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Cost-Effectiveness Analysis of Sewer Mining versus Centralized Wastewater Treatment: Case Study of Arga River Basin (Spain)

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Cost-Effectiveness Analysis of Sewer Mining versus Centralized Wastewater Treatment: Case Study of Arga River Basin (Spain)

In the context of the EU Water Framework Directive, a Cost-Effectiveness Analysis (CEA) was performed to compare centralized and decentralized wastewater treatment strategies aimed to improve the ecological status of a Spanish river. The implementation of several hybrid membrane bioreactors within the urban framework for sewer mining (SM) was compared with the more common wastewater treatment plant enlargement option. The assessment ranked 6 alternatives based on 12 potential scenarios, aimed at narrowing the uncertainty of the CEA. The cost analysis illustrated that SM is the most expensive option regarding both investment and operation and maintenance costs. However, the effectiveness of the alternatives evaluated depends significantly on the scenarios considered, being SM the most effective in most cases. Finally, the cost-effectiveness ratio showed SM as the best cost-effective alternative. CEA provides an ecological-economic indicator useful to prioritize wastewater treatment alternatives to achieve a given objective.

Keywords: cost-effectiveness analysis; hybrid membrane bioreactor; sewer mining; economics; decentralized wastewater treatment

Introduction

The European Union Water Framework Directive, WFD 2000/60/CE, adopted in year 2000, has supposed a significant reform of water management in Europe. The ultimate aim of the WFD is to achieve the good ecological status of the European water bodies. A key differentiating element is the role that economic tools and principles have been assigned in the WFD (Van Engelen *et al.*2008, Xenarios 2009,Berbel *et al.* 2011, Martín-Ortega 2012). To fulfil the environmental objectives of the WFD, each river water basin should have undertaken a program of measures (PoM) by 2009 which shall be reviewed and updated at the latest 15 years after the date of entry into force of the WFD and every 6 years thereafter. Therefore, the PoM issue has set the water agenda in the last 10 years and will continue to do so.

There are two basic methods to economically assess water management programs namely cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA). Even though CBA has the advantage of measuring the net benefits of each alternative in monetary terms ensuring the economic rationality of investments, within the WFD context, the most widely accepted method is CEA (Berbel *et al.* 2011, Molinos-Senante *et al.* 2011) because it allows for the outcome of the PoM to be evaluated in terms of physical units avoiding the complex processes of economic valuation.

Since CEA was proposed by the WATECO group (European Commission 2003) as a method to assess the PoM linked to the WFD, it has been used across Europe following different methodological approaches for several purposes (Balana *et al.* 2011, Perní and Martínez-Paz 2013). It has been widely applied to assess the cost-effectiveness of several strategies to control diffuse pollution and to mitigate eutrophication (Vinten *et al.* 2012, Mewes 2012, Panagopoulos *et al.* 2013) or to reduce water abstraction in areas of water stress (Blanco-Gutiérrez *et al.* 2011). In short, CEA provides an ecological-economic indicator to compare and evaluate strategies to achieve a certain objective.

One of the most significant environmental problems identified for many Mediterranean water bodies is related to summer low flow episodes leading to nitrogen and phosphorus pollution (European Commission 2007). The main source of these problems comes from water extraction together with pollution from farms and sewage works. Therefore, to achieve the good ecological status of water bodies, two kinds of measures can be implemented: those aimed at saving water and those designed to reduce pollution (Álvarez-Farizo and Hanley 2006). Because it has been accounted that wastewater discharges from wastewater treatment plants (WWTP) can represent a high percentage of the total stream flow -up to 90% during summer time- a significant number of measures within the WFD are aimed at improving wastewater treatment including water reclamation (Molinos-Senante *et al.* 2011).

Sewer mining (SM) consists of extracting wastewater from a sewer system, treating it using physical, chemical and/or biological onsite satellite treatment plants, close to the site for reuse, thus producing reclaimed water suitable for specific end use (McFallan and Logan 2008). It has been considered a sustainable management of water resources option to incorporate into urban development (Chanan and Woods 2006, Suriyachan *et al.* 2012, Dobbie and Brown 2014), also in developing countries (Massoud *et al.* 2009). Advantages of decentralized wastewater treatment (DWWT) versus widely used centralized wastewater treatment (CWWT) strategies are being largely discussed (Kamal *et al.* 2008, Libralato *et al.* 2012, Poustie *et al.* 2014). Nevertheless, most of the studies have focused on comparing both strategies from a technical point of view but not from an economic perspective.

