COMPREHENSIVE INVENTORIES FOR LIFE CYCLE ASSESSMENT IN WASTEWATER SYSTEMS

Sadurní Morera Carbonell

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DOCTORAL THESIS

Comprehensive inventories for Life Cycle Assessment in urban wastewater systems

One annex included

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DOCTORAL PROGRAMME IN WATER SCIENCE AND TECHNOLOGY

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Thesis submitted in fulfillment of the requirements for the degree of Doctor from the University of Girona

Certificate of thesis direction

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I per a què en prengueu coneixement i tingui els efectes que corresponguin, presentem davant la Facultat de Ciències de la Universitat de Girona, l'esmentada Tesi, signant aquest certificat.

Dr. Joaquim Comas Matas   Dr. Lluís CorominasTabares   Dr. Miquel Rigola Lapeña

Girona, 12 de gener de 2016

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Nadie cambiará el asfalto
por un manto verde y limpio.
Nadie cambiará el cemento
por un soplo de aire fresco.
Y si buscas el reflejo
de este ruin comportamiento
no, no, no busques muy lejos
búscalo en tu propio espejo
o búscalo en tu basurero.
Búscalo, búscalo.
Y mira bien que has tirado.
Mira bien que te ha sobrado.
Y sabrás quien eres.
Búscalo en tu basurero (¡Bulla!) El Último Ke Zierre (EUKZ) 2000

Família, amics, parella i tots els que alguna vegada m'han preguntat sobre com anava el desenvolupament de la meua tesi i n'han mostrat interès

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AC: Acidification
AD: Abiotic Depletion
CC: Climate Change
DWTP: Drinking Water Treatment Plant
EIA: Environmental Impact Assessment
EU: Eutrophication
FAET: Freshwater Aquatic Ecotoxicity
FD: Fossil Depletion
FE: Freshwater Eutrophication
GW: Global Warming
HDPE: High Density Polyethylene
HT: Human Toxicity
IRR: Internal Return Rate
LC: Life Cycle
LCA: Life Cycle Assessment
LCC: Life Cycle Costing
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment
LCSA: Life Cycle Sustainability Assessment
MAET: Marine Aquatic Ecotoxicity
MBRs: Membrane Bioreactors
MD: Metal Depletion
ME: Marine Eutrophication
MEC: Microbial Electrolysis Cell
MFC: Microbial Fuel Cell
MLE: Modified Ludzack-Ettinger
NPV: Net Present Value
OLD: Ozone Layer Depletion
PE: Population Equivalent
PHO: Photochemical Oxidation
PVC: Polyvinylchloride
SLCA: Social Life Cycle Assessment
TT: Terrestrial Ecotoxicity
UWC: Urban Water Cycle
UWS: Urban Water System
UWWS: Urban Wastewater System
WF: Water Footprint
WFA: Water Footprint Assessment
WFN: Water Footprint Network
WWT: Wastewater Treatment
WWTP: Wastewater Treatment Plant

RESUM

L'Anàlisi de Cicle de Vida (ACV) és una metodologia d'implantació ascendent que té per objectiu l'avaluació dels impactes ambientals potencials que pot causar un procés o producte al llarg de la seua vida. Aquesta metodologia va començar a desenvolupar-se a finals dels 60 i actualment compta amb una gran popularitat, amb un gran potencial per créixer i ser aplicat a molts i diversos camps. Una de les fases que exigeix més esforç en l'aplicació de la metodologia consisteix en la realització dels inventaris de consum de materials i energia, emissions, transports i generació de residus.Tot i haver-se aplicat diverses vegades en estudis de depuradores, la seva aplicació al sistema urbà de l'aigua residual encara presenta molts punts dèbils per superar. El sistema urbà d'aigua residual consta bàsicament de dos parts diferents: el sistema de col·lectors i les depuradores. Malgrat que existeixen alguns estudis publicats on s'ha analitzat el cicle de vida complet d'una depuradora, tot comparant diferents tecnologies o diferents estratègies d'operació, n'hi ha molt pocs que considerin amb detall la fase de la construcció d'una EDAR, i encara n'hi ha menysdel sistema de col·lectors d'un nucli urbà.

Aquesta tesi presenta l'aplicació detallada de la metodologia de l'ACV al sistema urbà d'aigües residuals. Està centrada en dos grans línies de treball: en la fase d'obtenció dels inventaris de construcció del sistema d'aigües residuals urbanes i en potenciar les aplicacions pràctiques de la metodologia ACV i petjada hídrica, com a eines d'avaluació ambiental.

Primerament, es presenta l'aplicació de la metodologia en la construcció de sistemes de col·lectors. En aquesta primera part es presenta un procediment que facilita els inventaris de construcció de les col·lectors, incloent una eina basada en Excel® que permet calcular de forma automàtica els inventaris i els impactes ambientals potencials per a la construcció de diferents tipus de col·lectors.

En segon lloc, es presenta l'aplicació de la metodologia ACV centrada en la fase de construcció de depuradores, presentant un procediment per calcular un inventari detallat de la seva construcció en una EDAR concreta de capacitat gran i, seguidament,comparant els impactes generats durant la construcció amb els generats durant l'operació.

En tercer lloc, es presenta l'estudi en que s'ha aplicat el procediment per la creació d'inventaris detallats de construcció de depuradores en 4 depuradores diferents de petita i

mitjana capacitat, per acabar trobant unes equacions que permeten relacionar la capacitat de les plantes amb el consum de materials i energia, els transports i el sòl que s'ha de dipositar en abocadors durant la construcció.

En quart lloc i, centrant-se en la segona línia de treball en que es fixa la tesi, es presenta una aplicació pràctica de la metodologia ACV que pot ser útil pelsòrgans de decisió per tal de considerar els impactes ambientals, juntament amb una anàlisi econòmica, en diferents estratègies de gestió de depuradores.

Finalment, la tesi presenta l'aplicació d'una altra metodologia que també es basa en el concepte de cicle de vida: la petjada hídrica. S'ha aplicat a una depuradora concreta amb eliminació de fòsfor, per tal d'analitzar com canvia l'impacte ambiental generat per l'aigua residual, abans i després de la seva depuració, referit a un sol vector ambiental, el consum equivalent d'aigua dolça.

Es considera que aquesta tesi compleix amb el seu objectiu ja que, gràcies als resultats adquirits, es podrà, en primer lloc, aconseguir inventaris per a la construcció tant de col·lectors com de depuradores d'una forma fàcil, consistent i molt més ràpida, i amb una gran versatilitat doncs permetrà anàlisis modulars de cadascun dels subprocessos de construcció dels col·lectors i de cadascuna de les unitats de procés en què típicament es divideix una EDAR. A més, ha permès veure i corroborar que la fase de construcció en depuradores també hauria de ser considerada. Finalment, mitjançant l'aplicació que se n'ha fet en sistemes reals ha permès mostrar de forma clara possibles aplicacions de la metodologia, a més de permetre mostrar la metodologia a òrgans de decisió, per tal d'aconseguir que la metodologia guanyi en acceptació i facilitat d'aplicació, i sigui encara més popular que avui en dia.

RESUMEN

El Análisis de Ciclo de Vida (ACV) es una metodología de implementación ascendente que tiene por objetivo la evaluación de los impactos ambientales potenciales que puede producir un proceso producto durante toda su vida. Esta metodología empezó a desarrollarse a finales de los años 60 y actualmente cuenta con una gran popularidad, y con un gran potencial para crecer y ser aplicada en muchos y distintos campos. Una de las fases que exige mayor esfuerzo en su aplicación consiste en la realización de los inventarios de consumo de materiales y energía, emisiones, transportes y generación de residuos. Aunque se ha aplicado muchas veces en estudios de depuradoras, su aplicación en el sistema urbano del agua residual aún presenta muchos puntos flacos a superar. El sistema urbano del agua residual se compone básicamente de dos partes diferentes: el sistema de colectores y las depuradoras. Aunque existen algunos estudios publicados dónde se ha realizado el ciclo de vida completo de una depuradora, comparando diferentes tecnologías o diferentes estrategias de operación, hay muy pocos que consideren con detalle la fase de construcción de una depuradora, i aún menos el sistema de colectores de un núcleo urbano.

