-0.389}$ ($R^2=0.950$)

considers that projects should only be commissioned when benefits exceed the aggregate costs. Such analysis methodology is based on the net profit calculation for each one of the available options, which is the difference between benefits and costs (Eq. (1)).

$$NP=\sum B_i-\sum C_i \tag{1}$$

where:NP is the net profit; B_i is the value of the benefit item i and C_i is the value of the cost item i.

The costs involve operation and maintenance costs (O&MC) and investment cost (IC) adjusted for the time period on which they occur. Therefore, the total annualized equivalent cost (TAEC) must be calculated by adding the annualized IC to the annual O&MC as:

$$TAEC=\frac{r\cdot(1+r)^t}{(1+r)^t-1}\cdot IC+O\&MC \tag{2}$$

where:TAEC is the total annualized equivalent cost; IC represents the investment cost; O&MC are the operational and maintenance costs; r is the discount rate; and t is the useful life of the measure. For more details see Molinos-Senante et al. (2011b).

Not only costs but also the benefits of implementing a treatment facility must be expressed in present value. Therefore, the NP must be discounted into present value terms. By means of a properly chosen discount rate, the investor becomes indifferent regarding cash amounts received at different points of time. The net present value (NPV) of an investment is calculated as a function of the NP and the discount rate as shown in Eq. (3).

$$NPV=\sum_{t=0}^{T}\frac{NP_t}{(1+r)^t} \tag{3}$$

where:NPV is the net present value; NPt is the net profit at time t; r is the discount rate and, t is the time horizon of the project.

The conventional CBA, namely financial analysis, only takes into account costs and benefits with market value. However, taking into account the principles of the WFD, the benefits without market value such as environmental ones must also be considered in the assessment of the economic feasibility of investment projects.

According to Hernández-Sancho et al. (2010), wastewater treatment can be considered a production process in which a desirable output (treated water) is obtained together with pollution (organic matter, phosphorus, nitrogen, etc.) using inputs (costs). Contaminants removed from wastewater are considered undesirable outputs because if they were dumped in an uncontrolled manner they would cause a negative impact on the environment. The methodology to quantify shadow prices was born in the framework of efficiency studies (Färe et al., 1993) and is based on the relationship of duality between the distance function of output and the revenue function (demonstrated by the Lemma of Shephard, 1970). In this paper quantification of environmental benefits from wastewater treatment is based on the shadow price values obtained by Hernández-Sancho et al. (2010) (Table 1). Hence, an indicator of economic feasibility of wastewater treatment technologies considering both internal and external impacts is obtained.

The integration of this methodology within the NOVEDAR_EDSS is pioneering and enhances the decision-making process due to the integrated assessment of the economic feasibility of a set of technologies under different scenarios and wastewater characteristics considering environmental externalities.

2.3. Case studies

2.3.1. Wastewater technologies evaluated

Regarding the primary treatment, previous research established adequate technologies based on the size of community (Comas et al., 2004; Ortega de Ferrer et al., 2011). Moreover, IC and O&MC for such processes are low compared with those associated with secondary treatment (Pengfei et al., 2000). In the case of sludge treatment, it is not feasible to consider the design of a complete treatment train since commonly, sludge treatment/disposal in most of the existing facilities of moderate/small size is not carried out at their premises. Although NOVEDAR_EDSS is capable of designing a complete treatment train for a specific wastewater management project, for the purposes of this work only the selection of technologies for secondary treatment was considered in order to carry out a more thoroughly and focused comparison between the selected technologies. Extraordinary conditions, such as flooding of the plant by extremely intense rain or stoppage of units, were also excluded, as these situations were considered exceptional and therefore, did not represent normal operation.

Among the secondary treatment units encompassed in S-KB, the nine more usually applied in WWTPs are presented in this study (Tchobanoglous et al., 2003; Ortega de Ferrer et al., 2011). Table 2 shows a short summary of each technology evaluated regarding its definition, average removal efficiencies of: nitrogen (N); phosphorus (P); organic matter measured as chemical oxygen demand (COD); and suspended solids (SS), IC and O&MC.

where:x is p.e.; y is total cost expressed as €/p.e. and R^2 is the determination coefficient.

