Journal of Environmental Management 92 (2011) 3091–3097

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Cost–benefit analysis of water-reuse projects for environmental purposes: A case study for Spanish wastewater treatment plants

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ARTICLE INFO

Article history:
Received 1 December 2010
Received in revised form
5 July 2011
Accepted 22 July 2011

Keywords:
Directional distance function
Cost–benefit analysis
Economic feasibility
Environmental benefit
Shadow prices
Wastewater reuse

ABSTRACT

Water reuse is an emerging and promising non-conventional water resource. Feasibility studies are essential tools in the decision making process for the implementation of water-reuse projects. However, the methods used to assess economic feasibility tend to focus on internal costs, while external impacts are relegated to unsubstantiated statements about the advantages of water reuse. Using the concept of shadow prices for undesirable outputs of water reclamation, the current study developed a theoretical methodology to assess internal and external economic impacts. The proposed methodological approach is applied to 13 wastewater treatment plants in the Valencia region of Spain that reuse effluent for environmental purposes. Internal benefit analyses indicated that only a proportion of projects were economically viable, while when external benefits are incorporated all projects were economically viable. In conclusion, the economic feasibility assessments of water-reuse projects should quantitatively evaluate economic, environmental and resource availability.

1. Introduction

Europe has witnessed growing levels of water stress, both in terms of scarcity and the deterioration of quality. This situation has prompted many municipalities to identify more efficient uses of water resources, including more widespread acceptance of the use of non-conventional water sources (Bixio et al., 2006). In this sense, water reuse has emerged as the most viable alternative since it performs two key functions: (i) increasing water supply and (ii) reducing pollution by discharging less wastewater into the environment (Hochstrat et al., 2007). These are the reasons for recognition of the growing importance of water reuse in areas that are subject to harsh conditions with respect to water stress or seasonal water demand (Salgot, 2008; Miller, 2006).

Feasibility studies are essential tools in the decision making process for the implementation of wastewater-reuse projects (AQUAREC, 2006). The methods that are commonly applied in this area typically show significant bias toward the strictly technical field. Fortunately, in recent decades there has been rapidly increasing acknowledgment in the need to implement "sustainability" in wastewater management (Lim et al., 2008). According to the concept of sustainable development, a water-reuse project must comply with environmental, socio-cultural and economic needs to be deemed sustainable (Balkema et al., 2002).

Economic considerations are therefore of high importance when assessing the potential of water-reuse projects (Asano, 1998, 2007). Furthermore, the Water Framework Directive (WFD) assigns significance to economic analysis to achieve suitable water resource management. However, economic feasibility of research on wastewater regeneration and reuse remains the least studied component. In part, this is because internal and external economic impacts of environmental based projects should be identified and quantified when analyzing economic feasibility, such as for water reuse (Molinos-Senante et al., 2010). While internal impacts may be easily translated into monetary units, external effects (or externalities) are not considered by the market, thus requiring economic valuation methods for their quantification. As a result, a series of statements about the advantages of wastewater regeneration and reuse are often presented, without supporting economic quantification. Consequently, the true benefits and costs of many projects are not properly evaluated (Seguí, 2004).

Nevertheless, there is growing interest in the monetary valuation of these externalities. For example, the cost–benefit analysis (CBA) of Godfrey et al. (2009) with respect to a system of greywater

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doi:10.1016/j.jenvman.2011.07.023

reuse in India. The monetary values of external benefits and costs, in terms of the environment and health, were derived by using scientific references (North and Griffin, 1993; Hanley and Spash, 1993; Field, 1997; Curry and Weiss, 1993; Hutton and Haller, 2004). The authors used conventional economic methods, such as hedonic valuation and contingent valuation. In comparison, Seguí et al. (2009) used travel costs to determine the environmental benefits arising from wastewater reuse for a wetland restoration project. Furthermore, Chen and Wang (2009) proposed a net benefit value model for cost–benefit evaluation of water-reuse projects in a residential area of China. The benefits relating to the environment were calculated by applying a mathematical equation developed by the Chinese Ministry of Environmental Protection.

The concept of directional distance function has been suggested (Färe et al., 1993, 2001, 2006) as an alternative to conventional methods of economic valuation (stated preference methods). This concept aims to calculate shadow price value of undesirable outputs arising from productive activities that have no market value. This method is derived from a "costs production perspective", which contrasts to the usual methods that are linked to a "demand perspective" (Diaz-Balteiro and Romero, 2008).

The advantages of the directional distance approach include the following: (i) shadow prices may be used to determine how much income would be gained if some of the resources were privatized; (ii) authorities may use the information provided by shadow prices to set rates for using environmental services, or to compare current rates with the marginal revenue generated (Färe et al., 2001); (iii) this methodology may help society understand the benefits generated as a result of environmental improvement programs; and (iv) shadow price models may offer economists further insights into estimated measures of willingness to pay produced by alternative models such as the contingent valuation method, or capitalization methods (Färe et al., 2001). Furthermore, shadow price quantification is relatively inexpensive when compared to surveying processes.