Esta tesis presenta la aplicación detallada de la metodología del ACV en el sistema urbano de aguas residuales. Está centrada en dos grandes líneas de trabajo: en la fase de obtención de los inventarios de construcción del sistema de aguas residuales y en potenciar las aplicaciones prácticas de la metodología ACV y huella hídrica, como herramientas de evaluación ambiental.

En primer lugar, se presenta la aplicación de la metodología en la construcción de sistemas de colectores. En esta primera parte se presenta un procedimiento que facilita la creación de inventarios de construcción de colectores, incluyendo una herramienta basada en Excel$^{®}$ que permite calcular de un modo automático los inventarios y los impactos ambientales potenciales para la construcción de diferente tipos de colectores.

En segundo lugar, se presenta la aplicación de la metodología ACV centrada en la fase de construcción de depuradoras, presentando un procedimiento para calcular un inventario detallado de su construcción, aplicándolo en una depuradora concreta de gran capacidad, y después, comparando los impactos generados durante la construcción con los generados durante la operación.

En tercer lugar, se presenta el estudio en que se ha aplicado el procedimiento para la creación de inventarios detallados de construcción de depuradoras en 4 depuradoras diferentes de pequeña y mediana capacidad, para acabar encontrando unas ecuaciones que permiten relacionar la capacidad de las plantas con el consumo de materiales y energía, los transportes y el suelo que se tiene que depositar en vertederos durante la construcción.

En cuarto lugar, y centrándose en la segunda línea de trabajo en que se fija la tesis, se presenta una aplicación práctica de la metodología ACV que puede ser útil para los órganos de decisión para poder considerar los impactos ambientales, conjuntamente con un análisis económico, analizando diferentes estrategias de gestión de depuradoras.

Finalmente, la tesis presenta la aplicación de otra metodología basada, también, en el concepto de ciclo de vida: la huella hídrica. Se ha aplicado a una depuradora en concreto con eliminación de fósforo, con el objetivo de analizar cómo cambia el impacto ambiental generado per el agua residual, antes y después de su depuración, referido a un solo vector ambiental, el consumo de agua dulce.

Se considera que esta tesis cumple con su objetivo ya que, gracias a los resultados adquiridos, se podrá, en primer lugar, conseguir inventarios para la construcción tanto de colectores como de depuradoras de un modo fácil, consistente y mucho más rápido, y con una gran versatilidad, pues permitirá análisis modulares de cada uno de los subprocesos de construcción de los colectores y de cada una de las unidades de proceso en que típicamente se divide una depuradora. Además, ha permitido ver i corroborar que la fase de construcción en depuradoras tendría que ser siempre considerada. Finalmente, mediante la aplicación que se ha hecho en sistemas reales ha permitido mostrar de una forma clara posibles aplicaciones de la metodología, además de permitir mostrar la metodología a órganos de decisión, para conseguir que la metodología gane aceptación y facilidad de aplicación, y sea aún más popular que actualmente.

SUMMARY

The objective of the Life Cycle Assessment (LCA) methodologyis to assess the potential environmental impacts that a process or product can generate throughout its lifetime. The development of this methodology started in the late 60s and since then we have seen it increasing in popularity and being applied to many diverse fields. One of the phases of the LCA methodology that requiresa significant effort is the creation of the inventories for the consumption of materials and energy, emissions, transport and residues. Although this has been applied in different studies of Waste Water Treatment Plants (WWTPs), its application toUrban Waste Water Systems (UWWS) presented some weaknesses to overcome. The UWWS includes mainly two different parts, the sewer system and the WWTPs. Although there have been a number of published studies in which the life cycle of a WWTP was investigated comparing different methodologies or different operational strategies, there are very few studies that consider in detail the construction phase of a WWTP, and few consider the sewer systems of an urban area.

This thesis presents the detailed application ofthe LCA methodology in UWWS. The work focused on two main areas: the inventory phase for the construction of UWWS and enhancing the practical applications of the LCA methodology and Water Footprint (WF), as environmental analysis tools.

The first section deals with the application of the methodology to the construction of sewer systems. This includes a procedure to obtain the inventories of construction of sewer systems, including a tool based in Excel® that calculates automatically the inventories and the potential environmental impacts of constructing different types of sewer systems.

The second section focuses on the application of the LCA methodology to the construction of WWTPs. This provides a procedure to calculate a detailed inventory for the construction of a high capacity WWTP and after compares the impacts produced during the construction phase with those from the operational phase.

The third section utilizes the procedure from the previous section to obtain detailed inventories of four WWTPs of different capacities, ranging from small to medium capacity. This is presentedto relate the capacity of these plants with the consumption of material, energy, transport and soil that has to be deposited in a landfill during the construction phase.

The forth section focuses on the practical application of the LCA methodology that can be used by decision makers to consider environmental impacts, together with an economical assessment in different management strategies.

The final component of this thesis presents the application of another methodology also basedon the life cycle concept: the water footprint. This methodology has been applied to a specific WWTP with phosphorus removal, in order to analyze how the environmental impact produced by the wastewater changes, before and after of its treatment, referred only to one environmental aspect, consumption of freshwater.

The objectives of this thesis have been accomplish becausethrough this work it is now possible to compile inventories for the construction of sewer systems and WWTPs in a easier, consistent and quick manner, and with high versatility allowing modular analysis of each sub-process for the construction of sewer systems, units making up a WWTP. Additionally, the work shows that the construction phase in WWTPs has to be considered. Finally, the applications of real cases clearly showpossible applications of the methodology, and its effectiveness as a tool for decision makers.

LIST OF PUBLICATIONS

The following list contains the journal publications resulting from this doctoral thesis:

Morera, S., Comas, J., Poch M., Corominas Ll., (2015)

Connection of neighboring WWTPs: economic and environmental assessment.

Journal of Cleaner Production 90, 34-42. Impact factor: 3.844

Morera, S., Corominas Ll., Poch M., Aldaya M.M., Comas, J. (2016)

Water footprint assessment in wastewater treatment plants.

Journal of Cleaner Production 112, 4741-4748. Impact factor:3.844

Morera, S., Comas, J., Remy, C., Corominas Ll.

Life cycle assessment of construction and renovation of sewer systems using a detailed inventory tool

Submitted

Corominas, Ll., Foley, J., Guest, J.S., Hospido, A., Larsen, H.F., **Morera, S.,** Shaw, A. (2013)

Life cycle assessment applied to wastewater treatment: State of the art.

Water Research, 47, 5480-5492.Impact factor: 5.528

1 INTRODUCTION

1.1.-THEURBAN WATER CYCLE

The natural water cycle is a complex continuous process in which water circulates through the Earth and its atmosphere through evaporation, condensation, precipitation and transpiration. The journey of water in the urban water cycle (UWC) involves being collected in catchments, utilized and then returned to the natural water cycle as purified wastewater. The UWC starts when water is collected from natural systems such as rivers, dams, wells or channels and is delivered via pipes to the population. In many countries the water collected is first treated in a drinking water treatment plant (DWTP) using a combination of physical and chemical processes. Once the water has been treated it is then delivered through the distribution network to municipalities where is used for domestic activities, irrigating gardens, recreational uses, industrial activities, etc. After its use the (now polluted) water (otherwise known as wastewater) is collected and transported through a sewer system to a wastewater treatment plant (WWTP), where physical and bio-chemical treatment processes remove solids, organic matter, pathogens and nutrients, before it is discharged into receiving water bodies.

Fig. 1-1: Urban water cycle (http://aca-web.gencat.cat/aca/appmanager/aca/aca/).

