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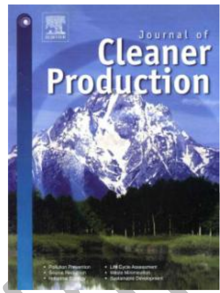

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Connection of neighboring WWTPs: economic and environmental assessment

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ABSTRACT

This paper explores the potential of integrated management of neighboring wastewater treatment plants (WWTPs) . The novelty lies in the integration of environmental aspects, with the application of life cycle assessment (LCA) methodology, together with economic criteria for the selection of best alternatives. A case study illustrates how the connection of neighboring wastewater systems by constructing an extra pipeline provides positive results in the economic assessment, and in the majority of the LCA categories used in the global environmental assessment. The consideration of local environmental constraints suggests that the usage of the connection should be limited to periods when the minimum ecological flow in the river section between the discharges of the two WWTPs is maintained. In this particular case, the scenario promotes the usage of the connection between the two WWTPs (but with some restrictions in dry weather periods) is preferred because it provides cost savings of 45,053€·year^{-1} and satisfies environmental criteria. A scenario analysis has been conducted to evaluate the influence of the pipe length on both economic and environmental aspects and the influence of individual cost terms on the economic assessment.

KEYWORDS. Life cycle assessment, economic evaluation, integrated management.

1. Introduction

Public or private companies operating wastewater systems are facing the challenge of reviewing their practices in terms of environmental and economic performance. Most of the studies resulting from such reviews focus on optimizing single wastewater systems, typically without considering the effects on the receiving media. However, recent water directives define that measures on a river basin scale, as the optimization of environmental performance and economics should be conducted for multiple wastewater systems in the same river basin and should take into account the impacts on the receiving media. The consideration of the specific characteristics of the receiving water bodies in the management of WWTPs is needed if aiming to minimize the impact on water bodies and fulfill the Water Framework Directive objectives of good environmental (i.e., ecological and chemical) status (Corominas et al., 2013a). This is especially relevant in semi-arid regions (such as the Mediterranean) with low river flows and significant contribution of WWTP discharges.

Some studies can be found in the literature evaluating the integrated management of multiple facilities from and environmental and/or economic point of view. The study of Thames Water (Dennison et al., 1998) on biosolids management showed that environmental impacts (by using life cycle assessment - LCA) influenced more the decision rather than capital costs.

Lundie et al. (2004) performed an LCA for Sustainable Metropolitan Water Systems Planning evaluating the integrated management of 31 wastewater systems, but no economical assessment was present in the paper. Yuan et al. (2010) demonstrated through a cost-effectiveness analysis, but without using a life cycle approach, that sharing WWTPs in an industrial Park in China was a better option compared to independent operation of several WWTPs. Similarly, Cost-effectiveness of integrated operation of two neighboring WWTPs together with the receiving water body impact was demonstrated using deterministic models for predicting water quality without including LCA criteria (Benedetti et al., 2009; Devesa et al., 2009 and Prat et al., 2012). Finally, there are some works with the aim of improving the environmental performance of the integrated urban water cycle (from drinking water production until wastewater treatment), proposing a procedure for the selection of sustainability indicators (Lundin and Morrison, 2002), analyzing different future scenarios (Lundie et al., 2004; Lassaux et al., 2007; Friedrich et al., 2009), identifying weaknesses to the current situation and proposing improvements (Mahgoub et al., 2010; Lemos et al., 2013), focusing on the water supply plans (Muñoz et al., 2010), evaluating sustainability of a Mediterranean city (Amores et al., 2013) or comparing different cities with different locations and specificities (Uche et al., 2013). However, none of these studies combined environmental and economical aspects in the assessment.

The combination of both economic and environmental assessment criteria improves the decision making process (Rodriguez-Garcia et al., 2011; Chong et al., 2012). In some cases, higher environmental benefits are achieved without cost incremental (e.g. Dennison et al., 1998). In other situations, the achievement of higher environmental benefits supposes an additional cost (e.g. Sharma et al., 2009). In any case, economic assessment has to also be addressed from a Life-Cycle perspective, including both capital and operational costs. Hence, LCA-based Life Cycle Costing allows for an integrated environmental and economic assessment of different options, therefore enabling decision-makers to make the best overall decision, or to tackle trade-offs, if they exist, on a transparent basis (Rebitzer et al., 2003).

So far, none of the published studies evaluated the integrated management of WWTPs by combining environmental and economic aspects. Furthermore, in the real world of environmental issues, it is absolutely necessary to understand what would the impact of WWTP effluents be on the receiving environment at a local scale. Since the provision of a set of “accepted” characterization factors that can be applied at local scale is still a challenge (Corominas et al., 2013b) within the LCA community it is proposed in this paper to combine local and global environmental aspects within the analysis.

Therefore, the goal of this paper is to propose a methodology to evaluate the integrated management of neighboring WWTPs including economical and environmental (local and global) criteria. The usefulness of the proposed methodology is illustrated with a case study which compares the reference scenario (i.e., the independent operation of two existing WWTPs) against a proposal that involves the construction of a pipeline of ~1 km that connects them and allows sending wastewater from the upstream to the downstream WWTP.

2. Materials and Methods

2.1. Proposed methodology

The proposed methodology for the assessment of integrated management of WWTPs and receiving water bodies we propose to combine: i) local environmental constraints (i.e. maintenance of the minimum ecological flow in the river into which the WWTPs discharge the treated water), ii) global environmental impact assessment through LCA applied according to the ISO 14040 (2006) standard; and iii) economic assessment, through the Net

Present Value (NPV) and the Internal Rate of Return (IRR) for the different management options.