There are a number of technologies validated at large-scale as reliable for obtaining reclaimed water (particularly advanced membrane solutions), unfavourable economics being the claimed obstacle for their application. This is mainly because of the reuse facilities such as transport pipelines, storage tanks and recycled water pumps (Butler and MacCormick 1996). Membrane systems have a high level of automation due to their mechanical configuration and need for continuous fouling management. This can readily be extended to the whole plant, to provide a completely automated system suited for decentralized or satellite treatment facilities (Kraemer *et al.* 2012) and to apply for sewage (Sartor *et al.* 2008) or grey water treatment (Jaboring 2014)in sites without a sewer system.

Membrane bioreactors (MBR) are very efficient for pathogenicity removal and capable of meeting other parameters for irrigation water quality such as heavy metals

(Arévalo *et al.* 2013, Norton-Brandão *et al.* 2013) or endocrine disruptor compounds and pharmaceuticals (Le Minh *et al.* 2010). Besides, hybrid membrane bioreactor (HMBR) incorporates fixed bed biofilm (Rodríguez-Hernández *et al.* 2012) providing some operational advantages over conventional MBR (Rodríguez-Hernández *et al.* 2014).

This contribution is focused on the reduction of the impact of WWTP discharge into a river, by means of: (i) an improvement in its quality (CWWT alternative); (ii) a reduction of its quantity coupled with the release of dammed water (DWWT alternative by SM). These alternatives can significantly increase the resilience status of the receiving water body, even though additional measures for the achievement of the overall WFD requirements could be needed.

The aim of this paper is to compare such alternatives by means of CEA in a case study and illustrate the usefulness of this analysis to prioritize measures.

Membrane technology is applied to obtain reclaimed water in both cases but for different applications: environmental (river discharge) and urban/agricultural uses (irrigation), respectively. The centralized, Advanced Tertiary Treatment (ATT) consists on membrane ultrafiltration, while decentralized management by applying HMBR is the alternative considered as SM technology. For comparison purposes, a centralized, Conventional Tertiary Treatment (CTT) is also evaluated.

To narrow uncertainty and to assess different situations, two discount rates and twelve scenarios with different river and discharge flows and qualities were analysed.

Materials and Methods

Case Study

The hypothetical application case here presented refers to the Arga river basin where the urban area of Pamplona (Navarra, Spain) and its industrial surroundings are located, with a population equivalent of 700,000 inhabitants. The case study is placed in a management and control unit area, identified to facilitate the future implementation of WFD, limited by the points where the Arga converges with the Elorz and the Arakil rivers (Figure 1). The Arga ecotype before the Arakil convergence is defined as "limestone wet mountain river", thereafter, where most of the concerns are noted, its ecotype is defined as a "low mineralised continental Mediterranean axis river" (Castiella *et al.* 2007, Orden ARM/2656, 2008). The Arga River is dammed in the Eugi, a head reservoir that mainly serves to supply fresh water. Finally, Arga empties into the Aragon River, tributary of Ebro River. That river basin, the largest in Spain, is highlighted as an example of the Spanish Mediterranean rivers and streams threats (Cooper *et al.* 2013, Grantham *et al.* 2013).

Figure 1. Case study location: Pamplona, WWTP, Arga River, Elorz River and Arakil River on Arga River Basin, Navarra, Spain.

Concerning wastewater management, 99% of wastewater from the whole area is collected and treated in a single WWTP finally discharging into the river. The WWTP effluent meets the requirement of discharge permit. Nevertheless, during the dry season, the reduction of the water availability implies that a large fraction of the river flow comes from the WWTP discharge or irrigation return-flows, containing mineral and organic loads. Similar problems are frequent in Mediterranean streams (González del Tánago *et al.* 2012). Even though the good quality drinking water supply is guaranteed, the Ebro Hydrographic Confederation (River Basin District Water Authority) stated that 'the Arga water flow, downstream Pamplona, is highly at risk of not meeting the 2015 objective'. A number of studies have been carried out at river basin level with the aim of increasing the Arga water quality. Among the measures proposed, the following are highlighted: increase of the river flow upstream by shutting down certain uses (with due compensation); reduction of the overflow of untreated wastewater by intervention on the sewer system (stormwater tanks); intervention on the diffuse pollution related to agricultural fertilizer or livestock manure runoff; reduction of the impact of WWTP discharge (Castiella *et al.* 2007).

The river flow rate during dry season estimated by the 7Q10 method, which Smakhtin (2001) defined as 'the lowest average flows that occur for a consecutive 7-day period at the recurrence intervals of 10 years', hardly reaches 0.5 m^3/s upstream the WWTP. Meanwhile, the WWTP discharges an average flow of 1 m^3/s. The water qualities of these flows are shown in Table 1.

Table 1. River upstream, WWTP[a], ATT[b] and CTT[c] effluent quality values.