1.2.- THE URBAN WASTEWATER SYSTEM

An urban wastewater system (UWWS) is comprised of a sewer system and a WWTP. There are mainly two types of sewers: combined sewer systems which are designed to manage rainwater run-off and wastewater from domestic and industrial use together in the same infrastructure, or separate sewer systems that have separate networks for rainwater run-off and wastewater from domestic and industrial use. A sewer system basically comprises pipes, manholes, pumping stations, overflows and connection points. Its construction requires large amounts of materials, civil work operations (e.g. excavating trenches) and transporting materials. A sewer system can be constructed with different materials, such as PVC, HDPE, concrete or ductile iron (Du *et al.*, 2013). Which material is selected depends on the characteristics of the area, local sewage requirements, traditions and economic costs (Petit-Boix *et al.*, 2014). The diameter of the pipes increases as more units are connected, thus the closer they get to the WWTP, the larger they become. Maintaining and renovating the infrastructure of a sewer is paramount and so pipes have to be replaced on a regular basis and depending on the life span of the material that was used to build them in the first place. Over the life span of the infrastructure, pipes must be replaced at least once and this means generating the same level of impact that the original construction work had. As it is preferable to transport wastewater by using the force of gravity, pumping stations are installed to make sure all the wastewater is collected and pushed through when required. Depending on the characteristics of the area and the wastewater, sewer system operation demands electricity consumption (water must be pumped), chemicals to avoid odor and corrosion problems (Ganigue*et al.*, 2011), and maintenance work (e.g. unblocking pipes).

Once all the wastewater has been collected, it is then transported to a WWTP. A WWTP is a combination of different processes that are typically in series (i.e. pre-treatment, primary treatment, secondary treatment, tertiary treatment and sludge treatment) and comprise of one or more operating units, each with a specific function designed to achieve better water quality. Pre-treatment and primary treatments are largely focused on particulate pollutants, while secondary treatment deals with dissolved pollutants. Specifically, the aim at the pre-treatment stage is to remove large solids, grit, oils and greases and then primary treatment works to remove most of the suspended solids. Secondary treatment, usually based on biological processes, treats the organic matter, nitrogen and phosphorous contained in the wastewater. The most commonly used biological secondary treatments are based on different configurations of an activated sludge system (a biological reactor followed by a settler). In some cases (normally when treated wastewater needs to be reused) a tertiary treatment is implemented to remove any remaining small particles, refractory organic matter and pathogens. Finally, sludge treatment treats the excess sludge reducing its volume and stabilizing it. In small plants this sludge is normally thickened and dewatered and then either used in agriculture or sent to composting plants, incineration plants or landfills. In larger plants the sludge is sometimes digested in the plant itself before being deposited and the biogas that is generated is used to warm the anaerobic sludge digesters or produce electricity. Constructing a WWTP is a complex process that requires a large amount of different types of materials (e.g. concrete, metals, plastics etc.) and it requires coordinating and controlling different operations and transporting materials. An operating WWTP normally calls for a large amount of electricity (for pumping and aeration) and chemicals (to enhance nitrogen and phosphorus removal, to improve settling or sludge dewaterability and to avoid problems with filamentous bacteria, etc.) along with a means to treat the by-products generated during the process (mainly gross solids in the pre-treatment and dehydrated wasted sludge).

1.3.- ENVIRONMENTAL IMPACT ASSESSMENT (EIA)

Despite the important role sewer systems and WWTPs play in the removal of pollutants, and the fact that water is treated before being discharged back into the receiving water bodies, their construction and operation generate certain environmental impacts. Nowadays, there are several methodologies for evaluating the environmental impacts particular technologies, products, communities and production processes may have. One of these is the Life Cycle Assessment (LCA). Life cycle thinking is an approach that considers all of the impacts in the different areas of sustainability (environmental, economic and social) that a product or service will produce throughout its life-cycle, i.e. from “cradle-to-grave”. Different areas are dealt within the life cycle thinking approach, such as life cycle assessment, life cycle costing or life cycle management. LCA is a systematic analysis used to assess the environmental impact generated by a product or process throughout all its life-cycle by considering the consumption of energy and materials it makes, along with the emissions it generates. LCA comprises four different phases, namely: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation, all of which must be carried out in accordance with ISO 14044:2006.

1.3.1.- HISTORY OF LCA

To the best of our knowledge, the environmental impact assessment of products started in the 1960s and has become increasingly important in the last 30 years.

As explained in Chacón (2008), Harold Smith carried out one of the first studies in which environmental impacts were taken into consideration and presented it to the World Energy Conference in 1963. During that decade although more studies into industry energy requirements and their associated environmental impacts appeared it was not until 1969 that the concept of Life Cycle (LC) first made its appearance. When it did finally appear it was in a study carried out by the Coca-Cola Company comparing the environmental impacts of different types of bottles, and quantifying energy and materials used from extraction to disposal. During the 1970s the assessment process began to take off and, as a result, Design for the Real World: Human Ecology and Social Change by Victor Papanek was published in 1971 and is widely credited with introducing the concept of life-cycle in product design. In 1973, the first LCA software appeared and then in 1979 the Society of Environmental Toxicology and Chemistry (SETAC) was created. In the 1980s interest was maintained as a result of the solid waste crisis and Europe issued the Council Directive of 27 June, 1985 on containers of liquid for human consumption 85/339/ECC, which acknowledged life cycle thinking by demanding manufacturers monitor energy and materials consumption and residue generation. During the 1990s interest in LCA increased exponentially and as such guidelines clarifying and generalizing its application were required. For these reasons, the first SETAC meeting specifically discussing LCA assessment processes took place in 1990. The Society for the Promotion of LCA Development (SPOLD), whose aim was to foster and standardize LCA, was founded in 1992 and worked with LCA issues until 2001. Meanwhile in the US, France and the north of Europe different LCA applicationguidelines appeared in 1993, 1994 and 1995, respectively. In 1997 ISO 14040 was published, which was the first ISO standard to describe the principles and framework for LCA. Furthermore, the International Journal of Life Cycle Assessment was created in 1995.

The decade of 2000 can be summarized as the decade where LCA methodology was finally consolidated. For example, the number of LCA software licenses increased by 100% between 1999 and 2003, two studies into the state-of-the-art of the design of sustainable products in Europe were published in 2001, new LCA associations and new impact calculation methods appeared between 2002 and 2006, and finally ISO 14044:2006 was published in 2006. For the interested reader more detailed information about the history of LCA methodology can be found in Chacón, 2008. Fig. 1-2 (at the top) shows a summary of the most important facts in LCA history (adapted from Chacón, (2008)), and (at the bottom) there is a summary of the history of LCA application in WWTPs, based on Corominas *et al*.(2013).