With the aim to integrate economic and environmental aspects in the design and implementation of wastewater-reuse projects, the current study presents a method to assess the economic feasibility of water-reuse projects taking both internal and external impacts into consideration. This was achieved by using the concept of shadow prices of undesirable outputs arising from the water regeneration process. The proposed methodological approach is subsequently used to assess the economic feasibility of various wastewater-reuse projects for environmental purposes in the Valencia region on the Mediterranean coast of Spain.

2. Methodology for assessing the feasibility of water-reuse projects

2.1. Background

Economic feasibility studies of wastewater-reuse projects should be completed by using conventional methodologies of economic analysis, such as cost–benefit analysis (CBA) (van der Bruggen et al., 2009). According to Seguí (2004) and Hernández et al. (2006), total benefit is calculated by considering internal benefit, external benefit, and opportunity cost, as shown in Equation (1).

$$B_{\mathrm{T}} = B_{\mathrm{I}} + B_{\mathrm{E}} - \mathrm{OC} \tag{1}$$

where B_{T} is the total benefit (total income minus total costs); B_{I} is the internal benefit (internal income minus internal costs); B_{E} is the external benefit (positive externalities minus negative externalities); and OC is the opportunity cost. CBA originates from the premise that a project is only economically feasible if all incomes exceed the aggregate costs. In other words, according to Equation (1) if the $B_{\mathrm{T}} > 0$, whereby the best option offers the highest total benefit.

2.2. Internal benefit

Internal impacts are directly linked with the process of wastewater regeneration, and subsequent reuse. The internal benefit represents the difference between internal income and internal costs. Internal income includes revenues from the sale of regenerated water and other recovered sub-products. If reclaimed water is used in agriculture, the nitrogen and phosphorus contents in water offer a saving in fertilizer costs. Alternatively, if reclaimed water is intended for environmental purposes, these nutrients may be recovered during wastewater treatment and subsequently sold for other uses. Internal costs are the result of the sum of investment costs (i.e. land, civil works, machinery and equipment, pipes, facilities), operating and maintenance costs (i.e. staff, energy, sludge management, reagents), financial costs, and taxes of both the wastewater treatment plant, WWTP and distribution network of the regenerated water. Internal benefit is expressed as:

$$B_{\mathrm{I}} = \sum_{t=0}^{T}[(\mathrm{AVW}_t{*}\mathrm{SPW}_t) + (\mathrm{ACP}_t{*}\mathrm{SPP}_t) + (\mathrm{ACN}_t{*}\mathrm{SPN}_t) - (\mathrm{IC}_t + \mathrm{OMC}_t + \mathrm{FC}_t + T_t)] \tag{2}$$

where B_{I} = internal benefit (€); AVW = annual volume of reclaimed wastewater (m^3); SPW = selling price of reclaimed wastewater (€/m^3); ACP = annual volume of recovered phosphorus (kg); SPP = selling price of recovered phosphorus (€/kg); ACN = annual volume of recovered nitrogen (kg); SPN = selling price of recovered nitrogen (€/kg); IC = investment costs (€); OMC = operational and maintenance costs (€); FC = financial costs (€); T = taxes (€); and t = year.

All the items considered in Equation (2) should be expressed as present monetary values. Therefore, it is necessary to apply the discount rate[3] "*d*" to each term that allows the inflation rate and other risks (see footnote as an example to the selling price of reclaimed wastewater) to be compensated.

2.3. External benefit

Externalities are costs or benefits that occur when the actions of firms and individuals have an effect on people other themselves without economic compensation. Water-reuse projects create a number of externalities, including negatives such as biological and chemical risks and positive ones as health benefits, education services, and especially environmental benefits. The U.S. Environmental Protection Agency (EPA) argues that the use of reclaimed water provides the following environmental benefits (EPA, 1998): (i) may decrease the diversion of freshwater from sensitive ecosystems, (ii) decreases discharge to sensitive water bodies, (iii) recycled water may be used to create or enhance wetlands and riparian habitats, and (iv) may reduce and prevent pollution.

According to Equation (1), an economic feasibility study of wastewater-reuse projects requires the consideration and

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[3] $\mathrm{SPW}_t = \overline{\mathrm{SPW}}_t{*}(1+d)^{-t}$, where: SPW_t = present selling price of reclaimed wastewater; $\overline{\mathrm{SPW}}_t$ = nominal selling price of reclaimed wastewater; d = discount rate; and t = year.

quantification of internal and external impacts. The external benefit is expressed as:

$$B_{\mathrm{E}} = \sum_{t=0}^{T} (\mathrm{PE}_t - \mathrm{NE}_t) \tag{3}$$

where B_{E} = external benefit (€); PE = positive externalities (€); NE = negative externalities (€); and t = year.

Similar to internal benefit, both positive and negative externalities should be expressed as present monetary values. Hence, the discount rate "d", which was defined in Section 2.2 should be applied to each of the two terms.

The estimation of external impacts is the main obstacle during economic feasibility studies of wastewater-reuse projects due to there being no market for this type of goods in most cases. Thus, decisions regarding wastewater reuse are generally based on the financial costs of the project, without consideration being given to non-monetary impacts, such as environmental protection.