Fig. 1 shows the proposed methodology, which includes environmental local constraints together with global environmental assessment and cost assessment in urban wastewater systems decision-making.

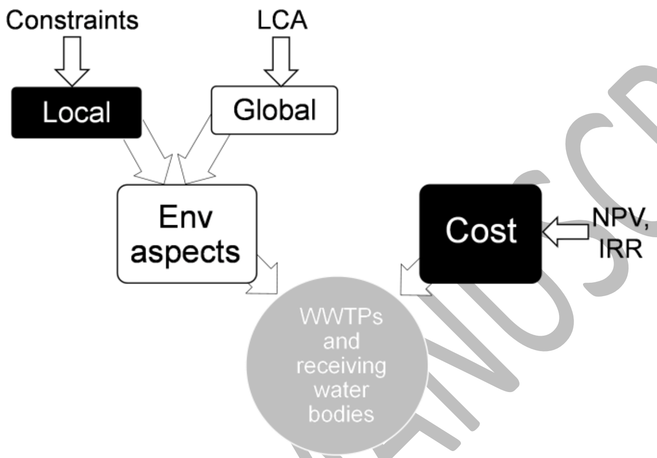

Fig. 1. Methodological approach proposed in this paper (the novelty is the inclusion of environmental local constraints and environmental assessment of urban wastewater systems, together with a cost assessment).

2.2. Case study

The system studied in this work is located in the Congost sub-catchment, which is part of the Besòs River catchment (NE Spain). The urban wastewater system consists of two different WWTPs: La Garriga and Granollers (Fig. 2). La Garriga (41º39'44.8"N, 2º17'13.5"E) is a 29,000 population-equivalent (PE) WWTP able to remove organic matter and nitrogen with a Modified Ludzack Ettinger configuration (MLE, Tchobanoglous, 2003). The sludge treatment consists of thickening and dewatering with polyelectrolyte addition, and the final dehydrated sludge is transported and treated in a composting plant. Granollers (41º34'05.0"N 2º16'19.5"E) is a 112,000 PE urban WWTP that biologically removes organic matter and nitrogen (also with a MLE configuration). Sludge treatment consists of anaerobic digestion with production of biogas, which is used to generate electricity that is sold back to the network. Sludge after the anaerobic treatment is dewatered (also with polyelectrolyte addition) and follows several pathways: approximately 25% of the sludge is land-applied in agriculture and 75% is treated in a thermal drying plant.

The reference scenario, i.e. the two WWTPs working individually, is compared in this study to two additional scenarios with integrated management of the two WWTPs after construction of the connecting pipeline, one bypassing 100% of the wastewater flow rate from La Garriga to Granollers WWTP (*bypass*$_{100\%}$), and the other one bypassing the limited wastewater flow rate (*bypass*$_{ecolflow}$) determined by the environmental local assessment (i.e. the minimum ecological flow; further explanation in the following section).

The connection between La Garriga and Granollers WWTPs requires the construction of a pipeline of 0.4 m in diameter and 1,139 m in length. The pipeline is gravity-flow, which means that it is not necessary to consume energy to send the water from one plant to the other. The construction of pumping stations is likewise unnecessary.

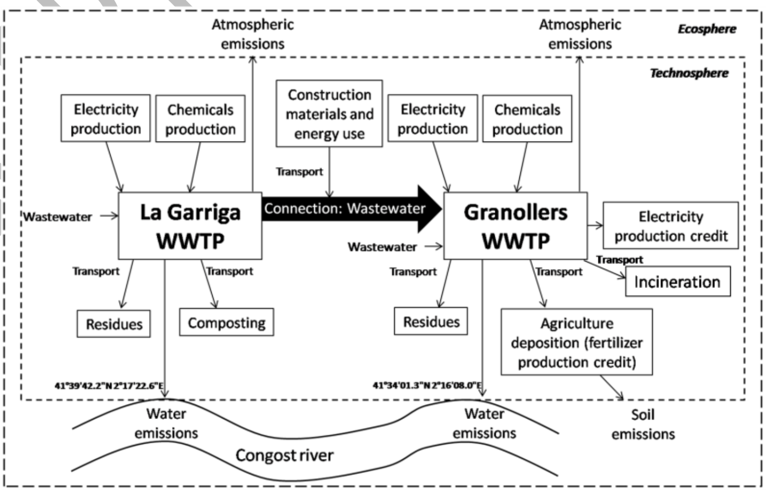

Fig. 2. System boundaries.

2.3. Local environmental constraints

During summer periods, the flow in the Congost river is very low (< $0.1 m^3 \cdot s^{-1}$) and the contribution of La Garriga WWTP effluent represents approximately 50% of the total flow in the river. Thus, using the connecting pipeline to bypass wastewater from La Garriga WWTP to the Granollers WWTP would represent a significant decrease in water availability in the river section from La Garriga discharge to the Granollers discharge.

Goal. The goal is to identify the critical months when the bypass would not be recommended due to water scarcity in the river.

***Inventory*.** Flow data were acquired from a monitoring station located in the Congost river and operated by the Catalan Water Agency. The period between 1996 and 2011 was used for this evaluation.

