A cost-effectiveness analysis of seminatural wetlands and activated sludge wastewater-treatment systems

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Abstract

A cost-effectiveness analysis was performed to evaluate the competitiveness of semi-natural Free Water Surface wetland (FWS) compared to traditional wastewater treatment plants. Six scenarios of the service costs of three FWS wetlands and three different wastewater treatment plants based on active sludge processes were compared. The six scenarios were all equally effective in their wastewater treatment capacity. The service costs were estimated using real accounting data from an experimental wetland, and by means of a market survey. Some assumptions had to be made to perform the analysis. A reference wastewater situation was established to solve the problem of the different levels of dilution that characterise the inflow water of the different systems; the land purchase cost was excluded from the analysis, considering the use of public land as shared social services, and an equal life span for both semi-natural and traditional wastewater treatment plants was set. The results suggest that semi-natural systems are competitive with traditional bio-technological systems, with an average service cost improvement of 2.1 to 8 fold, according to the specific solution and discount rate. The main improvement factor was the lower maintenance cost of the semi-natural systems, due to the self regulating, low artificial energy inputs and the absence of waste to be disposed of. In this work, only the waste treatment capacity of wetlands was considered as a parameter for the economic competitiveness analysis. Other goods/services and environmental benefits provided by FWS wetlands were not considered.

Key words: cost-effectiveness analysis, free water surface wetlands, service cost, wastewater treatment.

Abbreviations: free water surface (FWS)

Introduction

Wetland assimilation provides the same services as conventional methods in improving wastewater quality when used to provide advanced secondary and tertiary treatment (Breaux et al., 1995; Ko et al., 2004). Wetlands are particularly efficient for the removal of suspended solids and nutrients (Nichols, 1983; Ewel and Odum, 1984; Breaux and Day, 1994; Kadlec and Knight, 1996; Boustany et al., 1997; Zhang et al., 2000; Day et al., 2003), BOD, COD and pathogens (Wood, 1995; Nokes et al., 1999; Mitsch and Gosselink, 2000). It is now recognized that constructed wetlands can provide an improvement in landscape diversity and a valuable habitat for waterfowl and other wildlife, as well as areas for public education and recreation (USEPA 1993).

In comparison with waste water treatment plants, a semi-natural wetland involves low construction and maintenance costs over the long term, does not consume non-renewable energy and does not produce sludge to be disposed.

Constructed wetlands are generally used for treating domestic wastewater, for improving the quality of the water bodies, or as secondary and even tertiary treatment (Avsar et al. 2007). On the other hand, traditional wastewater treatment systems are designed to treat highly concentrated wastewaters: they remove pollutants from concentrated wastewater more efficiently than wetland systems.

For some kinds of wastewater (e.g. diluted waters), natural systems are as effective as traditional wastewater treatment plants in terms of depuration, but with a lower environmental impact. For example, Italian government legislation suggests the use of wetland systems to treat wastewater for urban agglomerates with less than 2000 inhabitants (e.g. D.L.vo n. 152/1999).

Traditional plants, like all other industrial plants, consume energy and produce waste (Tchobanoglous and Burton, 1991; Breaux et al., 1995; Viessman and Hammer, 1998; Mitsch and Gosselink, 2000). Natural systems can therefore represent a virtually expense-free alternative to other technological wastewater treatment processes (Breaux et al., 1995; Cardoch et al., 2000; Steer et al., 2003; Ko et al., 2004).

A monetary comparison of different kinds of plants is rarely made, despite the fact that minimisation of costs is often indicated by government legislation as a priority (D.L.vo n. 152/2006).

The aim of this work was to compare the economic benefit of a phytodepuration system (Free Water Surface wetland) with that of traditional wastewater treatment plants, for wastewater that can be treated in both these kinds of system. The economic benefit was assessed on the basis of surface wastewater treatment functions for the purposes of this study. The assessment was performed with a cost-effectiveness analysis.

Materials and methods

Monetary or non-monetary methods can be used to perform a comparison of different technologies. These methods assign a preference ranking based on qualitative parameters and a "social" weight for some judgment criteria. Monetary methods refer to the cost-benefit analyses, where benefits are the goods/services produced (or saved) and costs are the goods/services consumed in development of the project.

When there are difficulties in assigning a monetary value to the benefits, a cost-effectiveness analysis can be used (Gudger and Barker, 1993; Hanley and Spash 1993; Anderson, 1998; Wheeler, 1998; Heinzerling and Ackerman, 2002; OECD, 2006; Willan and Briggs, 2006). Based on defining the threshold effectiveness value, the cost-effectiveness analysis estimates the costs needed to reach it, and the benefit is maximised when the fixed goal is reached at the minimum cost.

Surface water and wastewater treatment is a benefit that is normally described in quantitative or chemical terms. In this case, the cost necessary to reach a threshold of (depuration) effectiveness was considered to obtain an economic benefit evaluation.

This cost was estimated as the “service cost”, defined as the total cost charged by a plant over a certain period relative to the service offered to the taxpayer or customer. The economic and efficiency data for the semi-natural Free Water Surface (FWS) treatment wetlands were obtained by three year monitoring of a real experimental plant.

The experimental treatment wetland

The Canale Nuovissimo Ramo Abbandonato phytodepuration system is an experimental FWS wetland defined as *semi-natural*, designed and built to minimise the input of exogenous matter and to minimise the time lag of the wet ecosystem’s stabilisation to a self-regulating and steady state. It was constructed in the Venice Lagoon watershed (Italy), to verify the efficiency of these systems in the treatment of water entering the Lagoon.