The quantification of shadow prices for the undesirable outputs obtained during the productive process provides an alternative method for the valuation of externalities. According to Hernández-Sancho et al., (2010) and Molinos-Senante et al. (2010), wastewater treatment may be considered as a production process, in which a desirable output (clean water) is obtained together with a series of pollutants (i.e. organic matter, phosphorus). The contaminants extracted from wastewater are considered undesirable outputs because their uncontrolled disposal would cause negative impacts on the environment. Therefore, the methodology proposed by Färe et al. (2006) may be used to quantify the environmental benefits arising from water reuse.

The shadow price valuation methodology (for a full description of this methodology, see Färe et al., 2006) is based on the concept of the directional distance function. This function generalizes the concept of conventional production functions and measures the difference between the outputs produced in the process that is under study and the outputs of the more efficient process. Inputs are denoted by $x = (x_1,\ldots, x_N) \in R^N$, desirable outputs by $y = (y_1,\ldots,y_M) \in R^M$ and undesirable outputs by $b = (b_1,\ldots,b_J) \in R^J$. Let $g = (g_y, g_b)$ be a directional vector and assume $g \neq 0$. The directional distance function is defined as:

$$D_0\left(x, y, b; g_y, g_b\right) = \mathrm{Max}\left\{\beta : \left(y + \beta g_y, b - \beta g_b\right) \in P(x)\right\} \tag{4}$$

The distance function provides the maximum expansion of desirable outputs and the maximum contraction of undesirable outputs that is feasible given the technology $P(x)$. Directional distance function parameterization is carried out with a quadratic form (Chambers, 1998). Hence, unlike the translog function, it may be restricted to satisfy the translation property. Given the directional vector $g = (1,1)$ and assuming $k = 1,\ldots,K$ treatment plants operating in $t = 1,\ldots,T$ periods, the quadratic directional distance function for WWTP k in period t is:

$$\begin{aligned} D_0^t\left(x_k^t, y_k^t, b_k^t; 1, 1\right) = {} & \alpha + \sum_{n=1}^{N} \alpha_n x_{nk}^t + \sum_{m=1}^{M} \beta_m y_{mk}^t + \sum_{j=1}^{J} \gamma_j b_{jk}^t + \frac{1}{2} \sum_{n=1}^{N} \sum_{n'=1}^{N} \alpha_{nn'} x_{nk}^t x_{n'k}^t + \frac{1}{2} \sum_{m=1}^{M} \sum_{m'=1}^{M} \beta_{mm'} y_m y_{m'} + \frac{1}{2} \sum_{j=1}^{J} \sum_{j'=1}^{J} \gamma_{jj'} b_j b_{j'} \\ & + \sum_{n=1}^{N} \sum_{m=1}^{M} \delta_{nm} x_{nk}^t y_{mk}^t + \sum_{n=1}^{N} \sum_{j=1}^{J} \eta_{nj} x_{nk}^t b_{jk}^t + \sum_{m=1}^{M} \sum_{j=1}^{J} \mu_{mj} y_{mk}^t b_{jk}^t \end{aligned} \tag{5}$$

For parameter estimation $(\alpha_0, \alpha_n, \alpha_{nn}, \beta_m, \beta_{mm'}, \gamma_j, \gamma_{jj}, \delta_{nm}, \eta_{nj}, \mu_{mj})$ the sum of the distance between the production frontier and individual observations for each period should be minimized. This may be expressed as:

$$\begin{aligned} & \mathrm{Min} = \sum_{t=1}^{T} \sum_{k=1}^{K} \left[D_0^t\left(x_k^t, y_k^t, b_k^t; 1, 1\right) - 0\right] \\ & \text{s.t.:} \\ & \text{(i)}\ D_0^t\left(x_k^t, y_k^t, b_k^t; 1, 1\right) \geq 0,\ k = 1,\ldots,K,\ t = 1,\ldots,T, \\ & \text{(ii)}\ \frac{\partial D_0^t\left(x_k^t, y_k^t, b_k^t; 1, 1\right)}{\partial b_j} \geq 0,\ j = 1,\ldots,J,\ k = 1,\ldots,K,\ t = 1,\ldots,T, \\ & \text{(iii)}\ \frac{\partial D_0^t\left(x_k^t, y_k^t, b_k^t; 1, 1\right)}{\partial y_m} \leq 0,\ m' = 1,\ldots,M,\ k = 1,\ldots,K,\ t = 1,\ldots,T, \\ & \text{(iv)}\ \frac{\partial D_0^t\left(x_k^t, y_k^t, b_k^t; 1, 1\right)}{\partial x_n} \geq 0,\ n = 1,\ldots,N, \\ & \text{(v)}\ \sum_{m=1}^{M} \beta_m - \sum_{j=1}^{J} \gamma_j = -1;\ \sum_{m'=1}^{M} \beta_{mm'} - \sum_{j=1}^{J} \mu_{mj} = 0;\ m = 1,\ldots,M; \\ & \sum_{j'=1}^{J} \gamma_{jj'} - \sum_{m=1}^{M} \mu_{mj} = 0;\ j = 1,\ldots,J;\ \sum_{m=1}^{M} \delta_{nm} - \sum_{j=1}^{J} \eta_{nj} = 0;\ n = 1,\ldots,N; \\ & \text{(vi)}\ \alpha_{nn'} = \alpha_{n'n};\ \beta_{mm'} = \beta_{m'm};\ m \neq m',\ \gamma_{jj'} = \gamma_{j'j},\ j \neq j' \end{aligned} \tag{6}$$

Because the methodology used to quantify the environmental benefits is derived from the so-called frontier methodologies, the objective function should minimize the distance between the production frontier and each observation (Färe et al., 1993).