	TSS[d] (mg/L)	BOD[e] (mg/L)	PO_4-P[f] (mg/L)	NH_4-N[g] (mg/L)	NO_3-N[h] (mg/L)
River upstream[i]	21	3	0.02	0.1	0.55
WWTP effluent	8	9	0.90	2.4	6.40
ATT effluent[j]	<1	2	0.10	0.9	1.90
CTT effluent[j]	2	3	0.10	1.0	6.00

a. Wastewater Treatment Plant

b. Advanced Tertiary Treatment

c. Conventional Tertiary Treatment

d. Total Suspended Solids

e. Biochemical Organic Demand

f. Orthophosphate Phosphorus

g. Ammonia Nitrogen

h. Nitrate Nitrogen

i. Daily average values from June to September 2009-2012 (Gobierno de Navarra 2013)

j. Effluent quality based on Asano *et al*. (2007)

CEA Methodology

The steps of CEA as a method to obtain an environmental-economic indicator of each alternative in our case study are as follows:

Identifying or defining alternatives to be evaluated

Two CCWT alternatives are compared with a DWWT alternative and two treatment flow rates (option 1 and option 2) are consider for each one, as summarised on Table 2.

Table 2. Alternatives and options assessed.

Alternatives	Option 1		Option 2	
	Facilities	Q (m^3/s)	Facilities	Q (m^3/s)
ATT[a]	Ultrafiltration Membrane Unit	0.143	Ultrafiltration Membrane Unit	0.250
CTT[b]	Coagulation-flocculation + settling tank + sand filter	0.143	Coagulation-flocculation + settling tank + sand filter	0.250
SM[c]	*HMBR*[d] *1*	*0.001*	*HMBR*[d] *1*	*0.001*
	HMBR[d] *2*	*0.002*	*HMBR*[d] *2*	*0.002*
	HMBR[d] *3*	*0.003*	*HMBR*[d] *3*	*0.003*
	HMBR[d] *4*	*0.007*	*HMBR*[d] *4*	*0.007*
	HMBR[d] *5*	*0.011*	*HMBR*[d] *5*	*0.011*
	HMBR[d] *6*	*0.012*	*HMBR*[d] *6*	*0.012*
	HMBR[d] *7*	*0.020*	*HMBR*[d] *7*	*0.020*
	HMBR[d] *8*	*0.023*	*HMBR*[d] *8*	*0.023*
	HMBR[d] *9*	*0.028*	*HMBR*[d] *9*	*0.028*
	HMBR [d]*10*	*0.036*	*HMBR*[d] *10*	*0.036*
			HMBR[d] *11*	*0.036*
			HMBR[d] *12*	*0.036*
			HMBR[d] *13*	*0.036*
	Total:	0.143	Total:	0.250

a. Advanced Tertiary Treatment

b. Conventional Tertiary treatment

c. Sewer Mining

d. Hybrid Membrane Bioreactor

The DWWT alternative involves the implementation of HMBR as SM facilities in those parks or green areas of the urban area and surroundings traversed by the sewer system where a reclaimed water demand exists (Figure 2). HMBR has been proposed as a suitable technology for sewer mining purposes (Díez *et al.* 2010) and its suitability to serve as a decentralized treatment facility was assessed at pilot-scale treating municipal wastewater (Rodríguez-Hernández *et al.* 2013). HMBR facilities were sized based on the irrigation water demand values calculated by the FAO-Penman Montheit method

(Allen *et al.* 1998), identifying the potential irrigation zones on the city and its surroundings.It should be noted that in Spain water reuse projects are regulated by the Royal Decree 1620/2007 which establishes the accepted uses and quality criteria of the reclaimed water.Hence, direct potable reuse is not permitted in Spain. Option 1 and 2 exemplify two SM implementation levels, which would be achieved as the water demand increased.