The water entering the system comes from a reclaimed agricultural channel and is characterised by non-point source agricultural and urban pollution. The system is brackish because of the influence of the Venice Lagoon. The wetland was created in a reclaimed lowland delta, currently below sea level, using an abandoned channel. There are no differences in hydraulic head across the wetland; therefore pumps are used to circulate surface water through the wetland. The wetland is 50 m wide and 4.14 km long with a mean depth of 80 cm and was divided into three subsystems of differing morphology and vegetation. The first ecosystem is a meandering riparian swamp ecosystem dominated by hydrophytic trees and shrubs. The second ecosystem is a wet riparian ecosystem. The channel is linear, and one third of the area of emergent plants consisted of trees and shrubs, whereas the remaining area is covered by marsh vegetation. Finally, the third ecosystem is a marsh ecosystem, with shrubs and trees playing an ancillary role (slope protection, habitat). Vegetation for restoring the three ecosystems was chosen in agreement with the phytosociological classification of the transitional zone between the mainland and the Venice lagoon. Construction of the first and part of the second ecosystems required extensive modification of the original conditions, which was achieved by adding agricultural soil to the previous channel banks.

The design (1999-2001), construction (2002) and monitoring (ongoing) of the experimental system were funded by the Ministry of Infrastructures - Venice Water Authority through its concessionary Consorzio Venezia Nuova.

Finding the depuration effectiveness threshold

A four-step procedure was followed to set the depuration effectiveness threshold.

Finding the reference parameters for the effectiveness threshold

The period to set the abatement rate of the experimental system (Table 1) was chosen on an annual basis, hence the restored wetland approximated to a steady state after the first stabilisation period (Kadlec and Knight, 1996; Anderson et al., 2005). The reduction in the pollutant loading rate was comparable with data in the literature regarding secondary wastewater treatment wetlands (e.g. Breaux et al., 1995). A further period was not undertaken because it would not have been concluded during this research. Moreover, further results confirmed the abatement rate.

The components of a traditional wastewater treatment system were determined starting from the inflow sewage characteristics defined quantitatively, as per capita water supply and the number of Equivalent Inhabitants[1],and qualitatively, as the daily load of pollutants. In this case, with the wetland inflow and outflow rates being equal (gauged during monitoring), the EI number (12975) was deduced from the mean daily flow rate of the experimental wetland (2595 m^3 day^{-1}).

Finding the reference wastewater for the effectiveness threshold.

Sewage with the same Equivalent Inhabitants was set from the mean daily flow rate of the experimental wetland. Sewage likely to be treated by a hypothetical wastewater disposal plant (fed by point and not a diffused pollution source) should be characterised by input concentrations higher than those of the experimental wetland inflow (Table 1).

To remedy difficulties in comparison with the literature, due to the dilution of the reclaimed waters treated by the experimental wetlands, a hypothetical reference wastewater value was set by making some assumptions.

The reference wastewater was obtained by using the input loads of the annual abatement rate of the experimental wetland, taking account of the law enforcement limits for surface water spillage (Table 2), by means of:

$$Ci - (Bi*Ci) = Ai \qquad (1)$$

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[1] The Equivalent Inhabitant is used as one of the parameters for the organic load of waste water and is equal to an Oxygen Chemical Demand of 130 g day^{-1} or a discharge volume of 200 l day^{-1}, whichever as higher (Art. 4, c.1, L.R.T. n. 5/86).

where: Ci = concentration of the i-pollutant in the hypothetical wastewater to be treated, Bi = the wetland abatement rate of the i-pollutant, Ai = the law limit concentration for spillage of the i-pollutant in the surface waters.

The loading abatement percentage was used to calculate the reference concentration because a constant was set for the wetland flow rate.

The implicit assumption of equation (1) took into account that the abatement processes follow a first order kinetics in the presence of concentrations equal to or higher than that set as the threshold.

These assumptions were admissible because in the treatment wetlands the abatement percentage tends to increase with input concentration, following first order kinetics (Kadlec & Knight, 1996; Rousseau, 2004), and this behaviour was also ascertained for the experimental wetland.

For these reasons the input concentrations of the reference wastewater, higher than those registered for the experimental wetland, should be abated in an equivalent or better way in treatment wetlands than the monitored one. Even though Rousseau (2004) highlighted that over a certain concentration threshold the wetlands abatement capacity decreases, and is no longer described by first order kinetics, all the recorded data and the set reference limits (Table 2) were below that threshold. A review of cases in the literature was used to assess the above assumptions (Table 3).

Even for total P or for SS the review data confirmed the capacity of FWS wetland to abate the upper limits of concentration hypothesised and explained by first order kinetics (Kadlec and Knight, 1996; ITRC-USEPA, 2001; ITRC, 2003; Braskerud et al., 2005a, Braskerud et al., 2005 b;). In the case of BOD and COD it seems that the abatement capacity is independent of input concentration, yet very efficient for higher or lower values than those set here (Nyakang'o, 1999; ITRC, 2003; Dass, 2004).

In the case of ammonium and nitrate the hypothesised input concentrations did not exceed the first order abatement kinetics reported in the selected literature (Kadlec and Knight, 1996; Kovacic, 2000; ITRC- USEPA, 2001;ITRC, 2003; Jordan, 2003; Mitsch et al., 2005;).

Therefore, for all the parameters monitored in the FWS wetland the literature analyzed reported: (i) the presence of a first order abatement kinetic; (ii) that input concentrations equal or higher than the hypothesised ones allow an abatement which is equal to or higher than those monitored in the experimental wetland.