Assessment. We use the indicator established by the Catalan Water Agency (ACA) of the minimum ecological flow that must be maintained in a river course to guarantee the viability of its natural systems. Ecological flow or environmental flow is defined as the flow regime required in a river to achieve desired ecological objectives (Acreman and Dunbar, 2004). For the Congost river in La Garriga the ecological flow is defined by the Catalan Water Agency (ACA, 2005) as a variable flow rate depending on the season of the year (i.e. 0.069 $m^3 \cdot s^{-1}$ in winter, 0.057 $m^3 \cdot s^{-1}$ in spring and autumn and 0.046 $m^3 \cdot s^{-1}$ in summer).

Data interpretation. The median value for the flow data measured during each month of the 15 years was compared to the ecological flow (Fig. 3).

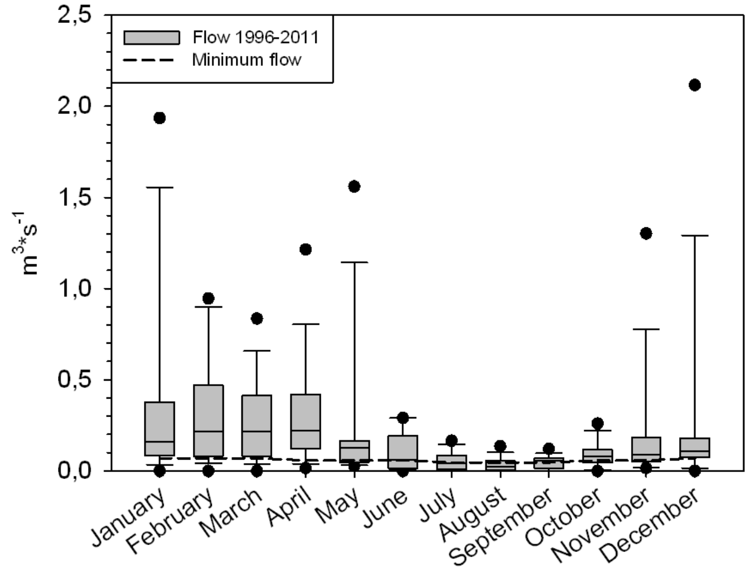

Fig. 3. Relationship between river flow and minimum river flow.

Fig. 3 shows a box plot of monthly median flows using data from 1996 until 2011 provided by the Catalan Water Agency (ACA). It can be observed that, from June to August, the median is below the ecological flow, and in September, the median is very close to the ecological flow. Therefore, the bypass of wastewater flow rate from La Garriga to Granollers during these months would not be recommended. This result establishes the bypass considering the ecological river flow defined in the second evaluated scenario ($bypass_{ecolflow}$), which means bypassing 100% of the wastewater flow rate for the entire year, except for the period with low river flow, when the by-pass should be 0%. The other scenario evaluated not considers the ecological river flow, for that scenario a bypass of 100% of the wastewater for all the year is considered.

2.4. Global Environmental Impact Assessment

Goal and scope. The goal is to assess the potential environmental impacts of the integrated operation of two neighboring WWTPs. In the reference scenario, the two WWTPs are already built. Hence, only the impact of the construction of the connecting pipeline and the operation of the two plants are considered. Dismantling of the infrastructure is not included. The functional unit is the volume of wastewater treated in the system during 20 years, which was 161,198,160 m^3 for Granollers and 3,094,560 m^3 for La Garriga. The 20-year period corresponds to the lifespan of the updated wastewater treatment infrastructure. The system boundaries (see Fig. 2) include a differentiation between ecosphere and technosphere. Ecosphere considers direct emissions from the system to the natural systems (water, air and soil). These emissions include atmospheric emissions related with the WWTP operation, soil emissions from the sludge deposited as fertilizers and water emissions to the river of the water discharged from the WWTP. Technosphere is defined as the man-world made and includes all the processes related with human activities and needs, it includes electricity and chemicals production, transports, construction materials, energy used, residues deposition and sludge treatments. Finally, no impacts from the pipeline operation were considered because the connection works by gravity flow. The maintenance of the pipeline was also excluded.

Inventory. The inventory data (see Table 1) comprises the following: i) inputs to the system from the technosphere (consumption of electricity, polyelectrolyte and transport); ii) outputs from the system (emissions to the water and air, and outputs to further treatment); and iii) avoided products (electricity produced from biogas and fertilizers). The data regarding the operation of the two WWTPs were provided by the water management board of the Besòs River Basin. We computed the mean of the monthly averages for the years between 2009 and 2010 for WWTPs. The concentrations of heavy metals at the effluent of the Granollers WWTP were provided by the Catalan Water Agency, as average concentrations of four analytical measurement campaigns between 2008 and 2011. The same heavy metals concentrations were assumed for the effluent of La Garriga WWTP. No data were available for the heavy metals concentrations in the sludge, and therefore we used the maximum concentrations established by the Spanish legislation that allow agricultural land application of sludge (REAL DECRETO 1310/1990, 1990). This assumption might lead to an overestimation of the toxicity-related impacts, since we would expect heavy metals concentrations in the biosolids from the WWTPs to be below the legislation limits. The air emissions (i.e., N_2O and CH_4 from secondary treatment, biogas combustion and the river) were calculated using the factors from Foley et al. (2010) (0.01 kg N_2O-N per kg N denitrified for secondary treatment, 0.025 kg CH_4 per kg COD discharged and 0.0025 kg N_2O-N per kg N discharged for the effluent and finally, 16.02 g CH_4 per Nm^3 biogas and 0.73 g N_2O per Nm^3 biogas for biogas combustion). Finally, the data related to transportation, measured in t·km were obtained from the transporting distances (40 km for composting; 60 km for the landfill; 100 km for agriculture; 5 km for thermal heating treatment; 10 km for grease disposal) and the metric tons of residues generated. The inventory for sludge composting was obtained by combining the inventories provided in Amlinger et al. (2008) and Sablayrolles et al. (2010)**.** For the agricultural application of the digested sludge, information from Doka (Doka, 2009) and the Spanish law regarding sewage sludge application were used (REAL DECRETO 1310/1990, 1990).