The deduction of shadow prices for undesirable outputs means assuming that the shadow price of an absolute desirable output coincides with market price. Equation (7) enables to obtain the value of each undesirable output:

$$q_j = -p_{\mathrm{m}} \frac{\partial D_0(x, y, b; g)/\partial b_j}{\partial D_0(x, y, b; g)/\partial y_{\mathrm{m}}} \tag{7}$$

where q_j = shadow price of each pollutant; p_{m} = market price of desirable output; b_j = each of the undesirable output and; y_{m} is the desirable output.

Once the shadow price of undesirable outputs in €/kg is quantified (Eq. (7)) and the amount of the different pollutants removed per cubic meter of regenerated water is known, the monetary value of the positive externalities in €/m^3 can be obtained directly (Eq. (8)).

$$\mathrm{PE} = \sum_{j=1}^{J} q_j \mathrm{VP}_j \tag{8}$$

where PE = positive externalities (€/year) q_j = shadow price of the pollutant j (€/kg) and VP$_j$ = volume of the pollutant j removed (kg/year).

2.4. Opportunity cost

The opportunity cost is defined as the value of goods in terms of the alternative use of these goods being lost. Therefore, the opportunity cost will be given by the specific use that provides the greatest economic efficiency. In water-reuse projects, the opportunity cost generally refers to land on which the WWTP is placed. Usually this land is not of great value, but there may be situations where alternative uses may have generated significant incomes.

Opportunity cost should also be expressed in the present value. Thus, the discount rate "*d*", which was defined previously, should be applied. By replacing Equations (2) and (3) in the initially proposed general Equation (1), the following expression is obtained:

$$B_{\mathrm{T}} = \sum_{t=0}^{T}[(\mathrm{AVW}_t{*}\mathrm{SPW}_t)+(\mathrm{ACP}_t{*}\mathrm{SPP}_t)+(\mathrm{ACN}_t{*}\mathrm{SPN}_t)-(\mathrm{IC}_t +\mathrm{OMC}_t+\mathrm{FC}_t+T_t)+(\mathrm{PE}_t-\mathrm{NE}_t)-\mathrm{OC}_t] \quad (9)$$

3. Case study: water-reuse projects in the Valencia Region

The theoretical methodology is implemented using several water-reuse projects located in the Valencia region. This region is situated on the Spanish Mediterranean coast, covering an area of 23,295 km^2 and including a population of 5,094,675 inhabitants. The regional authority responsible for the construction and operation management of sewerage networks and WWTPs is the "Entidad Pública de Saneamiento de Aguas Residuales de la Comunidad Valenciana (EPSAR)". The total number of facilities in service during 2009 was 443, with the volume of treated water being 502.9 hm^3/year, with a 6,300,000 population equivalent (PE) the average pollutant load (EPSAR, 2009). Water demand in the study region is about 3700 hm^3/year, while water supply is 3350 hm^3/year. This information implies that there is a water deficit of 350 hm^3/year. Therefore, the reuse of reclaimed water is emerging as a key alternative water resource to secure adequate water supplies. Today, 61.4% (i.e. 308.8 hm^3/year) of the total treated water in the Valencia region is reused for agricultural, industrial and environmental purposes.

According to the Spanish Royal Decree 1620/2007, reclaimed water should meet different quality criteria based on destination and use. Thus, the type of treatment required to achieve this quality is also different. Consequently, there are three major treatment types for wastewater regeneration in the Valencia region. The first type comprises secondary treatment, which is accomplished by biological process and sedimentation, allowing the removal of organic material. This treatment is applied when reclaimed water is intended for reuse in industrial or agricultural purposes, as long as its salt content is low. The second type comprises tertiary treatment, which permits the removal of specific contaminants not normally removed during conventional secondary treatments, such as nutrients. This treatment is applied when reclaimed water is intended for reuse in environmental purposes. The third type comprises advanced treatment, which includes filtration processes, such as microfiltration or reverse osmosis to reduce salt content of regenerated water allowing use for agricultural purposes without restrictions. In the study region, 44% of reused water (135.9 hm^3/year) is regenerated by secondary treatment, 49% (151.3 hm^3/year) by tertiary treatment, and 7% (21.6 hm^3/year) by advanced treatment (EPSAR, 2009).

This study analyzes the economic feasibility of 13 of the 35 WWTPs that reuse water for environmental purposes, in the Valencia region, with total reused water flow rates of approximate 50 hm^3/year. This sample was selected due to the valuation methodology of shadow prices requiring the sample data to be as homogeneous as possible, with respect to both the technology used for water regeneration and in the treatment capacity of the plant. All of the 13 selected WWTPs carry out a similar process to obtain a desirable output which is the reclaimed water and four undesirable outputs: suspended solids (SS); nitrogen (N); phosphorus (P); and organic matter measured as chemical oxygen demand (COD). According to external benefit valuation methodology (Section 2.3), the desirable output is denoted as $y=(y_1)$ while the undesirable outputs as $b=(b_1, b_2, b_3, b_4)$. The required inputs are energy, staff, reagents, waste management, and others. These variables are detailed in Table 1. The statistical information is obtained from EPSAR for the year 2009.