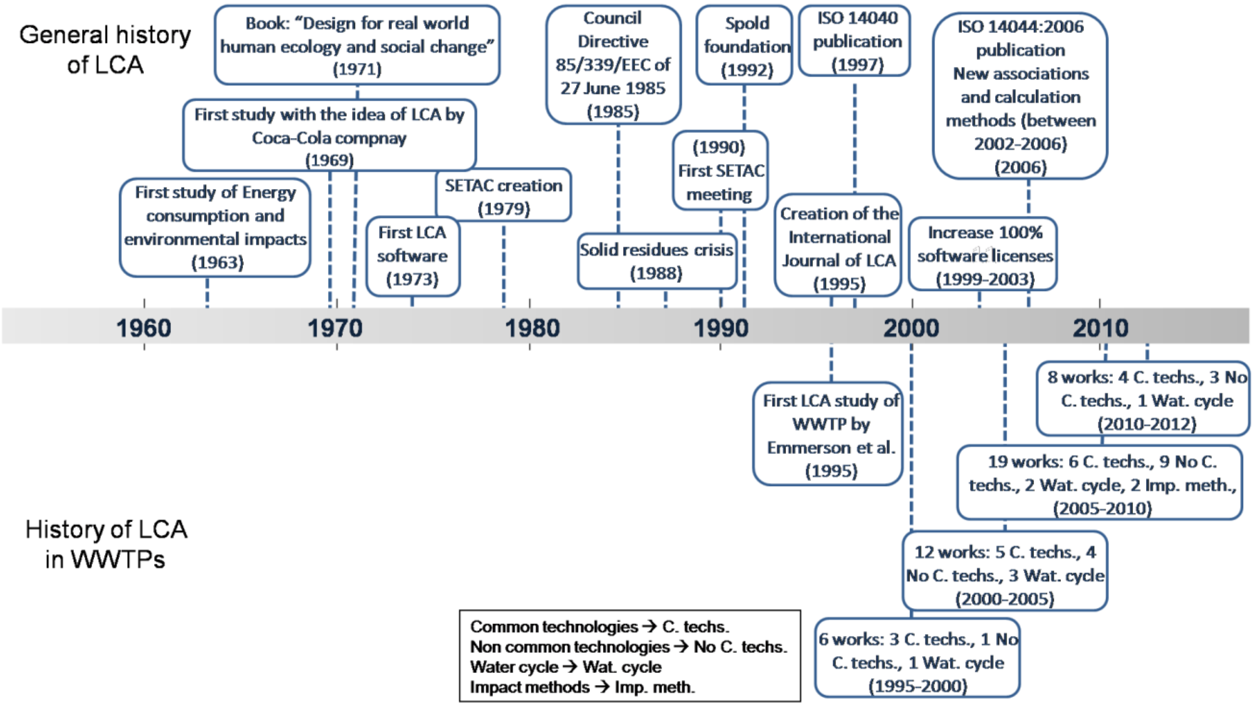

Fig. 1-2: History of LCA. General history of LCA (top). Summary of LCA in WWTPs (bottom).

1.4.- THE STATE-OF-THE-ART OF LCA APPLIED IN WASTEWATER TREATMENT PLANTS[1]

Although water sanitation dates from Mesopotamian times(Lofrano and Brown, 2010)the activatedsludge process currently used was not described until 1913 in the UnitedKingdom (Ardern and Lockett, 1914). During the 20th century,water sanitation systems protected large populations fromdisease. However, society did not realize that there wereother environmental costs associated with that water sanitation.After the term sustainable development was defined by theWorld Commission on Environment and Development(WCED, 1987), some wastewater treatment (WWT) practitioners and researchersincorporated LCA techniques in order to evaluate the

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[1] This subchapter is mainly redrafted from:
Corominas, Ll., Foley, J., Guest, J.S., Hospido, A., Larsen, H.F., **Morera, S.,** Shaw, A. 2013. Life cycle assessment applied to wastewater treatment: State of the art. Water Research, 47, 5480-5492.

environmentalimplications of WWT. In the pursuit of more environmentally sustainable WWT, it is clear that LCA is a valuable tool to elucidate the broader environmental impacts of design and operation decisions (Guest *et al.*, 2009; Larsen*et al.*, 2010).Within the wastewater treatmentfield, LCA was already being applied in the 1990s. Since thenmore than fiftystudies have been published in international peer-reviewedjournals using an array of databases, boundary conditions, and impact assessment methods for interpreting the results. LCA's evolutioncan be observed in the papers available in the literature and in the different objectives which have been evaluated.

Table 1-1lists peer-reviewed journal papers on wastewater treatment and LCA published from 1995 until 2015, with their maincharacteristics, i.e. including the objective of the study, the processes and phases considered, the inclusion of GHG emissions, the functional unit used, and the impact assessment methodology. In these studies LCA has been applied to:

- Estimating the environmental performance of conventional activated sludge technologies.
- Estimating the environmental performance of non-conventional activated sludge technologies.
- Evaluating management strategies for the whole urban water/wastewater system.
- Comparing sludge management strategies.

An in-depth analysis of LCA practices for each of the LCA levels (goal and scope, inventory, impact assessment and interpretation) in the studies published between 1995 and 2012 is also included in this chapter.

1.4.1.- EVALUATION OF THE ENVIRONMENTAL PERFORMANCE OF CONVENTIONAL ACTIVATED SLUDGE TECHNOLOGIES

To the best of our knowledge, the first LCA study applied to wastewater treatment plants (WWTPs) published in an international peer reviewed journal was focused on the inventory phase to evaluate different small-scale WWT technologies (Emmerson *et al.*, 1995). They highlighted the importance of including the emission of CO_2 associated with energy production, thus introducing second order (background) impacts in the evaluation of environmental performance. Electricity use was identified as one of the main contributors to the depletion of fossil resources and the generation of Greenhouse Gas

(GHG) emissions. The construction and demolition phases were included in the analysis in addition to the evaluation of operation of the system. Afterwards, a more sophisticated LCA methodology was used to evaluate the societal sustainability of municipal WWT in the Netherlands (Roeleveld *et al.*, 1997) and the results highlighted the importance of reducing effluent pollution (nitrogen, phosphorus) and minimizing the sludge production. Contrary to the previous study, it was concluded that the contribution of impacts related to energy consumption were very low. That conclusion was achieved after normalizing the results, meaning that the environmental impacts estimated from WWT in the Netherlands were expressed as a percentage of the total environmental impacts in the Netherlands. The outcome was that WWTPs contributed to lessthan 1% of energy consumption at that time. This example addresses the effect of normalizing the impacts in the LCA studies. Construction impacts and the use of chemicals were not found to be significant in their evaluation. Since the Roeleveld study, LCA has been applied to evaluate different types of conventional WWTPs. First, LCA has been used to characterize the environmental impact of specific case-studies (Clauson-Kaas *et al.*, 2001; Hospido *et al.*, 2004; Pasqualino *et al.*, 2009; Bravo and Ferrer, 2011; Venkatesh and Brattebø, 2011). Second, LCA has been applied to the outcomes of dynamic simulation exercises using activated sludge models; in the case of Flores-Alsina *et al.* (2010)and in Corominas *et al.* (2013) control strategies for nitrogen removal were evaluated and in Foley *et al.* (2010a)multiple biological nutrient removal configurations were analyzed. Third, LCA studies have been conducted to compare the performance of different configurations applied to a single system to improve the performance (Mels *et al.*, 1999; Vidal *et al.*, 2002; Rebitzer *et al.*, 2003; Clauson-Kaas *et al.*, 2004). Finally, multiple conventionalsystems have also been compared (Gallego *et al.*, 2008; Hospido *et al.*, 2008; Rodriguez-Garcia *et al.*, 2011; Niero*et al.*, 2014). The outcomes were very similar in all of the studies that involve nutrient removal, highlighting the trade-offs between eutrophication, toxicity and global warming impact categories caused mainly by water discharge emissions, sludge treatment and disposal and electricity use respectively. The improvement of local water quality is at the cost of regional/ global effects stemming from energy and chemical production. Overall, the best alternatives seem to be the ones that result in lower nutrient emissions.