2.3.2. Scenarios analyzed

Nine scenarios for small communities are considered in order to highlight the possible differences between treatment technologies. Three different types of wastewater are chosen and three different final destinations were selected for the treated water. The cases are focused in a small community with an estimated population of 1500 p.e. Taking into account that in Spain most of the sewerage systems are mixed (including wastewater and rainwater) (MMA, 2001), it has been considered an average flow rate of 400 m^3/day.

The characteristics of the three standardized types of wastewater (high loaded, moderate loaded and low loaded) correspond to a hypothetical situation and are an adaptation of the values provided by Metcalf and Eddy (2004) (Table 3). The selected contaminant concentrations represent the most significant types of wastewater that can be found in WWTPs (Poch Espallargas, 1999). According to Molinos-Senante et al. (2010), after the treatment process, three end-of pipe options have been considered for each of the aforementioned wastewater types: (i) no sale of treated water, (ii) sale of 50% of the treated water and (iii) sale of 100% of the treated water.

Table 3
Three main typical compositions of wastewater in WWTPs.
Source: adapted from Metcalf and Eddy (2004).

Parameter	High loaded	Moderate loaded	Low loaded
Population equivalent (p.e)	1500	1500	1500
Flow rate (m^3/day)	400	400	400
Biological oxygen demand (mg/l)	450	310	110
Chemical oxygen demand (mg/l)	1250	750	220
Suspended solids (mg/l)	350	285	100
Phosphorus (mg/l)	17.0	11.5	5.0
Total Kjeldahl nitrogen (mg/l)	85.0	62.5	20.0
Nitrate (mg/l)	4	2	1
Nitrite (mg/l)	2	1	0
Conductivity (μs/cm)	1000	700	400

Moreover, according to the prevailing hydrological and ecological circumstances, distribution of sensitive areas varies widely between regions, especially on small populations as they use to be settled in remote areas with higher natural interests (Calleja et al., 1999). This concerns particular water bodies which are eutrophic or at risk of becoming eutrophic. In this research, areas with different ecological considerations were considered for the CBA analysis, since the final destination of treated wastewater is crucial for shadow prices calculation.

3. Results and discussion

3.1. Environmental assessment

This section summarizes the results relative to the quality of the effluent which have been predicted by using the NOVEDAR_EDSS for the nine scenarios selected (see Section 2.3.2). It is important to clarify that any decision taken by the NOVEDAR_EDSS program normally implies a higher number of considerations and whether the answer or example might be, the decision will depend on influent characteristics (population served, wastewater composition, etc.), economics (based on the methodology described on this paper), environmental (life cycle analysis), legislation, fate of treated wastewater and technical aspects (operation simplicity, fiability, flexibility, control, innovation degree, etc.…). However, the main objective of this work strictly deals with economic factors associated with the selection of a treatment process. Therefore, the decision-making process was carried out according to the criteria required by UWWTD.[2] It is also necessary to consider that there are variables such as the price of the regenerated water or the performance of the treatment units, which are subjected to a certain degree of uncertainty that affects equally to all technologies. Hence a change on this or other variables would not necessarily involve a change in the rank of the technologies. Although there are approaches to reduce uncertainty, their integration in the NOVEDAR_EDSS program is still on progress. It is expected to use the simple Monte Carlo method, traditionally used in the EDSS framework for both uncertainty and variability analyses. Other possibilities, such as the Bayesian Networks (BNs) have barely been used for environmental science (Aguilera et al., 2010) and for the moment, are not currently being explored.

According to the NOVEDAR_EDSS results, almost all main options are capable to produce an effluent suitable for discharge in non-sensitive areas (Table 4) with the exception of six technologies which could not overcome the legislation limits in terms of COD concentration treating high-strength wastewater: ISF, CWS, SBR, MBBR and EA. Similarly, TF achieved a bad performance removing SS and PS technology did not present reliable efficiencies relative to both COD and SS. In the case of moderate influent load, only two technologies, TF and PS, do not remove SS at an extent high enough

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[2] Requirements of effluent stated by the Directive 91/271/ECC for small communities: Non-Sensitive areas: COD:125 mg/l; SS: 35 mg/l. Sensitive areas: COD:125 mg/l; SS: 35 mg/l; P: 2 mg/l; N: 15 mg/l.

Table 4
Expected concentration of COD, SS, N and P in the effluent.