4. Results and discussion

4.1. Internal benefit

Based on the methodology described in Section 2, internal benefit is the difference between internal income and internal cost. In the study region, the WWTPs simply remove nitrogen and phosphorus from wastewater, with no technology in place for their recovery and reuse. Hence, in our empirical application nutrients have not market price. As a result, the term internal income only includes the revenues earned from the sale of regenerated water. According to Hernández-Sancho et al. (2010), and as reported by the Spanish wastewater authorities, the reference price of reclaimed water for environmental purposes is 0.9 €/m^3.

In relation to internal costs, investment costs depend largely on the available technology and size of the WWTP. As a first approximation, EPSAR (2009) estimates that the mean investment costs of WWTPS in the Valencia region with secondary and tertiary treatment are 180 € per PE. In comparison, the quantification of operating and maintenance costs is straightforward because they are strictly controlled by the WWTPs operating companies. In general, these costs are influenced by the effluent quality. In this respect, the reuse of wastewater for environmental purposes requires tertiary treatment. Based on EPSAR (2009), the mean operating costs of the

Table 1
Sample description for the 13 WWTPs.

		Mean	Standard deviation	Minimum	Maximum
Inputs (€/m^3)	Energy	0.072	0.021	0.013	0.096
	Staff	0.075	0.040	0.022	0.170
	Reagents	0.030	0.019	0.009	0.066
	Waste management	0.025	0.011	0.007	0.035
	Others	0.008	0.006	0.003	0.021
Desirable output (m^3/year)	Wastewater treated	3,166,290	2,400,849	2,896,075	5,095,000
Undesirable outputs (kg/m^3)	SS	0.380	0.216	0.103	0.588
	N	0.028	0.007	0.005	0.064
	P	0.006	0.003	0.002	0.013
	COD	0.667	0.313	0.255	1.021

Valencian WWTPs with this type of treatment are 0.26 € per m^3. Similarly, in addition to the investment and operation costs of WWTPs, the cost of reclaimed water distribution should also be quantified and incorporated in the evaluation for a fully feasibility study. These costs are highly variable, due to their being dependent mainly on the transportation distance of reclaimed water and the level of head against which it is pumped.

Using the WWTP number 1 as an example, a detailed analysis is shown to demonstrate how the internal benefit can be calculated. The annual volume of reclaimed water in WWTP 1 (AVW) is 8,476,760 m^3/year and the selling price of the reclaimed water (SPW) is 0.9 €/m^3. According to Eq. (2), the internal income of WWTP 1 is 7,629,084 €/year. The investment costs for this WWTP are 3,440,184 €/year. Operation and maintenance costs include the following items: energy (420,930 €/year); staff (525,848 €/year); reagents (243,073 €/year); waste management (558,438 €/year); and others (327,276 €/year). Therefore, the total operation and maintenance costs are 2,066,565 €/year. As regards financial costs, they have been quantified in 123,994 €/year. Considering internal income, investment costs, operation and maintenance costs and financial costs, the internal benefit for WWTP 1 amounts to 1,998,341 €/year. The same approach has been followed to each of the 13 studied water-reuse projects. Results are shown in Table 2.

In order to express all items in present value, it has been assumed that the amortization period is 20 years, interest rate is 6% and discount rate is 3.5%.

By considering the internal income and internal costs, internal benefit resulting from wastewater reuse is calculated in €/year and €/m^3. According to Table 2, if we only consider internal impacts, some water-reuse projects are not economically viable since the internal benefit obtained is negative. Also, it may be observed that the internal benefit expressed as €/m^3 obtained for the different water-reuse projects is highly variable, since the minimum value is −0.373 €/m^3, while the maximum value is 0.474 €/m^3. The weighted average, depending on the volume of water reused, is 0.198 €/m^3.

4.2. External benefit

The external benefit is the difference between positive and negative externalities (see Eq. (3)). According to Bdour et al. (2009) the greatest challenge in implementing wastewater-reuse projects is to ensure compliance with health and safety standards. Therefore, the main negative externalities associated to water-reuse projects are biological and chemical risks. Nevertheless, in our empirical application we have considered that negative externalities are minimal since the Royal Decree 907/2007 developed by the Environmental Ministry of Spain sets out strict parameters (chemical and microbiological) to be met by the reclaimed according to its use.

In order to quantify the environmental benefits derived from water-reuse projects, the methodology described in Section 2.3 was applied for the entire sample of 35 WWTPs. According the criterion of homogeneity, both in technology and as treatment capacity, only the results obtained for 13 WWTPs are analyzed here.

The estimation of the directional distance function enables shadow prices to be calculated for each pollutant removed during the wastewater regeneration for each WWTP in the current study. The shadow price value, expressed in €/kg, is shown in Table 3.

The shadow prices obtained for undesirable outputs are negative because, from the viewpoint of the production process, they are not associated with marketable outputs that may generate income. However, from an environmental perspective, these shadow prices may be interpreted positively, because they represent environmental benefits that are obtained from the wastewater-reuse project (Hernández-Sancho et al., 2010; Molinos-Senante et al., 2011).