A new inventory was conducted for the construction of a pipeline of 1,139 meters. The construction process was divided into 4 different stages: i) trench excavation and preliminary work; ii) tube placement; iii) refilling; and iv) transportation of excess soil or distribution around the work. The required resources and energy at each stage were calculated. This inventory was conducted in collaboration with a construction company (Voltes S.L.U., Spain), using their databases together with public databases for the characterization of materials (BEDEC databases, publicly available (until spring-summer 2014) in the webpage of the Construction Technology Institute of Catalonia –ITEC-, www.itec.cat). These databases contain different types of items with information about resources used and unit prices for each and are used by architects and engineers to elaborate their budgets in construction projects. The process to construct the inventory was as follows: i) searching the typical items for this type of construction; ii) searching for these items in the databases; and iii) transforming each item into resources needed for the construction. Details about this inventory can be found in Table 2.

Impact assessment. The data from the inventories were introduced into Simapro 7.3.3, a software developed by Pre-sustainability company that permits easily to model and analyze complete life cycle assessments in a systematic and transparent way. To calculate the environmental impacts the CML 2 baseline 2000 method, developed by Institute of Environmental Studies (CML), University of Leiden (Guinée et al., 2001) was used. This method has been widely adopted in applied LCA literature (19 out of 26 papers about wastewater treatment applied CML, Corominas et al., 2013b). The evaluated categories are: Abiotic Depletion (ADP), Acidification (AP), Eutrophication (EP), Global Warming Potential (GWP), Ozone Layer Depletion (OLD), Human Toxicity (HTP), Freshwater Aquatic Ecotoxicity (FAETP), Marine Aquatic Ecotoxicity (MAETP), Terrestrial ecotoxicity (TTP), and Photochemical Oxidation (PHO) (Table 3).

***Data interpretation*.** The current situation (without the connecting pipeline) was taken as baseline for comparison. Then the two scenarios that required the pipeline construction were compared to this reference scenario, presenting the induced and the avoided impacts as a percentage.

2.5. Economic Assessment

***Goal*.** The objective is the assessment of the economic feasibility of the pipeline's construction and operation by estimating the benefits of the integrated operation of these two

WWTPs. The assessment was made for a 10 year horizon in order to ensure that the investment will be amortized during the operational period.

Inventory. The annual costs related to the plant operation included the cost of electrical energy consumption, revenues from the generated electricity sold back to the network, costs of the chemicals (polyelectrolyte), and costs associated to the disposal of the final residues. These data were provided by the Besòs River Basin water board. The costs of the construction of the pipeline were obtained using the databases from ITEC. Personnel costs were not included, as we assumed there would be no changes among the scenarios. The details of the inventory costs for the economic assessment can be found in Tables 1 and 2.

Table 1
Inventory of the Granollers and La Garriga WWTPs (values, expressed per 1 m^3 of treated wastewater)

	Granollers WWTP		La Garriga WWTP	
	Environmental assessment	Economic assessment	Environmental assessment	Economic assessment
Inputs to the system (electricity)	**kwh·m^{-3}**	**€·m^{-3}**	**kwh·m^{-3}**	**€·m^{-3}**
Electricity	$5.44\cdot10^{-1}$	$4.62\cdot10^{-2}$	$4.83\cdot10^{-1}$	$5.31\cdot10^{-2}$
Inputs to the system (materials)	**kg·m^{-3}**	**€·m^{-3}**	**kg·m^{-3}**	**€·m^{-3}**
Polymer	$3.61\cdot10^{-3}$	$1.08\cdot10^{-2}$	$1.44\cdot10^{-3}$	$4.32\cdot10^{-2}$
Emissions to water	**kg·m^{-3}**		**kg·m^{-3}**	
COD	$6.01\cdot10^{-2}$	--	$4.21\cdot10^{-2}$	--
Nitrite	$3.56\cdot10^{-4}$	--	$5.42\cdot10^{-5}$	--
Nitrate	$5.41\cdot10^{-3}$	--	$5.42\cdot10^{-3}$	--
Ammonium	$1.53\cdot10^{-2}$	--	$2.15\cdot10^{-3}$	--
Phosphorus, total	$5.18\cdot10^{-3}$	--	$3.54\cdot10^{-3}$	--
Arsenic	$1.28\cdot10^{-6}$	--	$1.28\cdot10^{-6}$	--
Cadmium	$5.00\cdot10^{-7}$	--	$5.00\cdot10^{-7}$	--
Chromium	$8.05\cdot10^{-6}$	--	$8.05\cdot10^{-6}$	--
Copper	$5.85\cdot10^{-6}$	--	$5.85\cdot10^{-6}$	--
Mercury	$1.00\cdot10^{-6}$	--	$1.00\cdot10^{-6}$	--
Nickel	$2.23\cdot10^{-5}$	--	$2.23\cdot10^{-5}$	--
Lead	$6.45\cdot10^{-6}$	--	$6.45\cdot10^{-6}$	--
Zinc	$1.01\cdot10^{-4}$	--	$1.01\cdot10^{-4}$	--
Emissions to air	**kg·m^{-3}**		**kg·m^{-3}**	
Methane, biogenic	$1.50\cdot10^{-3}$	--	$1.05\cdot10^{-3}$	--
Dinitrogen monoxide (river)	$4.11\cdot10^{-4}$	--	$2.40\cdot10^{-5}$	--
Dinitrogen monoxide (WWTP)	$6.03\cdot10^{-5}$	--	$4.11\cdot10^{-4}$	--
Methane (biogas combustion)	$1.29\cdot10^{-3}$	--	--	
Dinitrogen monoxide (biogas	$5.89\cdot10^{-5}$	--	--	