Finding the comparable traditional technologies

Having defined the reference wastewater (Table 2), the best traditional wastewater treatment solution to meet the effectiveness threshold was identified through a market survey. A representative sample of specialised companies was asked to make a detailed pre-proposal for the construction of a treatment system, including a quantitative and qualitative description of the wastewater. The pre-proposal had to be presented as cost categories (set-up, ordinary maintenance, special maintenance), and equipped with detailed technical reports on the adopted solutions.

The companies contacted were divided into two groups.

The first control group of 8 companies (Group A) received information on the real aim of the request, the reference wastewater definition method and the characteristics of the FWS experimental wetland. This group was then asked to make the best technical pre-proposal for the best available plant.

The second group of 12 companies was not told the real aim of the request, only given the specifics of the reference wastewater.

In this way it was possible to make a comparative evaluation of the information obtained from a different market survey approach. The results were essentially similar for the companies that gave a positive/useful reply (11 cases).

The reply that gave the most detailed and exhaustive information was selected to define the best available plant, which was a completely automated technological plant based on activated sludge processing of secondary treated sewage. The process comprised several stages: sewage arrival and pumping; pre-denitrification; nitrification; sedimentation; sludge recirculation; sludge settling and decanting.

The market survey also allowed the parameters of frequency and costs of ordinary and extraordinary maintenance to be specified for the set life span (20 years).

In the plant thus obtained, the sewage was pumped into the pre-denitrification tanks to transform nitrates into gaseous nitrogen. During nitrification the ammonium and organic matter were oxidised. The ammonium was removed in an aerobic environment using a bacterial driven process supported by forced oxidation. The aerated mixture was routed to the sedimentation stage, where particles with a higher specific weight than water were separated by gravity. The disposed activated sludge was partly recirculated to maintain an optimal bacterial level in the plant, and partly disposed and/or treated in the agricultural or composting sectors, if not classified as waste. To reduce the maintenance costs a dehydrator could be installed, which reduces the volume of disposable sludge.

The plant was designed to be proportioned to comply with the legal limits used in the equation 1 (Table 2). It was made of two sub-divided blocks (25 x 20 x 4.5 m) and a circular (15 m diameter x 2.5 m height) concrete tank.

The electro-mechanical system consisted of: 2 electric pumps for the sewage pumping; 1 submerged blender for the de-nitrification tank; 1 submerged aerator for the nitrification tank; 1 submerged pump for water-sludge blend circulation; 1 adapted overhead travelling crane for the sedimentation stage; 2 submerged pumps for sludge re-circulation; 1 electrical panel, an electrical system and a hydraulic system for the plant connections.

Finding the plant and cost categories to be compared.

The economic and technical data, monitored during the construction and operational phytodepuration of the experimental wetland, were gathered into *development* and *maintenance* cost categories to facilitate the comparison of operational phytodepuration and traditional wastewater treatment systems.
Moreover, only the costs that differentiate the water treatment technologies were considered: therefore the inflow and outflow connection costs to the final receptor, which are common to both approaches, were excluded

FWS wetlands

Costs. The monitoring system of the Canale Nuovissimo experimental phytodepuration plant corresponds to cost categories that do not exist in a normal FWS treatment wetland. Therefore, monitoring system costs were not included in this study
In the development category the costs actually considered accounted for planting, addition of soil and shaping of banks, service road construction, pumping stations,

electrical system and electric connections. The purchase of the land was not accounted for in this category. This item could have potentially added to the service costs, particularly compared to traditional technological treatment plants, which take up much less land. It was assumed that the FWS wetland treatment systems are at least partially built on public land, in order to deal with water purification or provide social benefits linked to restoration (Healy and Cawley, 2002; Knowlton et al., 2002; ITRC, 2003;Yang, 2006). Another reason was the extreme uncertainty of this item. The cost of the land needed to build the FWS could vary markedly from place to place, although it is generally lower than that of land suitable for traditional wastewater treatment plants. In the first place the remaining lowlands are problematical from an urban, industrial or commercial point of view; and secondly there are stronger technological and utility connection constraints for the site selection. Plantation management care (mowing, re-planting: only during the first three years) and maintenance of the pump stations were part of the ordinary maintenance cost category. Harvesting and regeneration of the wetland wood were part of the extraordinary maintenance cost category. The discounting back of this cost was set at 20 years; no incomes were considered.

Plants. Three realistic cost scenarios corresponding to three realistic FWS plants (WA, WB, WC) of equivalent abatement capacity were estimated, using single cost invoice accounting in each of the cost categories. The three plant scenarios were differentiated on the basis of increasing costs, according to realistic design and development constraints, like shaping necessities or accessing utilities, or water supply (gravity or mechanical feed). The three set plants were shown on a scheme of cost subdivisions (Table 4).

Development costs. WA: plantation, addition of soil and shaping of banks; WB: plantation, addition of soil and shaping of banks, service road construction; WC: plantation, addition of soil and shaping of banks, service road construction, pumping stations, electrical system and connections.

Ordinary maintenance costs. WA: plantation management care; WB: plantation management care; WC: plantation management care, maintenance of pump stations and utilities.

Extraordinary maintenance costs. WA: harvesting and regeneration costs; WB: harvesting and regeneration costs; WC: harvesting and regeneration costs.

Traditional wastewater treatment plant.

Costs. In the case of technological sewage disposal, the land purchase cost was excluded. We excluded the primary treatment costs, considering that the inflow wastewater to the experimental wetland was not pre-treated, and to maintain a rationale in the comparisons.

The selected development costs were: 1) construction of concrete tanks; 2) delivery and installation of the electric-mechanical devices; 3) plant automation, 4) possible delivery and installation of a mechanical dehydrator.