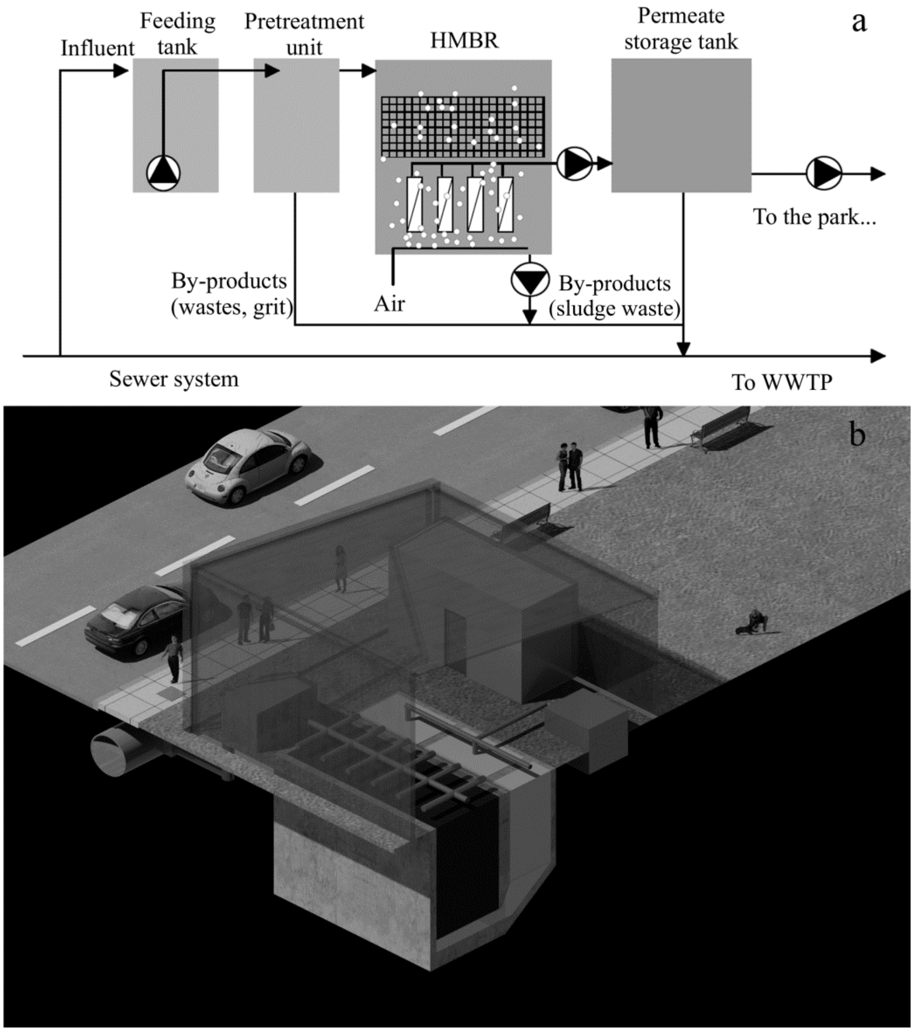

Figure 2. (a) Hybrid Membrane Bioreactor-Sewer Mining (HMBR-SM) facility scheme and components, and (b) a graphic visual representation of a possible HMBR-SM facility implementation.

The CWWT alternatives are based on the implementation of an advanced (ATT) or a conventional tertiary treatment (CTT) to treat the same fraction of WWTP discharge considered in DWWT alternative. ATT consists of ultrafiltration membrane modules while CTT refers to the well-known tertiary treatment consisting of coagulation-flocculation followed by settling tank and sand filter.

Estimating costs of each alternative

Following Aulong *et al.*(2009), Berbel *et al.* (2011) and Molinos-Senante *et al.*(2011), costs are the direct financial costs of each alternative while social costs are excluded. Hence, the CEA is a financial analysis instead of an economic analysis.

The costs of each alternative involve investment costs (IC) and operation and maintenance costs (OMC) adjusted for the time period in which they occur. The total annualized equivalent cost (TAEC) is then calculated (Molinos-Senante *et al.*2012) (Equation (1)):

$$\mathrm{TAEC} = \frac{\mathrm{r}\,(1+\mathrm{r})^{\mathrm{t}}}{(1+\mathrm{r})^{\mathrm{t}}-1}\,\mathrm{IC} + \mathrm{OMC} \qquad (1)$$

where TAECis the total annualized equivalent cost in €/year; ICis the investment cost in €; OMCare the operational and maintenance costs in €/year; ris the discount rate; and t is the useful life of the project or alternative.

The wastewater extracted in the SM alternative must be deducted from the WWTP influent, and it also replaces an amount of fresh water which therefore is not necessary to be treated in the drinking water treatment plant (DWTP). These costs savings are considered in the economic assessment. Thus, the TAEC is as follows (Equation (2)):

$$\mathrm{TAEC} = \frac{\mathrm{r}\,(1+\mathrm{r})^{\mathrm{t}}}{(1+\mathrm{r})^{\mathrm{t}}-1}\,\mathrm{IC} + \mathrm{OMC} - \mathrm{CS} \qquad (2)$$

where CSare the costs savings in €/year.

Estimating the effectiveness of each alternative

The effectiveness index (EI) calculation depends on the defined environmental objectives. In this paper, the effectiveness of each alternative is set as the improvement in the river water quality with respect to the current situation, assessed by a water quality index, WQI (Equation (3)):

$$\mathrm{EI} = \mathrm{WQI\ (alternative)} - \mathrm{WQI\ (current\ state)} \tag{3}$$

Water quality is characterized by the following physicochemical parameters: Suspended Solids, Biochemical Oxygen Demand, Ammonium, Nitrate and Total Phosphorous.