	COD			SS			N			P		
	High	Moderate	Low	High	Moderate	Low	High	Moderate	Low	High	Moderate	Low
PS	310	95	53	122	99	35	34	<2	<2	3	<2	<2
ISF	185	100	31	35	28	10	23	16	5	7	4	2
CWS	185	100	31	26	21	7	40	28	8	7	4	2
SBR	126	65	21	13	11	2	<2	<2	<2	<2	<2	<2
TF	96	53	16	100	85	3	40	29	7	7	4	<2
MBBR	185	100	31	35	28	10	32	22	6	7	4	2
RBC	96	53	16	10	8	3	35	24	7	6	3	<2
MBR	96	53	16	<2	<2	<2	<2	<2	<2	<2	<2	<2
EA	185	53	31	35	8	3	32	21	6	7	3	<2

Gray boxes indicates those values non-admissible for an effluent to be discharged in a sensitive areas, and black boxes those values no admissible for discharge in non-sensitive area.

to achieve the quality objectives. In case the load of the influent is low, all the technologies evaluated would be able to obtain an effluent suitable according to the criteria required by UWWTD. Hence, for non-sensitive areas, the technologies of RBC and MBR are the only ones capable to produce an effluent suitable independently of the influent load. In this case, the selection of the most suitable technology should consider other criteria such as the availability of space, environmental impact and economic aspects (Section 3.2). The only technology expected to remove nutrients at concentrations below the limits established for discharge in sensitive area are the MBRs. SBRs also fulfill the requirements regarding nutrients independently of wastewater characteristics. However, if the influent load is high, COD concentration is slightly above the limits and therefore, SBRs might not be a suitable technology in this concrete scenario. In the case of low-charged wastewater and discharge in non sensitive area, all the technologies evaluated are suitable with no exception.

For a better understanding of the results, Table 5 indicates the technologies that fulfill the requirements stated by the UWWTD both for non-sensitive and sensitive areas in the three scenarios evaluated.

3.2. Economic assessment

The tool selected to carry out the economic assessment is the CBA. In order to verify the role of the environmental benefits in the feasibility of the wastewater treatment technologies, two different approaches have been developed. Firstly, a conventional CBA have been carried out considering internal costs and benefits whose value is determined by the market. In a second approach the environmental benefits of treating wastewater have been included by considering the shadow price of the pollutants removed during wastewater treatment (Table 1).

The TAEC of the selected technologies has been calculated by considering IC and O&MC. In order to express the total cost in "present values", it has been assumed that the expected life of the plant is 30 years (Lundin et al., 2000) and the discount rate is 4%.

Table 5
Feasible technologies when the effluent is discharged to non-sensitive and sensitive areas for the three considered scenarios.

High		Moderate		Low	
Non-sensitive	Sensitive	Non-sensitive	Sensitive	Non-sensitive	Sensitive
RBC MBR	MBR	ISF CWS SBR MBBR RBC MBR EA	SBR MBR	PS ISF CWS SBR TF MBBR RBC MBR EA	PS ISF CWS SBR TF MBBR RBC MBR EA

Fig. 1 shows relevant differences between the 9 evaluated technologies since the maximum TAEC, which corresponds to EA, is approximately 3 times higher than the minimum value corresponding to PS. Focusing on O&MC, PS is characterized for its low costs whereas MBR and EA are heading the list of the most expensive technologies. No significant differences are found in terms of O&MC comparing with the other technologies. Regarding IC, the situation is indeed more diverse, being SBRs the most expensive technology and ISF the low cost choice.

During the decision making process, the parameter to take into account should be the TAEC since it involves both IC and O&MC during the life-span of the WWTP. In this sense, it is possible to identify three main groups. The first group belongs to those technologies with relative low operation and investment cost like PS, ISF and CWS. Higher costs are found for biofilm technologies as TF, MBBR and RBC. Although SBR is not an attached growth process shares similar economical parameters with this second group. Finally, a third group headed by EA and MBR, at the top of the most expensive technologies. However, it is remarkable that although these last two technologies do not present and excessive investment cost in comparison to SBR or others from the second group, their TEC leads both to the most expensive options due to their higher operation costs.

After cost estimation, the next step to carry out a CBA is to calculate the benefits. In a wastewater treatment project, the only benefits with market value are associated with the sale of reclaimed water. In this sense, and according to the scenarios defined in Section 2.3.2, three options for the reuse of the regenerated water have been evaluated (Fig. 2). Based on Spanish Environmental Ministry experiences (MMA, 2007), the value of 0.345 €/m^3 as the market price of regenerated water has been allocated.