The fixed ordinary maintenance costs were: 1) technical maintenance of the constructed and electric-mechanical devices; 2) analytical and technical management; 3) electrical energy use; 4) final sludge disposal.

It was assumed in the first instance that the final sludge (solid or liquid) was free of toxic elements and not classified as waste (therefore usable in the agricultural sector according to European, Italian and local body laws), and considering the cost of disposal as the cost of transport to the final destination.

Therefore, the dehydrator development cost allows for a decrease in the ordinary maintenance costs, reducing the final sludge volume and the number of transport journeys for its disposal/treatment. In this case (dewatered sludge), the final sludge could be transported to a composting plant, but with a charge for the management company.

The high uncertainty of extraordinary maintenance requirements was simplified by assuming these costs to correspond to further maintenance costs (replacement of electric-mechanical devices) at fixed deadlines.

Plant. Three possible technological solutions could be used for comparisons depending on the sludge disposal modality: (i) with a mechanical dehydrator and agricultural sludge use; (ii) without mechanical dehydrator and agricultural disposal; (iii) with mechanical dehydrator and transport for composting (solid sludge only). To determine the comparisons between equally effective alternative plant, the three technological solutions were combined with three transport distance ranges, giving 7 possible solutions. TA: liquid sludge – disposal within 0 km; TB: liquid sludge – disposal within 25 km; TC: liquid sludge – disposal within 50 km; TD: solid sludge – disposal within 0 km; TE: solid sludge – disposal within 25 km; TF: solid sludge – disposal within 50 km; TG: solid sludge – composting.

Service cost

The service cost (Cs) was defined as the total cost needed to give an annual wastewater treatment service per Equivalent Inhabitant over the life span of the plant. The econometric model used was (Tomasinsig et al., 2000):

$$Cs = (A_I + C_{GO} + A_{GS})/E.I. \qquad (2)$$

Where:

$$A_I = C_I * i *(1+i)t / [(1 + i)t-1] \qquad (3)$$

$$A_{GS} = C'_{GS} * (1 + i)-t' * i * (1 + i)t / [(1 + i)t - 1] \qquad (4)$$

Where: Cs = Service cost; A_I = annual refund rate of the plant cost; C_I = development cost; C_{OM} = ordinary maintenance cost; A_{SM} = annual refund rate of the present value of the extraordinary maintenance cost; C'_{OM} = ordinary maintenance cost at the t' moment; E.I. = Equivalent Inhabitants; t = plant life-span; t' = discounting back of ordinary maintenance expenses; i = discount rate.

Plant life span and discount rate

The life-span of all the compared plants was set at 20 years, determined as the mean period over which the capacity and the abatement effectiveness of the plants could become obsolete. This is indeed unlikely for the semi-natural treatment wetlands (Craft et al., 2002; Black and Wise, 2003, Mitsch et al., 2005; Hefting et al., 2006), but quite probable for the traditional wastewater treatment plants.

It was assumed that during this period maintenance would be regularly and correctly carried out, maintaining the set wastewater treatment effectiveness. The discount rate is generally higher in the case of higher development and maintenance investments, and in any event influences the final results of the econometric model (Equation 2).

A sensitive analysis was made of discount rate influence using a 5% or a 10% rate, values generally associated with the estimation of wastewater treatment plant performances (Breaux et al., 1995; Steer et al., 2003).

Finally, in order to show which system is more economic, the service costs of three different semi-natural systems (with increasing context limits and investment necessities) were compared with three different traditional wastewater treatment plants (selected from the most economically viable according to the type of sludge disposal) equally effective in their wastewater treatment capacity.

Results

The three selected FWS wetland treatment plants were equally effective in terms of wastewater treatment capacity, but at increasing costs (see Material and Methods). Their costs, for each cost category, are defined in Table 4. The same scheme was used for the traditional wastewater plant (Table 5). All maintenance costs were based on a 20-year plant life span. The estimate implementation in the econometric model (Equation 2) easily produced a first comparison for each equivalent plant at each discount rate (Figure 1).

FWS semi-natural wetland presented a development cost ranging from €1,393,523.00 to €1,747,637.00 whereas traditional wastewater treatment plants range from €200,000.00 to €250,000.00 (Table 4, Table 5, Fig. 1).

The development conditions were inverted compared to the ordinary maintenance costs (Figure 1), which showed unquestionably higher values, even for the cheaper traditional water treatment solutions (without mechanical dehydrator and disposal on annexed agricultural areas). Generally, the disposal of solid sludge (with dehydrator) was cheaper than for the liquid form, but when all the cost items were considered, the solid sludge option was only appropriate if the disposal site was further than 50 km from the site (Table 5). The absence of the dehydrator decreased the ordinary maintenance costs for the other threshold distances considered (0 km, 25 km). A distance of less than 50 km was never economic for disposal of the solid sludge as compost.

The estimated extraordinary maintenance costs were substantially equivalent. Considering all possible plants, the discount rate increase had a primary influence on the initial investment, and a secondary one on the extraordinary maintenance expenses (Figure 1). Independent of the discount rate, the FWS wetland service cost was always lower than that of traditional water treatment plants.

Finally, to select the most economic traditional treatment solution from the seven selected (Table 5) for the effectiveness cost analysis, we dealt with the service cost by the travelling distance for the sludge disposal using a 5 or 10% discount rate (Figure 2). The discount rate had a low influence on the critical transport threshold and on the final service cost, and the travel intensity remained the determining variable for economic performance and as a technological solution. If the distance from the agricultural disposal site ranged from 35.64 km to 320 km (i=5%), or from 36.12 to 320 km (i= 10%), the sludge dewatering solution was always the most economical. For greater distances, or in the case of agricultural disposal not being feasible, the most economic option would be disposal by composting.