The impact of wastewater discharge into the river is estimated by applying the initial mixing model for all the pollutants considered (Patry and Chapman 1989). The obtained concentrations of pollutants in the river are finally normalized in a single WQI, determined by (Equation (4)):

$$\mathrm{WQI} = \frac{\sum_i \mathrm{C_i P_i}}{\sum_i \mathrm{P_i}} \tag{4}$$

where C_i is the normalized value of the physicochemical parameter i and P_i is the relative weight assigned to parameter i. P_i and C_i with the corresponding range of analytical values, are based on Sanchez *et al.* (2007). The influence of different variables (WWTP discharge flow, river upstream flow, river upstream and WWTP effluent water quality) on EI and cost effectiveness ratio (CER) has been evaluated.

Estimating a cost-effectiveness ratio and ranking alternatives

Once the cost and the effectiveness of each alternative are estimated, a CER is calculated to rank alternatives. The CER represents an environmental-economic indicator of each alternative; therefore it provides very useful information to decision makers for environmental planning.

The standard CER (European Commission 2003) is defined as (Equation (5)):

$$\mathrm{CER} = \frac{\mathrm{TAEC}}{\mathrm{EI}} \tag{5}$$

where CER is the cost-effectiveness ratio, TAEC is the total annualized equivalent cost and EI is the effectiveness index.

The best alternative is the one with the lowest CER while the worst alternative is the one with the highest CER. The other alternatives fall in between based on their CER.

Sensitivity analysis to account for uncertainty

Accounting for uncertainty is important in the development of any CEA since uncertainty, could influence the ranking of management options (Berbel*et al.* 2011, Woods *et al.* 2013). Regarding cost estimations, higher discount rates favour solutions that are weighted toward future spending, i.e., those with relatively high OMC and lower IC. Based on this statement, the use of different discount rates was proposed to study the possible uncertainty in the TAEC, estimated for each of the alternatives. In particular and following the work of Woods *et al.* (2013) the two extreme discount rates of 3% and 9% were applied to narrow uncertainty.

With respect to effectiveness estimation, twelve scenarios (A-L in Table 3) were simulated to assess the sensitivity to water flows and qualities of the analysis. Minimum and average river upstream flow during dry season and average and a hypothetically reduced discharge flow were considered, in addition to real and hypothetically improved river and discharge water qualities in both cases.

Table 3. Scenarios characterization.

	Scenarios											
Variables	A	B	C	D	E	F	G	H	I	J	K	L
River flow (m^3/s)	0.5	1	1	0.5	1	1	0.5	1	1	0.5	1	1
Discharge flow (m^3/s)	1	1	0.5	1	1	0.5	1	1	0.5	1	1	0.5
River quality	R[a]	R[a]	R[a]	H[b]	H[b]	H[b]	R[a]	R[a]	R[a]	H[b]	H[b]	H[b]
Discharge quality	R[a]	R[a]	R[a]	R[a]	R[a]	R[a]	H[b]	H[b]	H[b]	H[b]	H[b]	H[b]

a. Daily average quality values during dry season (see Table 1)

b. Hypothetically improved quality values

Results and discussion

Cost Assessment

This section summarises the results of the economic assessment of the 6 alternatives evaluated in the CEA.Since CTT and membrane filtration are widely spread technologies (Côté *et al.* 2004, De Carolis *et al.* 2007, Gavasci *et al.* 2010, Verrecht *et al.* 2010, Hai and Yamamoto 2011), their cost assessment was carried out based on Spanish cost estimations as developed by JM Puigdengoles (personal communication, Ecosessions, Environment Sessions (Ecocity and Industry), 28 May 2009) and Iglesias *et al.* (2010). Since there is no available data about HMBR costs, a theoretical cost function was developed based on the design and costs estimation of six decentralized HMBR facilities to operate in a range between 0.001-0.046 m^3/s (Equation (6)).

$$y = 7477\, Q^{-0.295} \tag{6}$$

where Q is daily treated flow expressed in m^3/d). The main difference between a conventional MBR and the novel HMBR investment as decentralized technologies is the additional cost of the support for biofilm growing, so HMBR investment cost is considered to be higher than MBR. Then, even though HMBR maintenance is expected to be cheaper due to the reduced fouling rate obtained experimentally (Rodríguez-Hernández *et al.* 2014), in this study OMC values for MBR are applied for HMBR.