In Fig. 2, the net present value calculated for each technology is shown depending on the final destination. Obviously, when there is no sale of reclaimed water, the net profit is negative for all technologies since there is not any income considered. Similarly, when the 50% of the treated water is sold, none of the technologies evaluated is feasible in economic terms since the TAEC is again higher than the benefits. Even in the event that all the treated water is sold, only three technologies, PS, ISF and CWS, would obtain benefits after the proposed expected lifespan for the WWTP. The most favored technologies are obviously those entailing not excessive TAEC, while MBR and EA, both sharing the highest operation costs, appear as the less indicated options for the economic feasibility of the plant.

In order to improve and complete the economic assessment, a second feasibility study has been carried out. In this case, the CBA includes the monetary value of the environmental benefits derived from wastewater treatment. Hence, the new economic feasibility indicator takes into account internal and external impacts and will depend on the amount of pollutants removed from wastewater. Therefore, the case studies presented distinguish between high, moderate and low load in the influent.

By considering the volume of pollutants removed during the treatment process (kg/year), and their shadow prices (€/kg) depending

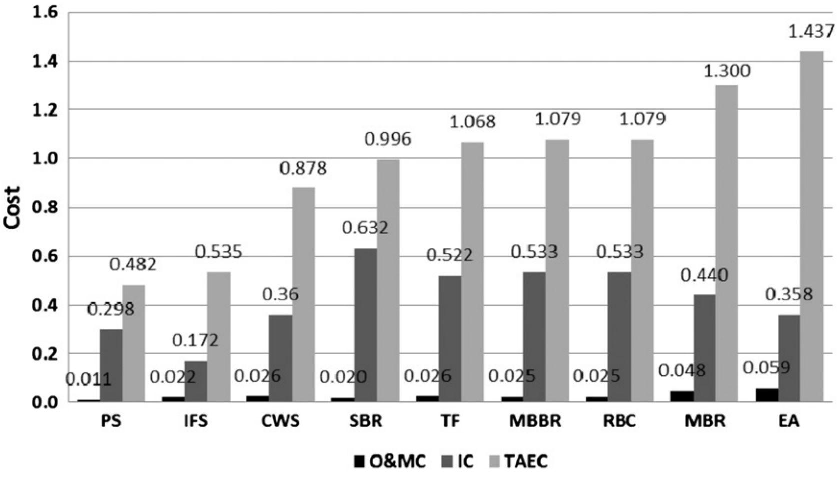

Fig. 1. Cost comparison for the selected treatments.O&M (M€/year); IC (M€) and TAEC (M€).

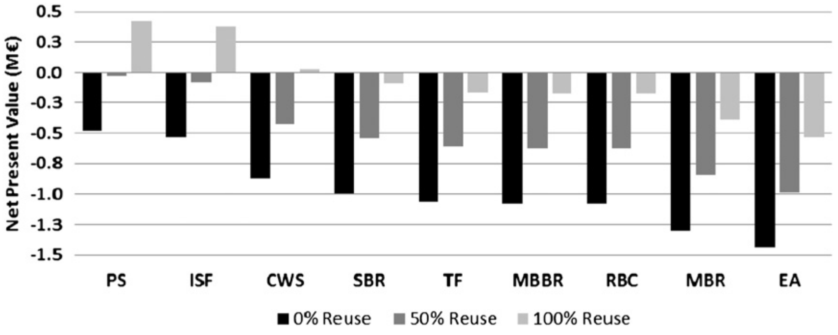

Fig. 2. Net present value without taking into account environmental benefits for the selected wastewater treatments.

on the destination of the effluent (Table 1), we can calculate the environmental benefits from wastewater treatment for the nine scenarios evaluated (Table 6). Note that the environmental benefits are calculated by considering the life-span of the WWTPs (30 years) and are expressed in present value. According to the previous environmental assessment, several technologies are capable of producing an effluent suitable to meet the requirements laid down by the legislation. Therefore, in the decision-making process, economics acquires special relevance.

The greatest environmental benefit is obtained for two specific scenarios: i) reuse of 100% of the regenerated water (since the shadow price of each pollutant is higher for this scenario) and ii) treatment of high loaded wastewater, because in this case eliminations are higher, which contribute to maximize the environmental benefits. Comparing the technologies assessed, MBR and SBR present the highest environmental benefits for the 9 scenarios analyzed, closely followed by PS. On the other hand, the lowest environmental benefit is obtained when the wastewater is treated using CWS and TF technologies.