combustion)				
Outputs to further treatment	**kg·m^{-3}**	**€·ton^{-1}**	**kg·m^{-3}**	**€·ton^{-1}**
Municipal solid wastes	$5.29 \cdot 10^{-2}$	60	$2.81 \cdot 10^{-2}$	60
Efficient heat treatment of sludge	$7.67 \cdot 10^{-1}$	10-120	--	--
Agriculture disposal of sludge	$2.18 \cdot 10^{-1}$	28-30	--	--
Fat wastes	$1.20 \cdot 10^{-2}$	60	$4.83 \cdot 10^{-4}$	60
Composting	--	--	$9.17 \cdot 10^{-1}$	45
Transports	**tkm·m^{-3}**		**tkm·m^{-3}**	
Landfill	$3.18 \cdot 10^{-3}$	--	$1.69 \cdot 10^{-3}$	--
Heat treatment	$3.84 \cdot 10^{-3}$	--	--	--
Agriculture	$2.18 \cdot 10^{-2}$	--	--	--
Composting	--	--	$3.66 \cdot 10^{-2}$	--
Fat treatment	$1.20 \cdot 10^{-4}$	--	$4.83 \cdot 10^{-6}$	--
Avoided products	**kwh·m^{-3}**	**€/kwh**		
Electricity	$2.04 \cdot 10^{-1}$	0.14	--	--

Table 2 shows the inventory of materials for the four steps involved in the construction of the 1,139 m length pipeline of a trench with a tube of reinforced concrete of a diameter of 40 cm, filled with a layer of granite sand, and using material extracted on site. The costs are also included in the table.

Table 2
Pipeline construction inventory for the 1139 meters of length

Phase	Material	Consumption	Cost (€)
Excavation	Diesel (MJ)	24,294	8,300
Tub placement	Diesel (MJ)	14,440	50,810
	Water (m^3)	172	
	Reinforcing steel (kg)	22,173	
	Concrete (kg)	246,146	
	Synthetic rubber (kg)	1,817	
	Portland cement (kg)	196	
	Mortar I (kg)	4,895	
	Mortar II (kg)	1,108	
	Cast iron (kg)	1,985	
	Steel (kg)	3	
	Transport (tkm)	7,370	
Trench filling	Diesel (MJ)	11,321	21,450
	Water (m^3)	43	
	Granite (kg)	1,554,928	
	On-site soil (kg)	586,357	
Transport of excess soil	Transport (tkm)	141,268	8,025

Assessment. The cost-effectiveness analysis was conducted including the construction of the pipeline and the operation of the WWTPs. The Net Present Value (NPV) and the Internal Rate of Return (IRR) were computed afterwards to assess the cost-effectiveness of the investment, taking into account a maximum payback time of 10 years. NPV is a procedure that permits to calculate the present value of a determined future number of cash flows (incomes less expenses) originated thanks to an investment. The methodology consists to discount to the current moment all the future cash flow and compare it with the investment. IRR assesses the profitability in the expiration of an investment and is defined as the interest tax that makes the NPV equal to 0 in the expiration of an investment. Equation 1 shows the calculation for the NPV

$$NPV = {}^{n}{}_{t=1}\sum V_t /(1+k)^t - I_0 \qquad \text{(Eq. 1)}$$

where n is the number of periods considered, t is the number of years considered, V_t is the cash flow for every t^{th} period, k is the discount rate or rate of return and I_0 is the investment. In this case, a discount rate of 7%, a period of 10 years, an investment of 112,265 € and two different cash flows of 72,085 € and 45,053 € were used to calculate the savings of the $bypass_{100\%}$ and $bypass_{ecolflow}$ scenarios, respectively.

***Data interpretation*.** The reference scenario (no existence of the connecting pipeline) was taken as the baseline for comparisons and the induced and avoided costs of the different scenarios are calculated. The NPV and IRR are presented for each scenario together with the length of the payback time. The interpretation also includes a scenario analysis conducted to assess the maximum length that the pipeline could have for these two scenarios and still have a cost-effective investment. In addition, a scenario analysis on the main factors influencing the overall costs of the reference scenario was conducted.