As reported in the methodology section, to narrow uncertainty two extreme discount rates (3% and 9%) were applied to calculate the TAEC. The expected life of the proposed wastewater treatment systems was assumed to be 20 years. A global cost savings value of 0.16 €/m^3 (Equation (2)) has been considered to take into account the decrease in the volume of water treated by WWTP and DWTP in SM alternatives. It must be pointed out that although sludge is not treated in the SM HMBR, as it is discharged into the sewer system it finally reaches the WWTP where it must be managed. Thus, savings in WWTP are related with the water line, not with the sludge line. Other savings costs, such as the potential reduction in the WWTP effluent taxes, have not been considered.

The results of the cost assessment are summarized in Table 4. Regarding IC, there are remarkable differences between the three technologies considered. As expected, CTT is by far the cheapest option, which is due to the high investment costs of membrane-based technologies. In addition, ATT is four times less expensivethan the decentralized option. This results can be explained, firstly, considering that the unitary cost (€/m^3/d) is smaller for ATT in the range of flow rates studied (up to 0.250 m^3/s). The effect of economies of scale also increases the difference, because smaller 10 or 13 facilities must be built in the decentralized option, which all together treat the same flow as the single ATT. Finally, the centralized options do not account for the secondary treatment facilities as decentralized ones. As the WWTP providing secondary treatment already exists, only the costs to tertiary treat this effluent are considered. Economies of scale also slightly improve unitary IC for alternatives 2 (0.250 m^3/s) with respect to alternatives 1 (0.143 m^3/s).

Table 4. Costs, effectiveness and cost-effectiveness assessment results for the three alternatives and the two flow rate options evaluated.

Option 1	Option 2

	SM [a]	CTT [b]	ATT [c]	SM [a]	CTT [b]	ATT [c]
IC [d] (10^6 €/y)	10.42	0.42	2.66	16.91	0.71	4.43
OMC [e] (10^6 €/y)	0.92	0.31	0.40	1.60	0.53	0.69
OMC-CS [f] (10^6 €/y)	0.20	0.31	0.40	0.34	0.53	0.69
TAEC 3% g (106 €/y)	0.52	0.32	0.48	0.85	0.55	0.82
TAEC 9% h (106 €/y)	1.14	0.35	0.64	1.86	0.60	1.09
EI i	1.45	1.00	1.51	5.24	1.78	2.69
CER j (TAEC 3%)	0.36	0.32	0.32	0.16	0.31	0.31
CER k (TAEC 9%)	0.79	0.35	0.42	0.35	0.34	0.41

a. Sewer Mining

b. Conventional Tertiary Treatment

c. Advanced Tertiary Treatment

d. Investment Costs

e. Operational and Maintenance Costs

f. Operational and Maintenance Costs-Costs Savings

g. Total Annualized Equivalent Cost, applying 3% discount rate

h. Total Annualized Equivalent Cost, applying 9% discount rate

i. Effectiveness Index

j. Cost-effectiveness Ratio, for the Total Annualized Equivalent Cost applying 3% discount rate

k. Cost-effectiveness Ratio, for the Total Annualized Equivalent Cost, applying 9% discount rate

Considering the same treatment flow, the OMC of the alternatives based on membrane processes (SM and ATT) are higher than those associated with the conventional filtration processes (CTT). This is especially true in the case of SM, with OMC values more than twice those of the other options.

Interestingly, when the cost savings in water and wastewater treatment arising from the SM alternatives are included in the calculation of total costs, SM options turn out to have a TAEC in the range of that of ATT, as long as the discount rate is around 3%. It has to be noted however that applying the higher discount rate (9%), SM cost nearly doubles that of ATT, in accordance with the high capital costs involved. Therefore, this case study illustrates the importance of considering, during the decision making process, the TAEC as representative parameter of the total costs.

The cost assessment of the 6 alternatives evaluated is consistent with previous studies (Gavasci*et al.* 2010, Molinos-Senante *et al.* 2013) which conclude that conventional filtration is a technology with low IC and OMC while membrane technologies are the most expensive ones.

Effectiveness Assessment

The resultant effectiveness indexes (EI) for the six alternatives are also displayed in Table 4 As expected, the Arga water quality improvement by reducing the WWTP discharge impact was limited by the slight reduction of pollutants that can be achievable with respect to the current WWTP effluent.

It resulted that SM option would improve river water quality twice the ATT option when 25% of the average WWTP discharge flow rate is treated (alternative SM2 versus ATT2). In contrast, SM1 and ATT1 effectiveness resulted fairly similar. This can be explained by considering the assessment method implemented in this work. To obtain the WQI, the parameter C_i varies from 0 to 100 in relation with specific ranges of concentration values for each physicochemical parameter. If the concentration value is above or below the fixed maximum or minimum limit of the range (boundary concentration values), no effect on the WQI is observed. For some parameters, centralized alternatives stay below that boundary value being C_i=0 in these cases. So, that reduction of pollutants is not quantified. If the minimum boundary value is exceeded, WQI will vary significantly revealing the reduction of the river pollution.