Discussion

Development cost

The results showed that the development cost of the FWS semi-natural wetland was 6-9-fold higher than traditional technological treatment plants (Table 4, Table 5, and Figure 1). This is because technological treatment plants are based on standardised technology, meaning that the construction elements are pre-determined, furnished with all necessary facilities and easy to supply and install, and the design and production are highly standardised. All these elements produce an economy of scale with direct effects on sale prices.

Despite the low technological investment, phytodepuration plants, particularly FWS wetlands, need a local design and construction study that is closely adapted to the context of the environmental conditions. The cost is therefore highly variable and highly dependent on site availability and supply of primary materials.

Ordinary maintenance costs

The ordinary maintenance costs were higher for the traditional wastewater treatment plant, even for the cheaper solutions. This is because of the need to maintain constant control over the water treatment stages and sludge disposal: such control requires constant inputs of technical skill (information), technical components and energy. Transport related to disposal was a particularly sensitive cost item: the dehydrator allows a reduction of the sludge volume set against an increase in energy consumption and maintenance costs. Generally, the disposal of solid sludge (with dehydrator) is cheaper than that of the liquid form (Table 5). Indeed, the companies involved predicted a mean of four journeys per month for the liquid sludge and one every 40 days for the solid. However, when all the cost items were considered, it was possible to posit a threshold value for the economic benefit related to the use of a dehydrator. The ordinary maintenance costs related to the presence of a dehydrator were lower than the costs needed to transport a larger amount of liquid than solid sludge only for distances greater than 50 km from the site.

In the case of FWS semi-natural wetlands, the artificial inputs of energy and information were very low, and the absence (or modest nature) of mechanical devices implied a reduction in human resources, maintenance and non-renewable energy consumption. There was no sludge production.

Service cost

The discount rate increase (from 5% to 10%) penalised the solution with the higher initial investment, as it did for the FWS wetlands.

Independently of the discount rate, the FWS wetland service cost was always lower than the traditional wastewater plant service cost. At a real operational scale, traditional plants were efficient from the point of view of their construction, but not economic in terms of service costs.

The discount rate had a low influence on the critical transport threshold and on the final service cost, while travel intensity remained the determining variable for economic performance and the technological solution.

On a conservative assumption, and considering only the most economically viable solutions, three final plants were selected for the cost effectiveness analyses.

- TA: a plant without a dehydrator for liquid sludge disposal at an agricultural site within 35.64 km (i = 5%) or 36.1 km (i = 10%);
- TB: a plant with a dehydrator for solid sludge disposal at an agricultural site between 35.6 and 320 km (i = 5%) or 36.1 and 320 km (i = 10%) away;
- TC: a plant with a dehydrator for solid sludge disposal in a composting plant, if agricultural disposal is not possible or the distance for disposal is over 320 km.

At wastewater treatment effectiveness parity the cheaper treatment wetland (WA) had a service cost from 6 (i=10%) to 8 (i= 5%) fold lower than the most expensive of the technological solutions (TC, composition sludge disposal) (Fig. 3). The FWS treatment wetland with the higher service cost (WC: plantation, addition of soil and shaping of banks, service road construction, pumping stations, electric system) had a service cost at the settled plant's life span from 2.1 (i=10%) to 2.5 (i= 5%) fold lower than the least expensive of the technological solutions (TA, liquid sludge disposal on attached agricultural fields) (Fig. 3).

Estimating the service cost for 20 separate life spans, from 1 to 20 years, a time trend of the service costs was obtained for each plant. All FWS wetland treatment appeared to become economically viable in comparison with the technological alternatives in one to three years (Figure 3).

Conclusions

The results suggested that FWS semi-natural wetlands are economically competitive with traditional technological plants for secondary wastewater treatment, given equal depurative effectiveness and independent of the discount rate.

Some assumptions on development costs and plant life span had to be made in order to perform the analyses. All assumptions were based on a conservative approach.

The three FWS wetland systems were always more economic than the traditional wastewater treatment plants, with a service cost 2.1 to 8-fold lower given the set plant's life span-.

This was mainly due to the maintenance costs, which were always much lower in semi-natural systems, while the difference caused by higher development costs was nullified and overturned in 2-3 years (Figure 3).

The higher maintenance costs of biotechnological systems were due to the constant need for monitoring and energy inputs to maintain the required functional processes.

On the contrary, FWS semi-natural wetlands are multifunctional treatment systems that are similar to natural ecosystems and are therefore self-regulating and in a steady state if within working range, in this case mainly related to the wastewater loads (hydroperiod and loading rate design).

Disposal was one of the management cost items that most strongly influenced the service cost, yet semi-natural wetlands did not produce process discards because matter was recycled within the system. An FWS wetland can have relatively low (presence of inflow and outflow pumping stations) or nil (gravity feed system) electrical energy consumption. All biological processes, even working at higher spatial- and time- scales, utilise solar or endogenous chemical energy.

Only the wastewater purification service was considered in this work. Yet the financial competitiveness of FWS wetlands increases when considering the reduction of impacts linked to non-renewable energy consumption and to waste production, to the role in integrated watershed resource management and to landscape restoration and requalification processes.