3. Results and discussion

3.1. Global Environmental Assessment

The results of the environmental impact assessment are presented in Fig. 4 for the two bypassing scenarios calculated with respect to the reference one. We can also see the separate impacts associated with the construction of the pipeline. First, it can be observed that the construction induces some impacts compared to the reference scenario (positive percentages), but they are negligible (always less than 1%). The results of the scenarios $bypass_{100\%}$ and $bypass_{ecolflow}$ (both after constructing the pipeline) show a trade-off between impact categories. Compared to the reference scenario, the avoided impacts are obtained for ADP, up to 22%; GWP, up to 5%; OLD, up to 22%; MAETP, up to 0.5%; and PHO, up to 17%. The increased electricity production in Granollers (thanks to the increased influent load with the activation of the bypass) has a positive effect on all these impact categories. Additionally, the increase of biosolids applied to agriculture reduces the consumption of chemical fertilizers, which production negatively impacts on the ADP, OLD and PHO (see Table S.1 on impact categories and processes in the Supporting information). Similar observations on the effects of electricity production on the impact categories is found in Pasqualino et al., (2009) and Niero et al., (2014). The work of Hospido et al., (2008) also confirms the benefits on the ADP when applying biosolids to agriculture. Compared to the reference scenario, induced impacts are observed for AP, EP, FAETP, HTP and TTP categories. AP becomes up to 2.7% and EP up to 3.8% worse (for the $bypass_{ecolflow}$ scenario) because the nutrient removal efficiency of the Granollers WWTP is lower than the La Garriga WWTP (but always within the legislation limits) which results with an increase in the nutrient loads discharged to the river. There is an increase up to 8.2% in the FAETP, an increase up to 11.3% in TTP and an increase up to 3 % in HTP which are explained by the increase of land-applied biosolids. The increased mass of heavy metals is released to the soil and finally to freshwater resources.

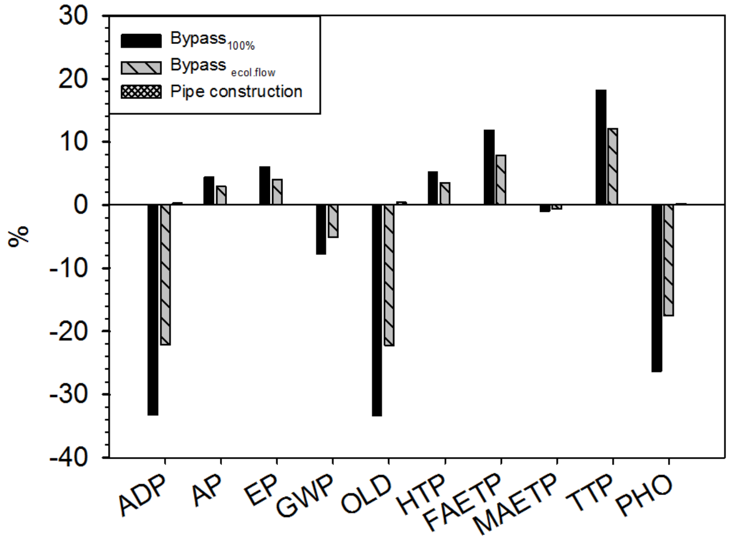

Fig. 4. Environmental assessment results for 20 years. Induced impacts compared to reference scenario correspond to positive percentages and avoided impacts are negative percentages. The reference scenario corresponds to 0%.

Table 3
Impact categories analyzed, with its name, abbreviation used and meaning

Name	Abbreviation	Meaning
Abiotic Depletion	ADP	Consumption of natural resources, including energetic resources, considered as non-living.
Acidification	AP	Impact of acidifying pollutants in the natural environment, man-made environment, human health and natural resources.
Eutrophication	EP	Potential impacts of excessively high environmental levels of macronutrients.
Global Warming Potential	GWP	Human emissions contributing to the radiative forcing of the atmosphere.
Ozone Layer Depletion	OLD	Thinning of the stratospheric ozone layer as a result of the human emissions.
Human Toxicity	HT	Impacts on human health as a result of toxic substances present in the environment.
Freshwater Aquatic Ecotoxicity	FAETP	Impact of toxic substances on freshwater aquatic ecosystems.
Marine Aquatic Ecotoxicity	MAETP	Impact of toxic substances on marine aquatic ecosystems.
Terrestiral Ecotoxicity	TTP	Impact of toxic substances on terrestrial ecosystems.
Photochemical Oxidation	PHO	Formation of reactive chemical compounds by the action of sunlight in certain primary pollutants.

3.2. Economic assessment

Fig. 5 shows the induced and avoided costs for the two bypassing scenarios compared to the reference scenario. Reference in the figure corresponds to current situation, when 0% by pass between La Garriga and Granollers WWTPs is produced. Any values presented in the figure are referred to that reference situation. Positive values represent additional costs generated in the scenarios and negative values represent savings. The integrated operation of the two WWTPs represents operational savings because the cost of the electricity (per kwh, see Table 1) and the cost for sludge treatment are lower for the Granollers system compared to La Garriga. Although electricity consumption in Granollers increases, there are additional savings generated by selling electricity back to the network. However, costs increase in Granollers because the consumption of chemicals and the generation of municipal solid waste per cubic meter of treated wastewater are higher. Overall, the annual savings for the *bypass*$_{100\%}$ scenario are 72,085 € and 45,053 € for the *bypass*$_{ecolflow}$ scenario with respect to the reference scenario. However, the construction of the connection involves an investment of 112,265 €.

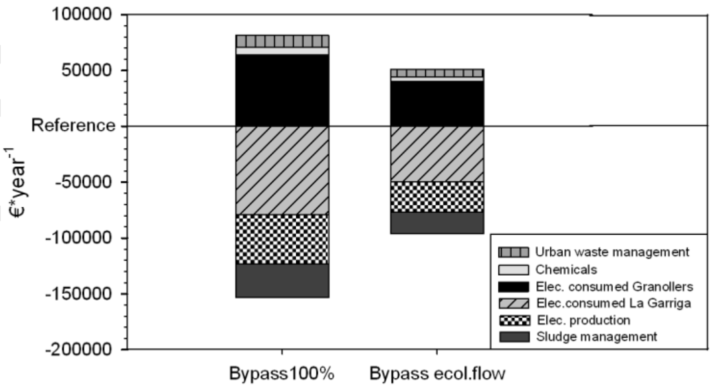

Fig. 5. Induced and avoided costs for the different evaluated scenarios compared to the reference scenario. Current situation (0% bypass between La Garriga and Granollers) is the reference scenario and all the changes are compared with the current situation.