In this case study, SM is accomplished by releasing dammed water. In other words, SM alternative makes possible to return a part of the dammed river water to its course. As mentioned, current WWTP actually reaches high effluent quality including nutrient removal, which explains why SM1 and ATT1 obtain very similar river water quality values. However, in those alternatives where treated or released flow increases

(SM2 and ATT2), differences between SM and ATT efficiency also increase thus overcoming the WQI range lower thresholds and resulting in a higher efficiency. On the other hand, CTT alternatives resulted in slightly smaller EI than ATT alternatives, as expected considering the slightly worst effluent quality of CTT technologies.

The sensitivity analysis of EI to variations in the main factors (flows and qualities of both the river and the discharge, and the percentage of wastewater tertiary treated), is displayed in Figure 3. SM resulted to be clearly the most effective alternative for all the scenarios analyzed except for alternative 1 in scenario A. On the other hand, CTT was always the less effective alternative.

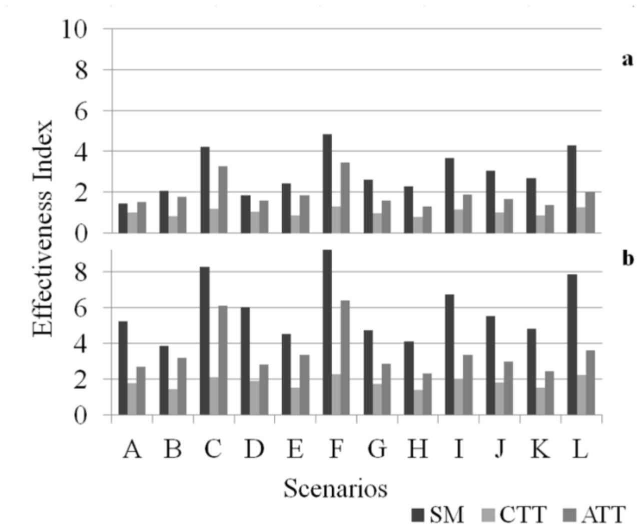

Figure 3. Sensitivity analysis results for Effectiveness Index (a) option 1 and (b) option 2.

Scenario A is defined as the worst situation, with the most adverse values in the dry season. That means that the current discharge flow and river and discharge qualities, with the minimum river flow calculated with 7Q10 method, are considered. With reference to this scenario, if the river flow is considered greater than WWTP effluent flow (scenarios C, F, I and L) SM effectiveness highly increases, in a higher extent for SM2 than for SM1. ATT effectiveness is also positively affected in these cases, but such benefit is slight when higher quality for the river upstream or WWTP effluent (I and L) is considered. These results support that SM effectiveness lies on the dilution effect of released dammed water.

Another important point is the river quality values. EI decreases in scenariosB, E, H and K which consider equal flowrate for river upstream and WWTP effluent, revealing how close effluent quality and the river upstream quality are.

Cost-Effectiveness Ratio (CER)

The CER of each alternative is also shown in Table 5. Results for TAEC 3% show that SM2 alternative is the most cost-effective solution in this case study while ATT and CTT are almost equivalent. Conventional centralized technologies resulted slightly less effective than ATT, but with a significant lower cost compared to the advanced one. It suggests that, in this case study, membrane technology is not economically suitable when the reclaimed water is finally discharged into the river.

As well as for the EI, the same twelve scenarios were proposed and simulated to check how the CER is influenced on the one hand by the river and WWTP effluent quality and quantity and on the other hand by the discount rate applied, as displayed in Figure 4.

Economic input variables such as the cost of labour, materials, equipment, land and electricity notably affect on MBR costs (Young *et al.* 2013). Both extreme discount rates express that costs variability, depending on factors beyond.

Considering the lower extreme discount rate (Figures 4a and 4b), it benefits on TAEC result for those facilities involving high investment cost. Hence, the decentralized alternative treating 25% of the average WWTP flow rate (SM2) was significantly better than the one treating only 14% (SM1), especially in scenarios A and D. That means that for SM alternatives, high sensitivity was observed when modifying the river and WWTP flow rate, and the quality of the WWTP discharge, while the modification of the river water quality didn't affect significantly the CER related to SM alternatives. Besides, SM2 was the most cost-effective alternative for all cases, while SM1 was the next one for all cases, excluding scenario A. It suggests that sewer mining could be a suitable alternative in this case study.