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Literature Cited

Anderson C.J., W.J. Mitsch, R.W. Nairn. 2005. Temporal and spatial development of surface soil conditions at two created riverine marshes. Journal of Environtal Quality 34: 2072-2081

Anderson W. 1998. Economic analysis and cost-effectiveness analysis of proposed effluent limitations guidelines and standards for industrial waste combustors. U.S. Environmental Protection Agency Washington, DC 20460

Avsar Y., H. Tarabeah, S. Kimchie, I. Ozturk. 2007. Rehabilitation by constructed wetlands of available wastewater treatment plant in Sakhnin. Ecological engineering 29:27-32

Black C.A., W.R.Wise. 2003. Evaluation of past and potential phosphorus uptake at the Orlando Easterly Wetland. Ecological Engineering 21: 277-290

Boustany R.G., C.R. Crozier, J.M. Rybczyk, R.R. Twilley. 1997. Denitrification in a South Louisiana wetland forest receiving treated sewage effluent. Wetland Ecology and Management 4: 273-283

Braskerud B.C., T. Hartnik, O. Lovstad. 2005a. The effect of the redox-potential on the retention of phosphorus in a small constructed wetland. Water Science and technology 51: 127-134

Braskerud B.C., K.S. Tonderski, B. Wedding, R. Bakke, A.G. Blanenberg, B. Ulen, J. Koskiaho. 2005b. Can constructed wetlands reduce the diffuse phosphorus loads to eutrophic water in cold temperate regions?. Journal of environmental quality 34: 2145-2155

Breaux A., J.W. Day. 1994. Policy considerations for wetland wastewater treatment in the coastal zone: a case study for Louisiana. Coastal Management 22: 285-307

Breaux A., S. Farber, J.W. Day. 1995. Using natural coastal wetlands systems for wastewater treatment: an economic benefit analysis. Journal of Environmental Management 44: 285-291

Cardoch L., J.W.Jr Day, J.M. Rybczyk, G.P. Kemp. 2000. An economic analysis of using wetlands for treatment of shrimp processing wastewater: a case study in Dulac LA. Ecological Economics 33: 93-101

Craft C., S. Broome, C. Campbell. 2002. Fifteen years of vegetation and soil development after brackish-water marsh creation. Restoration ecology 10: 248-258

Dass P., I. Ryuhei, N. Iwami, M. Mizuochi, Y. Inamori. 2004. Role of emergent macrophyte (Phragmites and Zizania) in nutrient removal and flux of green house gases from wastewater in constructed wetland. IWA Astee Conferences, 26 September – 1 October, Avignon, France

Day J.W., A.Y. Arancibia, W.J. Mitsch, A.L. Lara-Dominguez, J.N. Day, J.Y. Ko, R.R. Lane, J. Lindsey, D.Z. Lomeli. 2003. Using ecotechnology to address water quality and wetland habitat loss problems in the Mississippi basin: a hierarchical approach. Biotechnology Advances 22: 135-159

Decreto Legislativo 11 maggio 1999 n. 152. Disposizioni sulla tutela della acque dall’inquinamento e recepimento della direttiva 91/271/CEE concernente il trattamento delle acque reflue urbane e della direttiva 91/676/CEE relativa alla protezione delle acque dall’inquinamento provocato dai nitrati provenienti da fonti agricole”

Decreto Legislativo 3 aprile 2006 n. 152. Norme in materia ambientale.

Ewel K.C., H.T. Odum. 1984. Cypress swamps, University Press of Florida, Gainesville, FL

Gudger W.M., D. C. Barker. 1993. Banking for the environment. FAO Agricultural Services Bulletin, 103

Hammer D.A., R.L. Knight. 1994. Design constructed wetlands for nitrogen removal. Water Science and Technology 29: 15-27

Hanley N.D., C. Spash. 1993. Cost-Benefit Analysis and the Environment, Edward Elgar Publishing, Cheltenham

Hawke C.J., P.V. Josè. 1996. Reedbed Management for Commercial and Wildlife Interest, The Royal Society for the Protection of Birds

Healy M., A.M. Cawley. 2002. Nutrient processing capacity of a constructed wetland in western Ireland. Journal of Environmental Quality 31: 1739-1747

Hefting M., B. Beltman, D. Karssenberg, K. Rebel, M. Van Riessen, M. Spijeker. 2006. Water quality dynamics and hydrology in nitrate loaded riparian zones in the Netherlands. Environmental pollution 139: 143-156

Heinzerling L., F. Ackerman. 2002. Cost-Benefit Analysis of Environmental Protection. Georgetown Environmental Law and Policy Institute, Georgetown University Press

ITRC (2003) Technical and Regulatory Guidance for Constructed Treatment Wetlands, December 2003.

Jordan T.E., D.F. Whigham, K.H. Hofmockel, M.A. Pittek. 2003. Nutrient and sediment removal by a restored wetland receiving agricultural runoff. Journal of Environmental Quality 32: 1534–1547

Kadlec R.H., R.L. Knight. 1996. Treatment wetlands: theory and implementation, Lewish Publishers, Boca Raton, FL.