1.4.2.- EVALUATION OF NON-CONVENTIONAL TECHNOLOGIES

For non-conventional technologies (NonC techs) we understand any technology which is not based on activated sludge systems followed by a sedimentation tank. The reality is that conventional WWT technologies are costly and energy demanding, which is troublesome particularly in small communities (<2000 population equivalents, PE). Constructed wetlands, biological filters and sand filtration systems have been proposed as feasible alternatives with lower environmental impacts compared to conventional technologies after using LCA (Brix, 1999; Dixon *et al.*, 2003; Vlasopoulos *et al.*, 2006; Machado *et al.*, 2007; Nogueira *et al.*, 2009; Kalbar *et al.*, 2012a; Yıldırım and Topkaya, 2012). Although these low-tech processes require larger land areas for their implementation, they are often appropriate for rural zones because of the low energy requirements and the high efficiencies to remove heavy metals. Emerging technologies for wastewater treatment are being developed and it becomes a common practice to use LCA as the methodology to compare them against conventional technologies. This is the case for instance of microbial fuel (MFC) and electrolysis (MEC) cells (Foley *et al.*, 2010b), advanced oxidation processes (AOPs) (Muñoz*et al.*, 2005; Chong*et al.*, 2012)or membrane bioreactors (MBRs) (Tangsubkul *et al.*, 2006; Vlasopoulos *et al.*, 2006; Ortiz *et al.*, 2007; Høibye *et al.*, 2008; Wenzel *et al.*, 2008; Foley *et al.*, 2010a,b; Hospido *et al.*, 2012; Remy and Jekel, 2012). In the case of MEC technology, significant environmental benefits can be achieved through the cost-effective production of useful chemicals (e.g. hydrogen peroxide). Regarding the comparison of advanced oxidation processes, using solar energy reduces drastically the environmental impacts as the source of energy required is the key aspect. In the case of MBRs, energy use has also been pointed out as a key element that needs to be optimized in order to improve the environmental performance. It is worth noting that when using LCA in technology development, laboratory scale data is used, which certainly limits the usefulness of the results with regard to a real application. In recent years the effect of micropollutants (priority and emerging pollutants) on ecosystems and their fate and removal in WWTP have been studied (Verlicchi *et al.*, 2012). These pollutants include metals and organics such as pharmaceuticals and personal care products (including endocrine disrupters). As a result several technologies for micropollutants removal are being proposed (e.g. ozonation, advanced oxidation, activated carbon) and evaluated using LCA (Høibye *et al.*, 2008; Wenzel *et al.*, 2008; Larsen *et al.*, 2010). Due to uncertainty surrounding characterization factors for micropollutants, these studies showed moderate or even no environmental benefits from their removal depending on the evaluated technology. Therefore, further research is needed to better characterize the implications of micropollutants in the aquatic environment.

1.4.3.- EXPANDING BOUNDARIES FOR THE EVALUATION OF MANAGEMENT STRATEGIES FOR THE URBAN WATER/WASTEWATER SYSTEM

The boundaries of the WWTPs have been expanded in some studies to include the whole urban water/wastewater system(Amoreset *al.*, 2013; Lemoset *al.*, 2013; Ucheet *al.*, 2013; Barjoveanuet *al.*, 2014;Risch *et al.*, 2015), i.e. withdrawal of freshwater, drinking water production, distribution and use of drinking water, generation of wastewater and transport to the wastewater treatment plant.Further details on LCA applied to urban water systems can be found in the review of Loubet *et al.* (2014). LCA has also been applied to specifically study the construction of sewer systems (Piratla *et al.*, 2012, Du *et al.*, 2013; Petit-Boix *et al.*, 2014).Several studies (Tillmanet *al.*, 1998; Lundinet *al.*, 2000;Kärrman andJönsson, 2001; Lundin and Morrison, 2002; Lassauxet *al.*, 2007; Remy andJekel, 2008, 2012) modeled the entire urban wastewater system to evaluate the environmental consequences of changing from existing centralized WWTPs to more decentralized systems. These studies concluded that separation systems (i.e. urine, fecal matter and grey water separation) represent environmental advantages compared to conventional centralized systems, improving the opportunities for nutrient recycling and avoiding their direct release to the environment. These advantages become more evident when the model of the wastewater system is expanded to also include the offset production of fertilizers. This was addressed by Lundin *et al.* (2000)who demonstrated that if the nutrients in the wastewater were returned to agriculture, the demand for mineral fertilizer in agriculture would be reduced, and the substantial environmental loads imposed by the production and use of mineral fertilizer could be avoided. Also, recovering energy from the organic matter of toilet wastewater and household biowaste in a digestion process can significantly decrease the cumulative energy demand. So, Lundie *et al.* (2004)expandedthe boundaries to include the integrated water and wastewater system in the evaluation of the impact of Sydney total water operations for the year 2021. The boundaries of the WWTPs have also been expanded to consider the production and distribution of reclaimed water to decrease the dependency on potable and desalinated water. Besides the evaluationof sustainability for water reclamation (Chen *et al.*, 2012), two studies have been applied LCA in that area (Pasqualino *et al.*, 2009; Pasqualinoet *al.*, 2011). Both agree that the addition ofthe tertiary treatment to the traditional WWTPslightly increases

Table 1-1: Main characteristics of the references included in the literature review from 1995 until 2015.

Reference	Objective	Boundaries	Process considered	Waste disposal	Phases included	GHG emissions	FU	Impact assessment methodology
(Emmerson *et al.*, 1995)	C techs	D	(1)(2)(ST)(SD)	Yes (Agr)	Op, Const, dem	Direct & indirect	1000 PE, 15 ys	Only inventory
(Roeleveld *et al.*, 1997)	C techs	B	(1)(2)(3)(ST)	No	Op, Const	Direct & indirect	100000 PE	Not specified
(Tillman *et al.*, 1998)	Water cycle	F	(So)(2)(ST)(SD)	Yes (Agr)	Op, Const	Direct & indirect	1 PE per y	Not specified
(Brix, 1999)	NonC techs	B	(2)(3)	No	Op	No	1 m^3	Only inventory
(Mels *et al.*, 1999)	C techs	D	(1)(2)(3)(ST)(SD)	Yes	Op	No	100000 PE	Only inventory
(Lundin *et al.*, 2000)	Water cycle	H	(So)(2)(SD)	Yes (Agr)	Op, Const	Indirect	1 PE per y	Not specified
(Clauson-Kaas *et al.*, 2001)	C techs	D	(2)(ST)(SD)	Yes (Agr)	Op	Indirect	1 m^3	EDIP 2003
(Kärrman & Jönsson, 2001)	Water cycle	H	(DW)(So)(2)(SD)	Yes (Agr)	Op	Indirect	1 PE per y	Not specified
(Lundin & Morrison, 2002)	Water cycle	H	(DW)(2)(ST)(SD)	Yes (Agr)	Op	Indirect	1 PE per y	Not specified
(Vidal *et al.*, 2002)	C techs	C	(2)	No	Op	Direct & indirect	1 Tn	Not specified
(Beavis and Lundie, 2003)	NonC techs	A, G	(2)(3)(ST)(SD)	Yes (Agr)	Op	Direct & indirect	1 ML	Not specified
(Dixon *et al.*, 2003)	NonC techs	C	(2)	No	Op, Const	Direct & indirect	1 PE	Not specified
(Rebitzer *et al.*, 2003)	C techs	F	(1)(2)(ST)(SD)	Yes (Agr)	Op	Indirect	1 PE per y	Not specified
(Clauson-Kaas *et al.*, 2004)	C techs	D	(2)(SD)	No	Op	Direct & indirect	1 L	EDIP
(Hospido *et al.*, 2004)	C techs	F	(1)(2)(ST)(SD)	Yes (Agr)	Op	Direct & indirect	1 m^3 per d	CML 2000
(Lundie *et al.*, 2004)	Water cycle	H	(DW)(Sew)(2)(3)(ST)(SD)	Yes (Agr)	Op, Const	Direct &indirect	1 KL	Not specified