Figs. 3, 4 and 5 show the net present value for the three scenarios studied (high, moderate and low loads) considering the three options regarding water reuse. The economic assessment has been carried out only for those technologies that are viable from an environmental standpoint.

According to the environmental assessment, treating highly loaded effluents, only RBC and MBR technologies will be feasible if the regenerated water is discharged to non-sensitive areas. On the contrary, when the effluent is discharged into sensitive areas, only MBRs will

Table 6
Estimated environmental benefits (M€) for the selected wastewater treatments depending on the scenario for 30 years.

Technology	High loaded			Moderate loaded			Low loaded		
	100% reuse	50% reuse	0% reuse	100% reuse	50% reuse	0% reuse	100% reuse	50% reuse	0% reuse
PS	8.95	6.94	4.94	6.57	5.11	3.64	2.30	1.77	1.24
ISF	6.78	5.28	3.78	5.07	3.94	2.82	1.75	1.36	0.96
CWS	5.66	4.36	3.07	4.25	3.27	2.30	1.49	1.14	0.79
SBR	9.83	7.59	5.35	6.93	5.36	3.80	2.37	1.81	1.25
TF	5.63	4.35	3.07	4.11	3.18	2.24	1.66	1.27	0.88
MBBR	6.19	4.80	3.41	4.63	3.59	2.54	1.61	1.24	0.87
RBC	6.30	4.86	3.41	4.68	3.61	2.54	1.66	1.27	0.88
MBR	9.84	7.60	5.36	6.93	5.37	3.80	2.39	1.84	1.28
EA	6.19	4.80	3.41	4.79	3.71	2.63	1.66	1.28	0.90

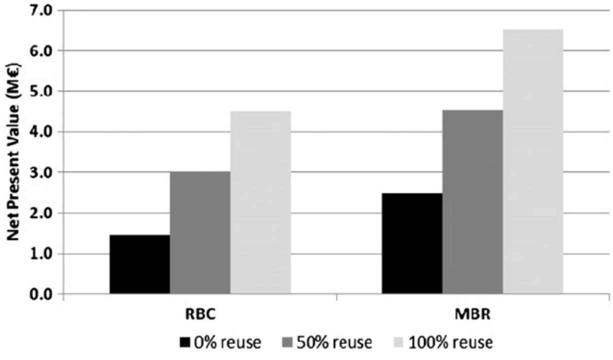

Fig. 3. Net present value taking into account the environmental benefits for the selected wastewater treatments for the high loaded scenarios.

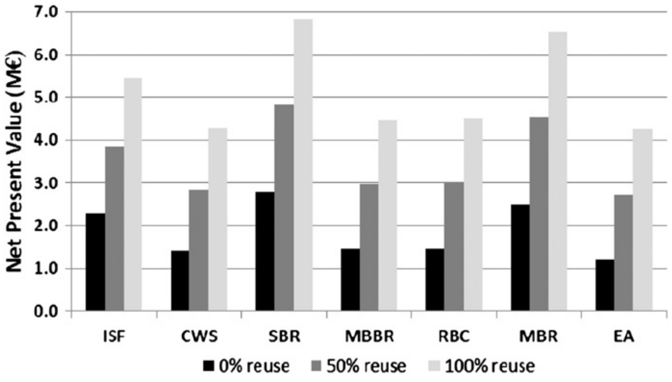

Fig. 4. Net present value taking into account the environmental benefits for the selected wastewater treatments for the moderate loaded scenarios.

stand as the only viable technological choice. From an economic point of view, as shown in Fig. 3, the most suitable technology is the MBR since it presents the highest net present value regardless the percentage of water reused. Moreover, it is observed that both technologies are feasible even if regenerated water is not reused, due to the addition of environmental benefits criteria in the economic analysis.

Fig. 4 shows the economic assessment of feasible technologies from the environmental point of view, when the load of the influent is moderate. It is noted that the net present value of MBR and SBR is clearly higher than the one calculated for other technologies due to their high performance removing pollutants but not for their cost, since for example, MBRs have the second largest TAEC from all the technologies assessed (Fig. 1). However, when the feasibility study includes externalities, the greatest environmental benefits of these technologies allow offset their higher cost.

It is also interesting to note that despite ISF achieve average environmental benefits (Table 6) compared with other technologies, it is on the top rank (third highest net present value) due to its low TAEC.