Knowlton, M.F., C. Cuvellier, J.R. Jones. 2002. Initial performance of high capacity surface flow treatment wetland. Wetlands 22: 522-527

Ko J.Y., J.W. Day, R.R. Lane, J.N. Day. 2004. A comparative evaluation of money-based and energy-based cost-benefit analyses of tertiary municipal wastewater treatment using forested wetlands vs. Sand filtration in Louisiana. Ecological Economics 49: 331-347

Kovacic D.A., M.B. David, E.G. Lowell, K.M. Starks, R.A. Cooke. 2000. “Effectiveness of constructed wetlands in reducing nitrogen and phosphorus export from agricultural tile drainage. Journal of Environmental Quality 29: 1262-1270

Lorion R. 2001. Constructed wetlands: passive system for wastewater treatment, Technology status report prepared for the USEPA technology innovation office under a national network of environmental management studies followship

Mitsch W.J., Gosselink, J.G. 2000. Wetlands, third ed., Wiley, New York

Mitsch W.J., L. Zhang, C.J. Anderson, A.E. Altor, M.E. Hernandez. 2005. Creating riverine wetlands: Ecological succession, nutrient retention, and pulsing effects. Ecological engineering 25: 510-527

Nichols D.S. 1983. Capacity of natural wetlands to remove nutrients from wastewater. Journal of Water Pollution Control Federation 55: 495-505

Nokes R.L., C.P. Greba, M.M. Karpiscak. 1999. Reduction of enteric organisms in small scale, subsurface flow constructed wetlands. In Wetlands and Remediation: Wastewater Remediation and treatment, (Ed.) Battelle Press, Columbus, OH, 195-203

Nyakang’o J.B., J.J.A. Van Bruggen. 1999. Combination of a well functioning constructed wetland with a pleasing landscape in Nairobi, Kenia. Water Science and Technologies 40: 249–256

OECD (2006) Cost-Benefit Analysis and the Environment, Recent Developments. ISBN 92-64-01004-1

Rousseau D.P.L., P.A. Vanrolleghem, N. DePauw. 2004. Model based design of horizontal subsurface flow constructed wetlands: a review. Water research 38: 1484-1493

Steer D., T. Aseltyne, L. Fraser. 2003. Life-cycle economic model of small treatment wetlands for domestic wastewater disposal. Ecological Economics 44: 359-369

Tchobanoglous G., F.L. Burton. 1991. Wastewater Engineering, Mc Graw-Hill, New York

Tomasinsig E., M. Vecchiet, F. Marangon, L. Ceccon. 2000. Valutazione economica delle tecniche di depurazione delle acque reflue per piccole utenze civili. Genio Rurale 6: 15-25

USEPA, United States Environmental Protection Agency. 1993. Constructed wetlands for wastewater treatment and wildlife habitat, 17 case studies

USEPA, United States Environmental Protection Agency. 2001. Constructed wetlands and wastewater management for CAFOs

Viessman W., M.J. Hammer. 1998. Water supply and pollution control, Addison-Wesley, Menlo Park, CA

Wheeler W. 1998. Cost-Effectiveness Analysis of Effluent Limitation Guidelines and Standards for the Centralized Waste Treatment Industry, U.S. Environmental Protection Agency Washington, DC 20460

Willan A., A. Briggs. 2006. Statistical Analysis of Cost-Effectiveness Data, John Wiley & Sons, NY

Wood A. 1995. Constructed wetlands in water pollution control: fundamentals to their understanding. Water Science and Technology 32: 21-29

Yang B., C.S. Lan, C.S. Yang, W.B. Liao, H. Chang, W.S. Shu. 2006. Long term efficiency and stability of wetlands for treating wastewater of a lead/zinc mine and the concurrent ecosystem development. Environmental pollution 143: 449-512

Zhang X., S.E. Feagley, J.W. Day, W.H. Conner, I.D. Hesse, J.M. Rybczyk, W.H. Hudnall. 2000. A water chemistry assessment of wastewater remediation in a natural swamp. Journal of Environmental Quality 29: 1960-1968

Figures Captions

Figure 1: Development (Ci,value on left y-axis), ordinary maintenance (CGO, value on left y-axis) extraordinary maintenance (CGS, value on left y-axis) and the service (Cs, value on right y-axis) cost are reported for each equally effective solution selected. The 5% (a) or 10% (b) discount rate results are reported. For abbreviation see Table 4 and Table 5.

Figure 2: The function of the service cost of the different technological solutions dealt with by the travelling distance and modality of the sludge disposal. TA= plant without dehydrator and agricultural sludge disposal; TB = plant with dehydrator and agricultural sludge disposal; TC = plant with dehydrator and competing plant sludge disposal. Figure a) i= 5%, b) i= 10%.

Figure 3: A time trend of the service costs estimated for each selected plant. TA=plant without a dehydrator for liquid sludge disposal at a agricultural site within 35,6 Km; TB = plant with a dehydrator for solid sludge disposal at an agricultural site between 35.6 – 36 and 320 Km; TC = a plant with a dehydrator for solid sludge disposal in a composting plant if agricultural disposal is not possible or the distance from the agricultural site is over 320 Km. For WA, WB, WC explanation see materials and methods - plant and the cost categories or table 4.

Tables

Table 1 Percent abatement of the pollutant (kg removed on input kg) during the steady state regime (14/04/2004-15/04/2005), and the daily inputs of the principal pollutants of the experimental wetland.

	Suspended solids	**Total P**	**$N\text{-}NH_4$**	**$N\text{-}NO_3$**	**Total N**	**BOD**	**COD**
	(%)	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**
% Abatement (kg removed on input kg)	57.09	43.82	71.70	86.28	59.35	12.04	39.53
Daily input (g/day)	484	49	4167	120	8604	7568	31385

Table 2 Estimation of the reference wastewater characteristics based on equation 1. Ai =Surface water spillage limits (Italian law, DLgs 152/99); Bi= abatement effectiveness (experimental FWS wetland); Ci = input concentration (hypothetical wastewater).

Pollutant (*i*)	**A*i* (mg/l)**	**B*i* (%)**	**C*i* (mg/l)**
Suspended solids	≤80	57.09	186.00
Total P *	≤10	43.82	3.57
$N\text{-}NH_4$	≤15	71.70	53.60
$N\text{-}NO_3$	≤20	86.28	143.00
BOD	≤40	12.04	45.45
COD	≤160	39.53	266.67

Table 3 Literature data for the input pollutant concentration and abatement rates compared to the experimental FWS wetland and to the hypothetical reference wastewater.