(Muñoz *et al.*, 2005)	NonC techs	A	(+)	No	Op	Indirect	1 m^3	Not specified
(Tangsubkul*et al.*, 2005)	NonC techs	D	(1)(2)(3)(ST)(SD)	Yes (Agr)	Op, Const	Direct & indirect	1 mL of recycled water	Not specified
(Tangsubkul*et al.*, 2006)	NonC techs	A	(2)	No	Op, Const	Indirect	1 ML per d	Not specified
(Vlasopoulos*et al.*, 2006)	NonC techs	A	(1)(2)(+)	No	Op, Const	Indirect	10000 m^3/d for 15 ys	CML 2000
(Lassaux *et al.*, 2007)	Water cycle	H	(DW)(Sew)(2)(ST)(SD)	Yes (Agr)	Op, Const	Indirect	1 m^3	Eco-Indicator 99
(Machado *et al.*, 2007)	NonC techs	F	(2)(SD)	Yes (Agr)	Op, Const, Dem	Direct & indirect	1 PE	CML 2000
(Ortiz *et al.*, 2007)	NonC techs	B	(1)(2)(3)(ST)	Yes	Op, Const, Dem	Indirect	3000 m^3/d for 25 ys	CML 2000, Eco-Points 97, Eco-Indicator 99
(Gallego *et al.*, 2008)	C techs	F	(1)(2)(ST)(SD)	Yes (Agr)	Op	Direct & indirect	1 PE per y	CML 2000
(Høibye *et al.*, 2008)	NonC techs	D	(3)(ST)(SD)	Yes	Op	Indirect	1 m^3	EDIP
(Hospido *et al.*, 2008)	C techs	F	(1)(2)(ST)(SD)	Yes (Agr)	Op	Direct & indirect	1 PE	CML 2000
(Muñoz *et al.*, 2008)	Impact method	A	(1)(2)	Yes (Agr)	Op	No	1 L	EDIP 97 (USES-LCA)
(Remy and Jekel, 2008)	Water cycle	H	(So)(2)(ST)(SD)	Yes (Agr)	Op, Const	Indirect	1 PE per y	CML
(Renou*et al.*, 2008)	Impact method	D	(1)(2)(ST)(SD)	Yes (Agr)	Op, Const	Indirect	1 m^3 per y	CML 2000, Eco-Indicator 99, Ecopoint 97, EDIP 96, EPS
(Wenzel *et al.*, 2008)	NonC techs	D	(3)(SD)	Yes	Op	Indirect	1 m^3	EDIP 2003
(Nogueira *et al.*, 2009)	NonC techs	D	(2)(SD)	Yes (Agr)	Op, Const	Direct & indirect	1 PE	CML 2000
(Pasqualino *et al.*, 2009)	C techs	F	(1)(2)(ST)(SD)	Yes (Agr)	Op	Indirect	1 m^3	CML 2000
(Flores-Alsina *et al.*, 2010)	C techs	F	(2)(ST)(SD)	Yes (Agr)	Op	Direct & indirect	753,3 Hm^3	CML 2000

(Foley *et al.*, 2010)	NonC techs	D	(+)(ST)(SD)	Yes	Op, Const	Direct & indirect	2200 m^3/d at 4000 mg COD/l over 10 ys	IMPACT 2002+
(Foley *et al.*, 2010)	C techs	F	(1)(2)(ST)(SD)	Yes (Agr)	Op, Const	Direct & indirect	10 ML/d over 20 ys	Only inventory
(Larsen *et al.*, 2010)	NonC techs	D, F	(1)(2)(3)(+)(ST)(SD)	Yes (Agr)	Op, Const, Dem	Direct & indirect	1 m^3	EDIP97
(Stokes and Horvath, 2010)	C techs	H	(1)(2)(ST)(SD)	Yes (Agr)	Op, Const	Direct & indirect	1 Ml	Not specified
(Bravo and Ferrer, 2011)	C techs	B	(1)(2)(3)(ST)	No	Op	Indirect	50000 PE	CML 2
(Pasqualino*et al.*, 2011)	C techs	D	(1)(2)(3)(ST)(SD)	Yes	Op	Indirect	1 m^3	CML 2000
(Rodriguez-Garcia *et al.*, 2011)	C techs	F	(1)(2)(3)(ST)(SD)	Yes (Agr)	Op	Direct & indirect	1 m^3 and 1 kg of PO_4^{3-} removed	CML
(Venkatesh and Brattebø, 2011)	C techs	F	(1)(2)(ST)(SD)	Yes (Agr)	Op	Direct & indirect	1 m^3	CML 2001
(Hospido *et al.*, 2012)	NonC techs	F	(2)(ST)(SD)	Yes (Agr)	Op	Direct & indirect	1 m^3	CML 2000, RECIPE and IMPACT 2002
(Kalbar *et al.*, 2012a)	NonC techs	D	(2)(ST)(SD)	Yes (Agr)	Op	Direct & indirect	1 PE per y	CML 2000
(Remy and Jekel, 2012)	Water cycle	H	(So)(2)(ST)(SD)	Yes (Agr)	Op, Const	No	1 PE per y	Not specified
(Yıldırım and Topkaya, 2012)	NonC techs	D	(1)(2)(ST)(SD)	Yes (Agr)	Op, Const	Direct & indirect	1 PE	CML 2000
(Amores *et al*, 2013)	Water cycle	H	(DW)(1)(2)(3)(ST)(SD)(Sew)	Yes (Agr)	Op, Const (Distribution, sewer)	Indirect	1 m^3 at consumer	CML 2001
(Lemos *et al.*, 2013)	Water cycle	H	(DW)(1)(2)(ST)(SD)(Sew)	Yes (Agr)	Op, Const (Distribution, sewer)	Direct & indirect	1 m^3 at consumer	ReCiPe

(Uche *et al.*, 2013)	Water cycle	H	(DW)(1)(2)(ST)(SD)(Sew)	Yes (Inc)	Op, Const, Dem(part)	Indirect	1 m^3 before to be used	IPCC, Eco Indicator 99, ReCiPe
(Barjoveanu *et al.*, 2014)	Water cycle	H	(DW)(1)(2)(ST)(SD)(Sew)	Yes (landfill)	Op	Indirect	1 m^3 potable water at consumer	CML, Ecological Scarcity
(Niero *et al.*, 2014)	Ctechs	D	(1)(2)(ST)(SD)	Yes (Inc, Agr)	Op	Indirect	1 m^3 inlet wastewater	ReCiPe
(Risch *et al.*, 2015)	Water cycle	H	(1)(2)(ST)(SD)(Sew)	Yes (Agr)	Op, Const, Dem	Direct & indirect	1 day operation of the system	ReCiPe

(DW) drinking water; (So) source treatment; (1) primary treatment; (2) secondary treatment; (3) tertiary treatment; (+) advanced treatment; (ST) sludge treatment; (SD) sludge disposal; (Sew) sewer system; C techs: Evaluation of conventional technologies; NonC techs: evaluation of non-conventional technologies; Agr: agriculture; Inc: incineration; Op: operation; Const: construction; Dem: demolition.

the environmental impact of the plant, but this is still considerably smaller than the environmental impact of other water production methods, especially if comparing to desalination.

1.4.4.- COMPARISON OF SLUDGE MANAGEMENT STRATEGIES

This was first incorporated in LCA studies by Dennison *et al.* (1998). From then, several studies have been conducted,enlarging the system boundaries, including heavy metals ornitrous oxide (N_2O) emissions, and also evaluating beneficialconsequences when energy is recovered from anaerobicdigestion processes and nutrients are returned to the environmentas soil amendment. The studies available in theliterature(Suh and Rousseaux, 2002; Hospido *et al.*, 2005, 2010; Houillon and Jolliet, 2005; Johansson *et al.*, 2008; Hong *et al.*, 2009; Peters and Rowley, 2009; Uggetti*et al.*, 2011; Cao andPawłowski, 2013; amongst other) compare sludge treatmentoptions inside the WWTPs (anaerobic digestion, thermalprocess, lime stabilization, silo storage) and sludge managementoutside the WWTPs (agriculture spreading, incineration,wet oxidation, pyrolysis, landfill, wetland, composting andrecycling with cement material). Although the studies arenormally case-specific, the conclusions generally indicate thatit is better to centralize sludge management and to performdewatering at the facility in order to decrease potential impacts.Regarding technologies, anaerobic digestion combinedwith energy recovery is recommended combined with incinerationor land application. The latter is restricted by theamount of heavy metals, priority and emerging pollutantsbecause of their potentially significant toxicity effects. Also,the environmental impacts related to the final disposal ofsludge by agricultural spreading cannot be neglected. Further details on LCA applied to sludge management strategies can be found in Yoshida *et al.* (2013).