Remaining technologies (CWS, MBBR, RBC and EA) have very similar net present values being approximately 1.5, 3.0 and 4.5 M€ for 0%, 50% and 100% reuse respectively. Thus, when the treated water is either discharged into non-sensitive or sensitive areas, SBRs generate the highest net present value over the useful life of the WWTP, achieving the quality requirements stated by the legislation.

Whether the load of the influent is low, all technologies evaluated are suitable to achieve the quality requirements required by UWWTD. Thus, Fig. 5 shows the net present value of the 9 technologies assessed for the three reuse scenarios considered. In this concrete scenario, we found negative net present values for 6 out of 9 technologies (CWS, TF, MBBR, CBR, MBR and EA) which consequently, would not be considered viable from an economic point of view. This situation is observed only in case reclaimed water is not sold, even though externalities are included in the feasibility study. In the other two scenarios (50 and 100% water reuse), the net present value of all technologies is positive, i.e., they are economically viable. The technologies with the lowest TAEC (PS and ISF) have the highest net present value. Because the influent load is low, the amount of pollutants removed is small and therefore the environmental benefits do not outweigh the higher costs of other technologies with better performance removing pollution. Hence, if the load of the influent is low, extensive wastewater technologies such as PS, ISF or CWS will be very suitable from both environmental and economic points of view.

4. Conclusions

This work presents an innovative methodology which integrates an environmental decision support system (EDSS) developed to generate feasible flow-diagrams for specific wastewater management scenarios and a pioneer cost–benefit approach based in the estimation of the economic value of the environmental benefits derived from the removal of wastewater pollution. Nine different technologies set-up for the secondary treatment step in small WWTPs have been assessed under nine scenarios regarding wastewater strength (low, moderate or high) and water discharge options (reuse, river discharge or sensitive area).

- In relation to the total equivalent cost, the extended aeration process was the most expensive technology whereas pond systems were the cheapest option.
- Treating low-strength wastewater, all the assessed technologies were feasible, regardless of the destination of the effluent. For moderate/high loads some technologies were not adequate for discharge of the effluent in sensitive areas, being the membrane bioreactors (MBRs) the only option able to produce an effluent suitable for all analyzed scenarios.
- All technologies were found feasible for treating high and moderate loads thanks to the inclusion of environmental externalities in the cost–benefit analysis (CBA). MBRs (high load) and sequencing batch reactors (moderate load) achieved the best rank in this case. On the contrary, only three systems (pond systems, constructed wetlands and intermediate sand filters) were feasible with the conventional CBA approach.
- The reuse of treated effluent was crucial for the feasibility of specific units, particularly in the case of low-strength wastewater. In this sense, extensive wastewater treatment technologies were found very suitable from both environmental and economic points of view, whereas a widely used process, the extended aeration, was one of the less favored options to implement in small agglomerations.

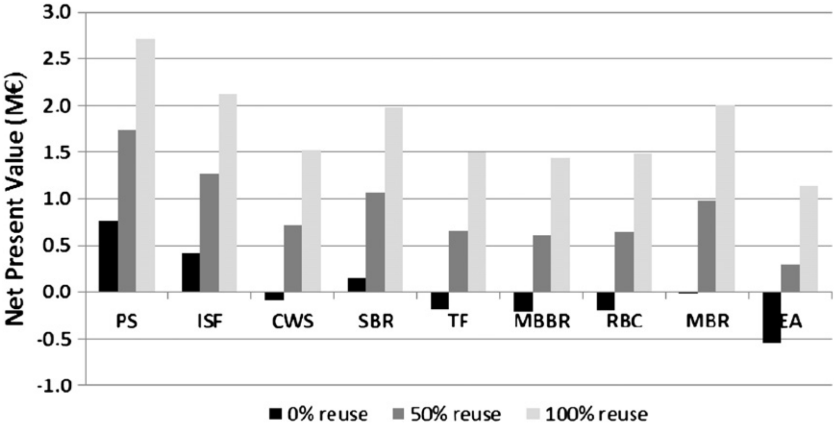

Fig. 5. Net present value taking into account the environmental benefits for the selected wastewater treatments for the low loaded scenarios.

The combination of environmental performance and economic assessment within the EDSS, and the new approach which considers the economic value of the environmental benefits, has proven its usefulness for the development of feasibility studies for wastewater management projects, justifying the implementation of technologies aimed to increase the level of environmental protection.

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