Regarding the advanced centralized alternatives (ATT1 and ATT2), in general their CER were significantly higher compared to SM1 and SM2. When comparing ATT2 to ATT1, both of them resulted similarly cost-effective for all the scenarios. The sensitivity of the CER was almost the same for both advanced alternatives. However, when the river flow rate was increased, not increasing the WWTP effluent quality (scenarios B, C, E and F), the CER of both advanced alternatives dropped significantly below the CER corresponding to conventional alternatives. For the remaining scenarios, the obtained CER for conventional and advanced alternatives were fairly similar or slightly higher in the case of conventional ones. It suggests that, in this case study, the suitability of membrane technology as a centralized post-treatment could be cost-effective compared to conventional alternatives in some specific cases.

When the higher extreme discount rate is considered (Figures 4c and 4d), CER results drastically change. Sewer mining seems to be the least cost-effective alternative, especially in scenarios A and D treating 14% (SM1). In contrast, SM2 in these scenarios is slightly more cost-effective than ATT2. As already stated, SM presents high sensitivity when modifying the river and WWTP flow rates, and the quality of the WWTP discharge stream.

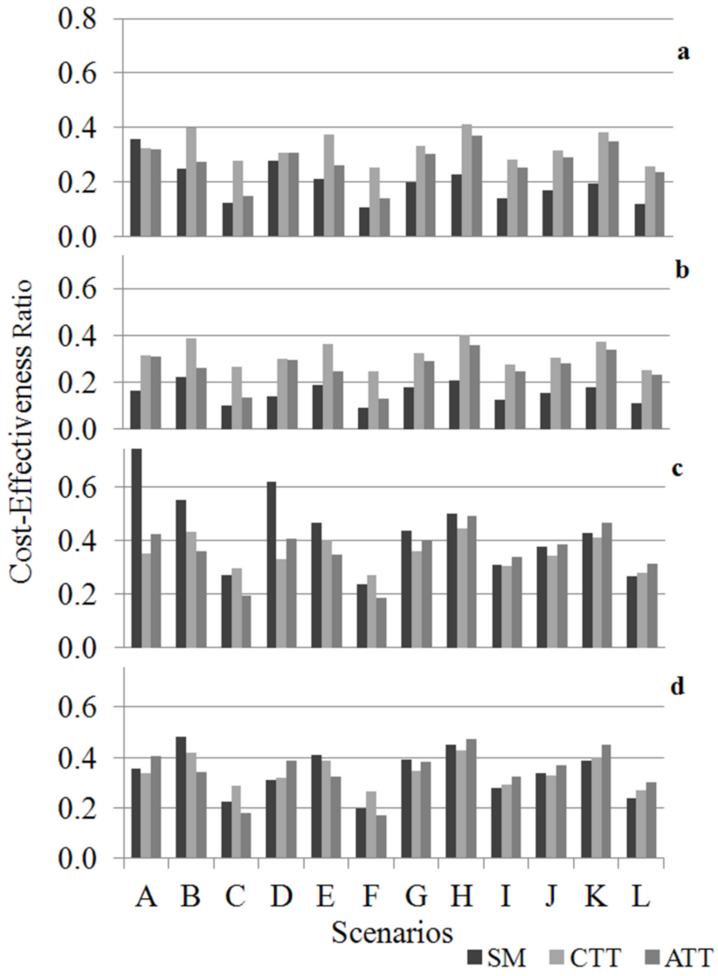

Figure 4. Sensitivity analysis results for Cost-effectiveness Ratio applying (a) Total Annualized Equivalent Cost (TAEC) and 3% discount rate in option 1, (b) TAEC 9% in option 1, (c) TAEC 3% in option 2 and (d) TAEC 9% in option 2.

Conclusions

In this paper, cost effectiveness analysis is illustrated as a useful analysis tool to prioritize alternatives. It is applied in a Spanish Mediterranean river basin case study in order to compare wastewater treatment alternatives with the aim of improving river water quality, as WFD requires.

This case study may illustrate a pattern of urban development in cities within a context of water scarcity, where increasing demand and decreasing supply take place. New tools are needed to support the stakeholders in the decision-making process, in order to develop integrated water resources management plans in which alternatives of different nature are considered.

Cost Effectiveness Ratio results show that sewer mining is more cost-effective than centralized alternatives (upgrading the WWTP), although based on local construction costs. Nevertheless, the present paper allows for a useful assessment and could also be adapted to better data, if available.

The analysis underlines that those alternatives involving water reclamation technologies give rise to a new water supply, and they therefore lead to cost savings that should be taken into account during CEA implementation. Decentralized management options like sewer mining are often dismissed due to the capital costs involved, but it is suggested that they could be more cost-effective than conventional ones.

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