1.4.5.- EVALUATION OF LCA PRACTICES IN THE STUDIES REVIEWED

An in-depth analysis was conducted on the reviewed studies in Corominas *et al.* (2013) (which include published papers from the 90s until 2012 fromTable 1-1) aiming at identifying the different methodological approaches followed (within the constraints of the ISO standards) and their transparency to communicate the results. Fig. 1-3summarizes the analysis regarding the proper definition and justification of the goal and scope, the inventory, the impact assessment and the interpretation phases. It can be seen that 100% of the studies defined the goal and scope of the project, covering a wide range of functional units and system boundaries. Regarding the inventory, only 38% of the papers provided the inventory data within the paper or as supporting information, making the exercise reproducible (or almost) to others. The impact assessment was addressed in 82% of the studies evaluated. However, 38% of these studies did not explicitly indicate the methodology they used. Finally, only 33% of the studies provided an in depth interpretation of the results including limitations of the methodology and/or performing a sensitivity analysis. Further analysis at each of the ISO levels is provided in the following sections.

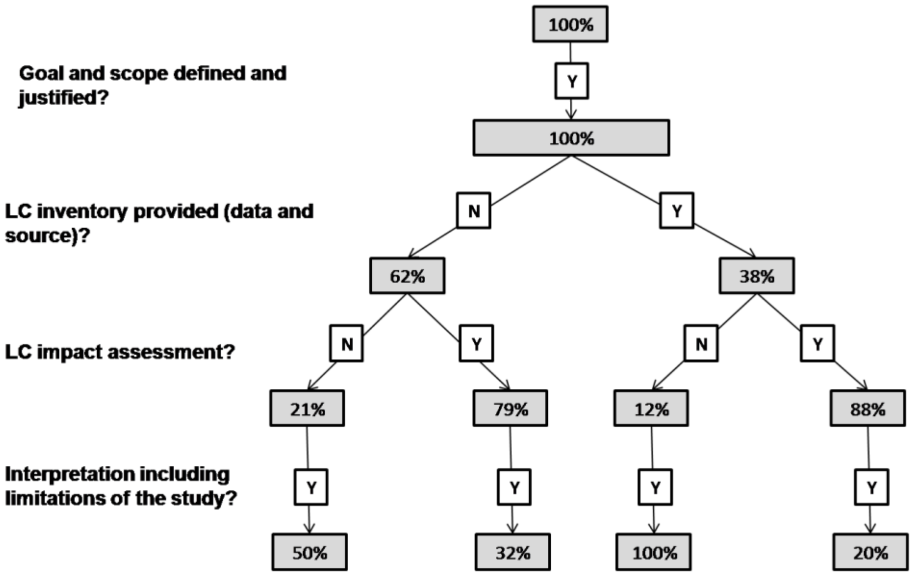


Fig. 1-3: Assessment of LCA practices of 45 reviewed studies.

Goal and scope definition

Functional unit. The most commonly used functional unit in the reviewed studies is a volume unit of treated wastewater (60% of the papers used volume as m^3 or ML). However, this unit is not always representative, because it does not reflect the influent quality or the removal efficiency of the WWTP. For instance, comparing two systems with different influent loads or with different removal efficiencies might result in misleading conclusions if using volume unit only as the functional unit. In some cases (e.g. Tillman *et al.*, 1998; Gallego *et al.*, 2008), in order to include quality of wastewater besides quantity, the unit population equivalent is used, defined as the organic biodegradable load having a five-day biochemical oxygen demand (BOD_5) of 60 g of oxygen per day. So as to describe the functions of removing both organic matter and nutrients from water Rodriguez-Garcia *et al.* (2011)propose another definition of the FU expressed in terms of kg PO_4^{3-} eq. removed. Also, Godin *et al.*(2012)proposed the net environmental benefit approach which requires assessing the potential impact of releasing wastewater without and with treatment besides assessing the impact of the WWTP's life cycle. On the other hand, only 9% of the studies refer the functional unit to the life span of the plant. In Emmerson *et al.* (1995)they assume that the useful life of a typical treatment works, regardless of structural type, is limited to an average of fifteen years and inLarsen *et al.* (2010) 30 years are used for buildings and construction, 20 years for pipes and valves and 15 years for electronic equipment. In Foley *et al.* (2010b)they consider 10 years of operation within the functional unit. This is conducted to consider replacement of equipment during the life of the plant.

Boundaries. With regards to the life cycle of the WWT process, 23 of the studies included only the operation of the WWTP and neglected the environmental load of the constructionand demolition phases. Among the studies that did include the construction phase, 6 references found out that construction of WWTPs had an impact worth to be considered. Firstly, for low-tech processes (e.g. constructed wetlands, reedbeds) the construction phase can account up to 80% of the impact for some impact categories (Emmerson *et al.*, 1995; Dixon *et al.*, 2003; Vlasopoulos *et al.*, 2006; Machado *et al.*, 2007). Secondly, construction phase was also reported as a relevant stage for conventional activated sludge system and MBRs, with contributions up to 43% and 31% of the total impact, respectively (Ortiz *et al.*, 2007). Finally, Remy and Jekel (2008)found out that construction affects up to 20% of the total impact for some impact categories. As these are case-specific studies highly depending on the materials used for the construction and the considered life span of the infrastructure no generalization is possible. In Frischknecht *et al.* (2007)they stated that for wastewater treatment capital goods dominate most impact category results, especially because of the sewer infrastructure and the diluted pollutant content in domestic wastewater. Toxicity related environmental impacts are generally sensitive to the exclusion of capital goods. Hence, capital goods cannot be excluded per se, and a justification would be required when this stage is excluded from the system boundaries. Complete overviews of the geographical area boundaries were described in Lundin *et al.* (2000), Lundin and Morrison (2002), and Foley *et al.* (2010a)including the foreground (emissions and usages directly related with the product/process) and background (the emissions and usages related with the provision of goods or services for theforeground subsystem) sub-systems. Within the foreground sub-systems, nutrient discharges in the aqueous phase were always considered. However, only 53% of the studies included the direct greenhouse gas emissions generated either in the biological treatment, during sludge treatment or after sludge disposal in land fields. All the studies presented the selected boundaries according to the defined objectives, but no strong justification for the selection was normally provided. Fig. 1-4shows the boundaries selected for the reviewed studies. Since the beginning of LCA studies applied to wastewater treatment, sludge treatment and disposal were included in the system boundaries because of the significant contribution to the overall impacts. In fact, this sub-system has been included in 36 of the reviewed studies. The few publications that did not include sludge treatment and disposal were studies comparing non-conventional technologies especially for tertiary treatment that did not generate sludge. Agricultural application was the most common scenario for final disposal (30 papers), which took into account the positive effects of the nutrient value of the sludge and expanded the system to include the avoided production of synthetic fertilizers (i.e. Houillon and Jolliet, 2005) as well as the negative consequences associated with the heavy metals also present in the sludge (i.e. Dennison *et al.*, 1998; Hospido *et al.*, 2004; Pasqualino *et al.*, 2009).One case(Larsen *et al.*, 2010) also included the heavy metal content of mineral fertilizers and the content of some organic pollutants (e.g. DEHP and PAH) in the sludge. However, only 6 studies included GHG emissions from the decomposition of sludge applied to agriculture (i.e. Dennison *et al.*, 1998; Suh and Rousseaux, 2002; Houillon and Jolliet, 2005; Tangsubkul *et al.*, 2005; Gallego *et al.*, 2008; Hospido *et al.*, 2008).