Table 3 shows that the greatest environmental benefit for all the 13 plants studied here is associated with phosphorus removal followed by nitrogen. In the empirical application carried out here, wastewater reuse is performed for environmental purposes, mainly for wetland restoration and maintenance. As a consequence, regenerated effluent is discharged into wetlands or other inland water bodies. For this reason, in the current study the phosphorus shadow price is greater than the shadow price of nitrogen. For the shadow price of organic matter (measured as COD), the obtained value is considerably lower than that of nitrogen and phosphorus. This is because water bodies have a certain capacity to self-purify this pollutant (Ostroumou, 2007). Once the shadow prices of pollutants are quantified in €/kg, and the amount of pollutants removed per year and per cubic meter of reclaimed water is known, the monetary value of the environmental benefit of wastewater reuse in €/year and €/m^3 is directly obtained by using Eq. (8) (Table 4). The results are expressed as present monetary values, using a discount rate of 3.5%.

Following the same approach that in Section 4.1 a detailed analysis is shown for WWTP 1 while for the rest of WWTPs have proceeded in the same way. The external benefit to each pollutant equals to shadow price expressed in €/kg ($q_{SS} = 0.010$; $q_N = 10.473$; $q_P = 62.840$; and $q_{COD} = 0.062$) multiplying the amount removed

Table 2
Internal income and internal costs for each WWTP.

WWTP	Internal income	Internal costs			Internal benefit	
	Income (€/year)	Investment costs (€/year)	O&M costs (€/year)	Financial costs (€/year)	Internal benefit (€/year)	Internal benefit (€/m^3)
1	7,629,084	3,440,184	2,066,565	123,994	1,998,341	0.236
2	6,448,455	1,628,504	2,707,417	162,445	1,950,090	0.272
3	4,689,995	768,051	1,375,393	123,785	2,422,765	0.465
4	2,466,050	674,970	605,816	36,349	1,148,915	0.419
5	2,647,053	1,523,003	1,196,514	71,791	−144,255	−0.049
6	2,432,871	752,353	878,997	52,740	748,781	0.277
7	1,236,146	354,223	979,201	78,336	−175,615	−0.128
8	1,488,105	316,009	663,456	39,807	468,834	0.284
9	853,443	439,981	512,408	30,744	−129,690	−0.137
10	2,692,386	363,170	787,558	63,005	1,478,653	0.494
11	2,763,014	373,445	896,428	53,786	1,439,355	0.469
12	513,559	228,326	626,165	37,570	−378,502	−0.373
13	785,444	83,295	291,476	5830	404,843	0.464
Mean	2,318,892	821,962	996,184	57,706	764,040	0.198

Table 3
Shadow prices for pollutants (€/kg).

WWTP	SS	N	P	COD
1	−0.010	−10.473	−62.840	−0.062
2	−0.001	−1.500	−9.000	−0.007
3	−0.008	−38.840	−45.826	−0.243
4	−0.002	−1.500	−2.166	−0.007
5	−0.059	−59.104	−70.792	−0.360
6	−0.004	−61.267	−367.602	−0.534
7	−0.001	−1.500	−3.519	−0.012
8	−0.007	−35.126	−42.126	−0.192
9	−0.003	−10.810	−28.579	−0.403
10	−0.010	−21.705	−130.227	−0.152
11	−0.016	−73.904	−167.671	−0.238
12	−0.006	−55.209	−63.809	−0.235
13	−0.007	−56.693	−78.794	−0.242
Mean	−0.010	−35.188	−82.535	−0.207

Table 4
Environmental benefits of water-reuse.

WWTP	SS (€/year)	N (€/year)	P (€/year)	COD (€/year)	Overall (€/year)	Overall (€/m^3)
1	30,015	2,180,418	3,803,303	417,185	6,430,921	0.759
2	5574	258,476	599,706	82,298	946,054	0.132
3	13,854	10,400,542	1,631,024	592,995	12,638,415	2.425
4	1628	216,930	41,181	12,341	272,081	0.099
5	28,097	2,195,534	480,968	452,122	3,156,721	1.073
6	9261	862,861	1,460,736	1,386,821	3,719,680	1.376
7	452	130,990	62,541	13,648	207,631	0.151
8	3749	1,357,902	275,827	166,866	1,804,343	1.091
9	1229	290,203	322,222	420,165	1,033,818	1.090
10	7011	2,199,178	1,694,672	236,637	4,137,498	1.383
11	5050	2,268,857	947,142	78,713	3,299,762	1.075
12	683	1,002,670	115,938	29,014	1,148,305	1.131
13	1003	1,798,480	352,076	51,808	2,203,367	2.525
Mean	8277	1,935,618	906,718	303,125	3,153,738	1.022

Table 5
Internal, external and total benefit derived from water-reuse projects.