Reference	Concentration in (mg/l)	Concentration out (mg/l)	% abatement	notes
Total P				
Braskerud 2005, 2005 b	<2,15			I order kinetics described
Kadlec & Knight 1996	3.78		57	I order kinetics described
Knowlton et al., 2002	2.1	2	4	
USEPA 2001	28.4	6.8	76.1	Cited by McCaskey & Hannah
	25.3	10.8	57	Cited by Reaves & Dubowy 1996
	33	17	48	Cited by Moore & Niswander 1996
ITRC 2003	4		48	
Suspended solids				
USEPA 2001	135.7	15.5	88.6	Cited by McCaskey & Hannah
	483.4	113.2	77	Cited by Reaves & Dubowy 1996
	1596	48	97	Cited by Hermans & Pries
	542	142	74	Cited by Moore & Niswander 1996
Nyakang'o 1999	200-600	70	85	
BOD-COD				
Dass 2004	50-200		80-95	BOD and COD
ITRC 2003	20-100		67-80	BOD
Nyakang'o 1999	500-750	20	98	BOD
	800-1000	20	96	COD
N-NH4				
Kadlec & Knight 1996	<20		54	
USEPA 2001	55.6	8.6	84.5	Cited by McCaskey & Hannah
	199.4	99.8	50	Cited by Reaves & Dubowy 1996
	12	2.4	80	Cited by Hermans & Pries
	126	65	48	Cited by Moore & Niswander 1996
ITRC 2003	230		91	Cited by Mulamoottil et al.,1999
Nyakang'o 1999	60-80	10	90	
N-NO3:				
Jordan 2003	<1			I order kinetics described
Kovacic 2000	7.5-14.5		25-99	
Lorion 2001	100-150	10		

Table 4 Cost descriptions for the selected and equally effective FWS treatment plants. WA = wetland, which includes as cost: plantation, addition of soil and shaping of banks, plantation management care, harvesting and regeneration costs; WB = wetland, which include as cost: plantation, addition of soil and shaping of banks, service road construction, plantation management care, harvesting and regeneration costs; WC = wetland, which include as cost: plantation, addition of soil and shaping of banks, service road construction, pumping stations, electrical system and connections, plantation management care, maintenance of pump station and utilities, harvesting and regeneration costs.

Cost category	**Cost description**	**WA (€)**	**WB (€)**	**WC (€)**
Development (C_I)	Addition of soil and shaping of banks	1096276.50	1218085.00	1218085.00
	Electrical system, electric connections			16113.00
	Inflow pumping station			118992.00
	Outflow pumping station			97200.00
	Plantation	297247.00	297247.00	297247.00
Sub total (C_I)		1393523.50	1515332.00	1747637.00
Ordinary maintenance (C_{GO})	plantation management care	34008.69	34008.69	34008.69
	maintenance of pump station and utilities			134.278,80
Sub total (C_{GO})		34008.69	34008.69	168287.49
Extraordinary maintenance (C_{GS})	harvesting and regeneration of the wetland wood	40000.00	40000.00	40000.00
Sub total (C_{GS})		40000.00	40000.00	40000.00
Total		**1467532.19**	**1589340.69**	**1955924.49**

Table 5 Cost descriptions of the selected and equally effective technological treatment plants. TA1: liquid sludge – disposal within 0 km; TB1: liquid sludge – disposal within 25 km; TC1: liquid sludge – disposal within 50 km; TD1: solid sludge – disposal within 0 km; TE1: solid sludge – disposal within 25 km; TF1: solid sludge – disposal within 50 km; TG1: solid sludge – composting.

Cost category	**Cost description**	**TA1 (€)**	**TB1 (€)**	**TC1 (€)**	**TD1 (€)**	**TE1 (€)**	**TF1 (€)**	**TG1 (€)**
Development (C_I)	construction of 2 concrete tanks	85000.00	85000.00	85000.00	85000.00	85000.00	85000.00	85000.00
	delivery and installation of the electric-mechanical devices	95000.00	95000.00	95000.00	95000.00	95000.00	95000.00	95000.00
	plant automation	20000.00	20000.00	20000.00	20000.00	20000.00	20000.00	20000.00
	delivery and installation of a mechanical dehydrator				50000.00	50000.00	50000.00	50000.00
Subtotal (C_I)		200000.00	200000.00	200000.00	250000.00	250000.00	250000.00	250000.00
Ordinary maintenance (C_{GO})	technical maintenance	300000.00	300000.00	300000.00	420000.00	420000.00	420000.00	420000.00
	analytical and technical management	108000.00	108000.00	108000.00	108000.00	108000.00	108000.00	108000.00
	Energy consumption	360000.00	360000.00	360000.00	375000.00	375000.00	375000.00	375000.00
	Final sludge disposal	0.00	120000.00	240000.00	0.00	22500.00	45000.00	288000.00
Subtotal (C_{GO})		768000.00	888000.00	1008000.00	903000.00	925500.00	948000.00	1191000.00
Extraordinary maintenance (C_{GS})		40000.00	40000.00	40000.00	40000.00	40000.00	40000.00	40000.00
Subtotal (C_{GS})		40000.00	40000.00	40000.00	40000.00	40000.00	40000.00	40000.00
Total		1008000.00	1128000.00	1248000.00	1193000.00	1215500.00	1238000.00	1481000.00