Table 4 shows the results of the NPV and the IRR calculations. The results show that for these two scenarios the investment is economically feasible. Considering a discount rate of 7%, the NPV shows a positive value of 204,171 € for the $bypass_{100\%}$. The IRR calculation shows a percentage greater than 7%, indicating that this investment will be economically feasible until discount rates of 63% and 38% for the $bypass_{100\%}$ and the $bypass_{ecolflow}$ scenarios, respectively, occur. The table also shows that by applying the 7% discount rate, an amortization period of 1 year and 10 months would be required for the $bypass_{100\%}$ scenario and 2 years and 11 months for the $bypass_{ecolflow}$ scenario.

Table 4
NPV and IRR results

Scenario	By-pass $_{100\%}$	By-pass $_{ecolflow}$
NPV	394,033€	204,171€
IRR	63 %	38 %
Amortization (time when NPV becomes 0)	1 year and 10 months	2 years and 11 months

3.3. Integrated Assessment discussion

By identifying synergies that minimize the overall environmental impacts and costs, the results demonstrate that the connection of neighboring WWTPs can be economically and environmentally feasible both at global and local levels. In particular, for the case study of the Congost sub-catchment, it is economically and environmentally feasible to connect La Garriga and Granollers WWTPs, primarily due to the energy produced in Granollers, which generates avoided environmental impacts and results in a net economic income. Additionally, the treatment costs per unit volume are lower in Granollers WWTP. Finally, the sludge management in Granollers (anaerobic digestion with biogas recovery) is cheaper and more environmentally friendly compared to La Garriga (dehydrating and composting) (confirming the findings in Suh and Rousseaux, 2002). The drawback is the significant increase of the aquatic and terrestrial ecotoxicity (FAETP and TTP) (by more than 10%). The underlying cause for such an increase is related to the heavy metals. First, by using the maximum values allowed by the legislation we are probably overestimating these impacts. Second, the limitations of current toxicity models for assessment of metals are being discussed in literature (Hospido et al., 2005; Corominas et al., 2013b; Lane, 2014) and studies have confirmed wide variability of the toxicity impacts depending on the method used (e.g. (Gandhi et al., 2011) and have reported large uncertainties (Niero et al., 2014). Lane (2014) confirms that LCA Terrestrial Ecotoxicity models contradict the best available Australian risk assessment, and should be excluded from analysis of biosolids disposal options. In fact, application of biosolids to agriculture is a common practice in Spain which is also promoted by the government with the objective to achieve 70% of biosolids application to agriculture in 2015 (BOE núm. 49, of 20 of January of 2009) and the conclusions obtained in this study on the ecotoxicity impact categories without this proper interpretation might be discouraging the continuation of such practice. Hence, the $bypass_{100\%}$ scenario provides the best results in terms of only global environmental aspects and costs. However, the $bypass_{ecolflow}$ scenario is the one fulfilling both local and global environmental aspects, i.e. the minimum ecological flow that has to be maintained in the Congost river, at expenses of decreased annual savings (45,053 € compared to 72,085 € for the $bypass_{100\%}$). Under the economic situation with the financial problems in the water sector in Catalonia, the Besòs River management board decided to use that connection applying the $bypass_{ecolflow}$ scenario. This is the first time that such an analysis has been performed and brought into practice and therefore we believe that this is a significant contribution to the field.

4. Scenario analysis

4.1. Criticality of pipeline length

A scenario analysis was applied in this study to understand the influence of the pipeline length on the costs and on the global warming impact category. Hence, it is possible to provide an assessment of the maximum pipeline length that would make the investment economically and environmentally feasible. NPV calculations were repeated for pipeline lengths from 1 km to 6 km, evaluated every 200 meters. Fig. 6a shows the results obtained for the two scenarios that were evaluated. The investment would be cost-effective (considering a discount rate of 7% and 10 years of amortization) up to a length of 5 km and 3.2 km for the scenarios *bypass*$_{100\%}$ and *bypass*$_{ecolflow}$, respectively.

Fig. 6b shows the scenario analysis of the pipeline length on the net global warming potential impact (avoided minus induced emissions). We can see the maximum length of the pipeline for which the induced CO_2 emissions from the construction of the pipeline are compensated by the emissions from the operation of the system. The results show that maximum connection lengths of 75 km and 50 km are feasible in terms of CO_2 emissions for the scenarios *bypass*$_{100\%}$ and *bypass*$_{ecolflow}$, respectively. Hence, the limiting factor to connect two neighboring WWTPs with the similar characteristics to the ones used in this study would be economic more than environmental.