WWTP	Internal benefit (€/year)	External benefit (€/year)	Internal benefit (€/m^3)	External benefit (€/m^3)	Total benefit (€/year)	Total benefit (€/m^3)
1	1,998,341	6,430,921	0.236	0.759	8,429,262	0.995
2	1,950,090	946,054	0.272	0.132	2,896,144	0.404
3	2,422,765	12,638,415	0.465	2.425	15,061,180	2.890
4	1,148,915	272,081	0.419	0.099	1,420,996	0.518
5	−144,255	3,156,721	−0.049	1.073	3,012,466	1.024
6	748,781	3,719,680	0.277	1.376	4,468,461	1.653
7	−175,615	207,631	−0.128	0.151	32,016	0.023
8	468,834	1,804,343	0.284	1.091	2,273,177	1.375
9	−129,690	1,033,818	−0.137	1.090	904,128	0.953
10	1,478,653	4,137,498	0.494	1.383	5,616,151	1.877
11	1,439,355	3,299,762	0.469	1.075	4,739,117	1.544
12	−378,502	1,148,305	−0.373	1.131	769,803	0.758
13	404,843	2,203,367	0.464	2.525	2,608,210	2.989
Mean	764,040	3,153,738	0.198	1.022	3,917,778	1.220

from wastewater expressed in kg/year ($AV_{SS} = 3{,}001{,}500$; $AV_N = 208{,}194$; $AV_P = 60{,}523$; and $AV_{COD} = 6{,}728{,}790$). The sum is the total overall environmental benefit of water reuse. As Table 4 shows, for WWTP 1 it has been quantified as 6,430,921 €/year.

On average, the greatest environmental benefit is associated with nitrogen removal, which represents nearly 60% of the total benefit. Phosphorus follows in importance, with a percentage weight of 28%. These results reflect the fact that these pollutants have the highest shadow prices (see Table 3). The total environmental benefit derived from wastewater-reuse projects varies greatly between the different plants; the minimum value being 0.132 €/m^3 while the maximum is 2.525 €/m^3. The weighted average, depending on the volume of wastewater treated, is 1.022 €/m^3, meaning that for every cubic meter of regenerated water that is reused, the environmental benefit generated equals € 1.022.

Once both internal and external benefits have been identified and quantified, we may calculate the total benefit[4] associated with wastewater reuse for each WWTP in the current study.

4.3. Total benefit

In this section, total benefit is calculated by the sum of internal and external benefits for each water-reuse project of the study sample.

Table 5 shows that if the economic feasibility study is based on internal benefits (internal incomes and internal costs), not all water-reuse projects are feasible because a negative value is obtained for some. However, by following the proposed methodology, when external benefit is taken into consideration, water reuse is feasible for all projects in the current study since the results obtained are positive. In this respect, the total benefit derived from water reuse varies greatly between the different projects under consideration. In this sense, the least feasible WWTP is number 7 since it presents the minimum total benefit (0.023 €/m^3) while the most feasible one is number 3 because it presents the maximum value (2.989 €/m^3). The weighted average, depending on the volume of water reused, is 1.220 €/m^3. On the other hand, the total benefit expressed in €/year enables us to obtain an indicator of the economic feasibility of a proposed water-reuse project, considering not only internal impacts but also environmental externalities.

5. Conclusions

Due to the importance that WFD assigns to the economic analysis to achieve a suitable water resource management, feasibility studies are essential for assessing the potential of water-reuse projects. Usually, such studies are focused on internal impacts without consideration being given to non-monetary benefits derived from water reuse, such as environmental protection.

The current study presents a cost–benefit analysis of water-reuse projects for environmental purposes with an economic valuation of environmental externalities. The results show that the greatest environmental benefit is the prevention of nitrogen and phosphorus discharge, since these nutrients are primarily responsible for problems of eutrophication in inland water bodies. The analysis of water reuse with respect to just the internal benefit, indicates that some plants are not economically viable. However, if the external benefit of these projects is also incorporated, the economic feasibility analysis provided positive results for all water-reuse projects in the current study.

As a general conclusion, we emphasize that when the economic feasibility of a water-reuse project is assessed, water management authorities and companies should not only consider the benefits of market value, because the development of such projects may also be justified by other reasons, such as environmental benefits or the increase in the availability of a scarce resource. Hence, for the objective evaluation of water-reuse projects, economic feasibility studies should incorporate all parameters including economic, environmental and resource availability.

Acknowledgments

The authors acknowledge the statistical assistance from the *Entitat de Sanejament d'Aigües (EPSAR)* and the financial aid received from the Spanish government through the NOVEDAR-Consolider Project (CSD2007-00055) and FPU program (AP2007-03483) and the Generalitat Valenciana government (ACOMP/2010/138). They would also like to thank five anonymous referees for their valuable comments and suggestions.

References

AQUAREC, 2006. In: Bixio, D., Wiintgens, T. (Eds.), Water reuse system management natural. Project Report.

Asano, T. (Ed.), 1998. Wastewater Reclamation and Reuse. Water Quality Management Library, vol. 10. Technomic Publishing, PA.

Asano, T., 2007. Water Reuse: Issues, Technologies and Applications. Metcalf & Eddy/AECOM.

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[4] According to Eq. (1) to calculate the total benefit, the opportunity cost should be quantified. However and taking into account that in water-reuse projects, the opportunity cost generally refers to land on which the WWTP is placed and the fact that the WWTPs under study are already built, in our empirical application, there is not opportunity cost.