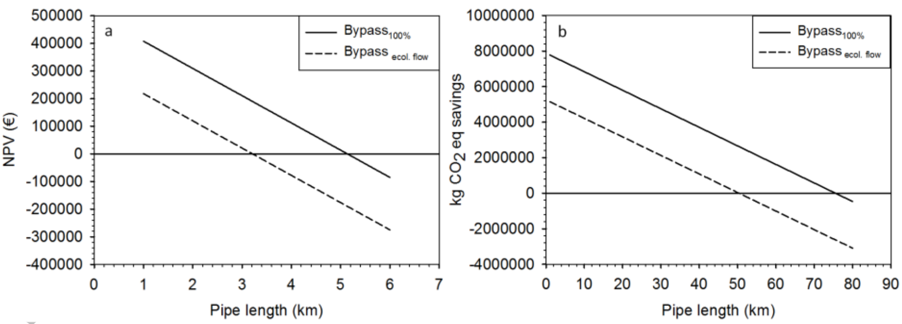

Fig. 6. Sensitivity analysis of the pipeline length on a) the VAN and b) the global warming potential.

4.2. Effect of tariffs evolution

A scenario analysis was conducted to evaluate the effect of tariffs (e.g., for treatment and disposal of residues or for electricity consumption) on the overall operating costs applied to the reference scenario. The analysis was conducted by increasing and decreasing one tariff at a time by 10%. Fig. 7a shows that the tariff for electricity (kwh·€$^{-1}$) in Granollers is the parameter that has the largest impact and hence, WWTP managers should make efforts to optimize energy consumption. The second most important tariff is the price for electricity sent back to the network, demonstrating the importance of maximizing energy production. These measures would also have positive effects on the environmental impact categories that are highly influenced by energy consumption (e.g., ADP, GWP). The same scenario analysis applied to the $bypass_{ecolflow}$ scenario (Fig. 7b) would lead to even more importance to the price of electricity in Granollers.

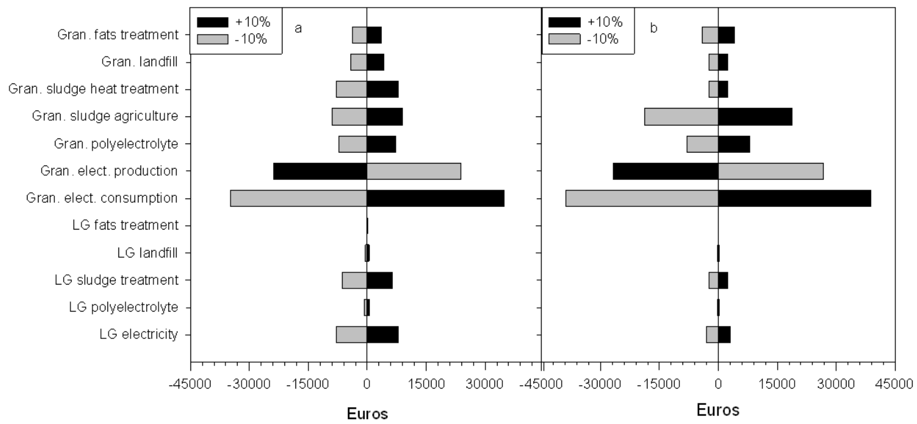

Fig. 7. Sensitivity analysis of the tariffs on the operating costs for reference scenario (a) and $\text{bypass}_{\text{ecolflow}}$ (b).

5. Limitations of the study and implications for practice

The results of this study are case-specific, and some of the assumptions made might affect the final outcomes. First, there are issues related to the construction and the operation of the connecting pipeline. We considered 20 years to be the lifespan of the upgraded infrastructure. However, there are different opinions about the lifespan of WWTPs and sewer systems (from 30 to 50 years in Lundin et al., (2000) and Doka (2009). Second, some processes considered (composting and agriculture disposal) and some emission factors applied (i.e. ammonia emissions and green house gases emissions from sludge, heavy metal emissions) were taken from literature which might not be fully in agreement with the real system. Third, toxicity-related categories are strongly related to the concentration of heavy metals present in the sludge and large uncertainties are behind currently applied models. Fourth, we assumed that the operation of the system and the infrastructure would not change over the lifespan of 20 years. But actually, changes in the demography of the region or industrial activities would be possible and then the overall balance would change.

Finally, technical feasibility should be carefully analyzed. For instance, turning a biological process such as an activated sludge system on and off is not that easy and might lead to undesired performances during the start-up of the process. Additionally, the connecting pipeline link to the sewer system infrastructure of Granollers was not designed to cope with the load from La Garriga. Currently, this is not a limitation, but in the future (if population increases) the percentage of wastewater bypassed might be limited by the capacity of that sewer system. An alternate management strategy then would be to treat the wastewater independently in both WWTP and to transport the sludge from La Garriga to the Granollers system, still gaining the benefits from energy production in Granollers (the transport distances might then become the limiting factor then).

6. Conclusions

A new methodology that includes economic and both local and global environmental aspects has been proposed for the integrated management of WWTPs and rivers. The methodology has been successfully applied to the assessment of the connection of two neighboring WWTPs in a Mediterranean river basin where the discharge of WWTPs has a significant impact. The study concludes that the inclusion of local environmental constraints (i.e. minimum ecological flow in the river) determines the selection of the most appropriate alternative. More specifically, the most economically feasible scenario is that with bypass activated the entire year, with cost savings of 72,085 €·y^{-1}. The consideration of local environmental aspects suggests that the usage of the connection should be limited to periods when the minimum ecological flow in the river section between the discharges of the two WWTPs is maintained (from October until May). Our study demonstrates that the feasibility for operating two neighboring WWTPs, for different capacity, different sludge treatment and disposal and energy recovery, in an integrated way must include, a part from the technical assessment, an economic and environmental impact assessment of the construction and operation of the two WWTPs and the required pipeline. In that sense, the length of the pipeline and the cost of energy are critical issues.

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