Balkema, A., Preisig, J., Otterpohl, H.A., Lambert, F.J.D., 2002. Indicators from sustainable assessment of wastewater treatment systems. Urban Water 4, 153–161.

Bdour, A.N., Hamdi, M.R., Tarawneh, Z., 2009. Perspectives on sustainable wastewater treatment technologies and reuse options in the urban areas of the Mediterranean region. Desalination 237, 162–174.

Bixio, D., Thoeye, C., De Koning, J., Joksimovic, D., Savic, D., Wintgens, T., Melin, T., 2006. Wastewater reuse in Europe. Desalination 187, 89–101.

Van der Bruggen, B., Goossens, H., Everard, P.A., Stemgée, K., Rogge, W., 2009. Cost–benefit analysis of central softening for production of drinking water. Journal of Environmental Management 91 (2), 541–549.

Chambers, R., 1998. Input and output indicators. In: Färe, R., Grosskopf, S., Russell, R. (Eds.), Index Numbers: Essays in Honour of Sten Malmquist. Kluwer Academic Publishers, Boston.

Chen, R., Wang, C., 2009. Cost–benefit evaluation of a decentralized water system for wastewater reuse and environmental protection. Water Science & Technology 59 (8), 1515–1522.

Curry, S., Weiss, J., 1993. Project Analysis in Developing Countries. MacMillan Publishers.

Diaz-Balteiro, L., Romero, C., 2008. Valuation of environmental goods: a shadow value perspective. Ecological Economics 64, 517–520.

EPA, 1998. Water Recycling and Reuse: The Environmental Benefits. http://www.epa.gov/region09/water/recycling/brochure.pdf Water Division Region IX.

EPSAR, 2009. Public Entity of Wastewater Treatment of Valencia Region. http://www.epsar.gva.es/sanejament/quienes-somos/INFORME-DE-GESTION-Castellano.pdf Management Report 2009 (in Spanish).

Färe, R., Grosskopf, S., Lovell, C.A., Yaisawarng, S., 1993. Derivation of shadow prices for undesirable outputs: a distance function approach. Review of Economics and Statistics 75 (2), 374–380.

Färe, R., Grosskopf, S., Weber, W., 2001. Shadow prices of Missouri public conservation land. Public Finance Review 29 (6), 444–460.

Färe, R., Grosskopf, S., Weber, W., 2006. Shadow prices and pollution costs in U.S. agriculture. Ecological Economics 56, 89–103.

Field, B.C., 1997. Environmental Economics. McGraw-Hill, Boston.

Godfrey, S., Labhasetwar, P., Wate, S., 2009. Greywater reuse in residential schools in Madhya Pradesh, India. A case study of cost–benefit analysis. Resources, Conservation and Recycling 53, 287–293.

Hanley, N., Spash, C.L., 1993. Cost–Benefit Analysis and the Environment. Edward Elgar, Cheltenham, UK.

Hernández-Sancho, F., Molinos-Senante, M., Sala-Garrido, R., 2010. Economic valuation of environmental benefits from wastewater treatment processes: an empirical approach for Spain. Science of the Total Environment 408 (4), 953–957.

Hernández, F., Urkiaga, A., De las Fuentes, L., Bis, B., Chiru, E., Balazs, B., Wintgens, T., 2006. Feasibility studies for water reuse projects: an economical approach. Desalination 187, 253–261.

Hochstrat, R., Joksimovic, D., Wintgens, T., Melin, T., Savic, D., 2007. Economic considerations and decision support tool for wastewater reuse scheme planning. Water Science & Technology 56 (5), 175–182.

Hutton, G., Haller, L., 2004. Evaluation of the Costs and Benefits of Water and Sanitation Improvements at the global level. World Health Organization.

Lim, S.-R., Park, D., Park, J.M., 2008. Environmental and economic feasibility study of a total wastewater treatment network system. Journal of Environmental Management. 88 (3), 564–575.

Miller, G., 2006. Integrated concepts in water reuse: managing global water needs. Desalination 187 (1–3), 65–75.

Molinos-Senante, M., Hernández-Sancho, F., Sala-Garrido, R., 2010. Economic feasibility study for wastewater treatment: a cost–benefit analysis. Science of the Total Environment 408 (4), 953–957.

Molinos-Senante, M., Hernández-Sancho, F., Sala-Garrido, R., Garrido-Baserba, M., 2011. Economic feasibility study for phosphorus recovery processes. AMBIO 40 (4), 408–416.

North, J., Griffin, C., 1993. Water source as a housing characteristics: hedonic property valuation and willingness to pay for water. Water Resources Research 29 (7), 1923–1929.

Ostroumou, S.A., 2007. Biotic self-purification of aquatic ecosystems: from the theory to ecotechnologies. Ecologica 15 (50), 15–21.

Salgot, M., 2008. Water reclamation, recycling and reuse: implementing issues. Desalination 218 (1–3), 190–197.

Seguí, L., 2004. Reclamation and reuse system wastewater. Methodology for the technical–economic analysis and cases. Doctoral thesis, Polytechnic University of Catalonia (in Spanish).

Seguí, L., Alfranca, O., García, J., 2009. Techno-economical evaluation of water reuse for wetland restoration: a case study in a natural park in Catalonia, Northeastern Spain. Desalination 246, 179–189.