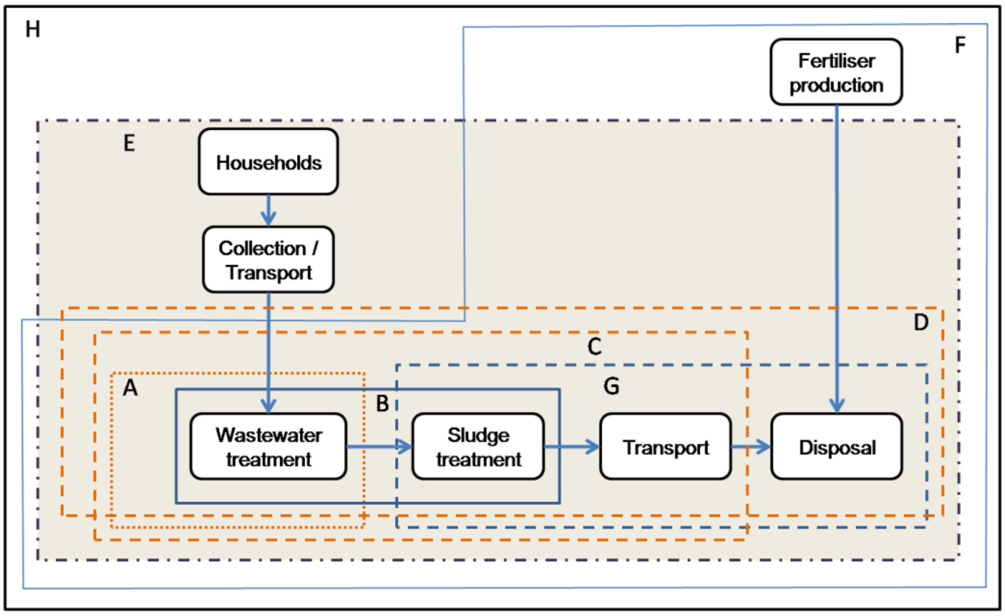


Fig. 1-4: Boundaries of the urban wastewater system. Adapted from Lundin*et al.* (2000). The letters A until H indicate the different system boundaries of the reviewed studies listed in Table 1-1. Studies with the G boundaries (i.e. only dealing with sewage sludge management) were not included in this review.

Inventory

Within this phase, the studies face problems associated with data availability and data quality. Data for the inventory is collected from lab or pilot facilities as well as real plants, estimation from experts, relevant literature and/or LCA databases. The foreground life cycle inventory (LCI) data is normally compiled directly from measurements, detailed design documents and vendor-supplied information. Background information (e.g. electricity generation systems, concrete and chemicals production processes) is normally provided by LCI databases, e.g. the Ecoinvent (www.ecoinvent.ch). From the 22 studies that included the construction stage, original inventory data was used in 68% of them while the others estimated construction loads from other works. In a nutshell, around half of the papers revised do not include inventory data at all (49%), while others just include partial information (18%) and a remaining fraction (33%) do provide the detailed level of data that is desirable in order to reproduce the work.

Life cycle impact assessment (LCIA) (impact assessment methodology and impact assessment categories)

According to the ISO standard, the third step of an LCA study is comprised of compulsory (classification and characterization) and voluntary elements (normalization and weighting).

Classification and characterization. Most wastewater LCA studies did move beyond the inventory stage to the impact assessment step. Among the 45 studies revised, 27 stated the impact assessment methodology used: 19 selected CML (Guinée, 2001), 7 EDIP 97 (Wenzel *et al.*, 1997), 3 Eco-indicator 99 (Goedkoop and Spriensma, 2001), 2 Impact 2002+(Jolliet *et al.*, 2003), 1 EPS (Bengt, 1999), 2 eco-points 97 (Braunschweig *et al.*, 1998) and 1 ReCiPe (Goedkoop *et al.*, 2013). The remaining references did not indicate the method selected or used a mixture of characterization factors. To the best of our knowledge,Ortiz *et al.*(2007), Renou *et al.*(2008) and Hospido *et al.*(2012)are the only studies that investigated whether the choice of one of the existing LCIA methods, could influence LCA results. In the study of Ortiz *et al.* (2007)three methods were used for the life cycle impact assessment (CML baseline 2000, Eco-Points 97 and Eco-Indicator 99). Although no specific discussion on that topic was addressed in that paper, the results of Eco-Points 97 and Eco-Indicator 99 were very similar, contrary to the results obtained with CML 2000. The work done by Renou *et al.* (2008)concluded that for impact categories such as global warming, acidification, eutrophication, or resource depletion, the choice of an impact assessment method is not a critical issue as the results they provide are similar. However, large discrepancies were observed with human toxicity, which has been already reported byPizzol *et al.* (2011) who compared nine different methodologies with focus on impacts of metals on human health. Finally, Hospido *et al.* (2012)compared three impact assessment methods (CML 2000, ReCiPe and IMPACT 2002+) to evaluate the robustness of the environmental ranking obtained for four MBRs. Among the four impact categories evaluated there (i.e. eutrophication, acidification, terrestrial and freshwater ecotoxicities), the main divergences where found for eutrophication potential due to the different significance given by the different impact assessment methods to P-related emissions. Concerning the set of impact categories evaluated, global warming potential, acidification, and eutrophication are the indicators that received more attention (being evaluated by 38, 27 and 28 out of the 45 papers, respectively). Afterwards, photochemical oxidation (17 studies) and toxicity-related aspects (18 studies dealing with human toxicity, 17 with terrestrial ecotoxicity, 15 with freshwater toxicity, and only 9 with marine ecotoxicity) were the issues of concern. Terrestrial ecotoxicity played an important role when sludge disposal options were evaluated and heavy metals or micropollutants were considered. Finally, ozone layer depletion and abiotic depletion (includes fossil energy and material depletion) were not found to be significant decision-making drivers in these studies, only being assessed by 14 and 20 papers, in that order.

Normalization and weighting. Normalization, which allows comparing all of the environmental impacts on the same scale, was used in 18 of the reviewed studies. Normalization factors were obtained from regional and global databases (e.g. PE, 1990 Denmark; SCB, Sweden statistics; EU15 world 1994; Western Europe 90s). Weighting, which is used to convert and aggregate indicator results across impact categories into one single indicator, was only applied in 5 studies. The justification is that the process of applying weights depends on subjective value-choices that are more relevant to decision making processes than elucidation of the relative environmental sustainability of a set of design alternatives. The approaches used in the 5 studies to define weights were the EPS method (Steen and Ryding, 1992), the Weighted Environmental Theme and the Ecological scarcity (as applied in Baumann *et al.*, 1993), the hierarchist perspective with average weighting of Eco-Indicator 99, the use of weights provided by CML 2001 methodology, or using the cardinalor ordinal scale by decision-makers based on their preferences or importance for various attributes (Kalbar *et al.*, 2012b).

Interpretation

According to ISO 14044:2006, the interpretation should include: a) identification of significant issues based on the results of the LCI and LCIA phases of an LCA; b) evaluation of the study considering completeness, sensitivity and consistency checks; and c) conclusions, limitations and recommendations. Hence, it would be expected that the LCA studies would incorporate a sensitivity analysis to determine which parameters influence the most the LCA outcomes. However, amongst the reviewed studies, sensitivity analysis wasonly applied in 15 papers. The communication of the results is a challenging issue since multiple criteria are normally combined with multiple scenarios evaluated. This creates a space of large number of dimensions difficult to explain to the audience. One of the widely used ways of presenting the results is taking a reference scenario for which the impacts are calculated and relate the impacts of the other scenarios to that reference situation. In such a way induced and avoided impacts can be calculated for each scenario. Finally, only 34% of the studies discussed the limitations of the approach and related the recommendations to these limitations.

1.5.-CHALLENGES TO OVERCOME THROUGH THE DEVELOPMENT OF THIS THESIS

The literature review also identified the limitations and current challenges in LCA application to UWWS. In this thesis we propose addressing the two most relevant challenges: (1) the need to improve life cycle inventories and (2) to facilitate LCA use by decision-makers through proper application to case-studies.

1.5.1.- IMPROVING LIFE CYCLE INVENTORIES OF UWWS

The inventory phase is normally conducted by using a mixture of experimental or full scale data and existing databases. The goal of the LCA study determines the accuracy required for the inventory data, and indicates where the efforts should be made in data collection. The inventory phase is crucial and should be accurately designed as for other model-based approaches (e.g. for activated sludge mechanistic model calibration following the methodology described in Rieger *et al.* (2013)closing mass balances for the compounds evaluated). It is crucial to identify critical aspects in the wastewater treatment sector that might significantly influence LCA results. One of these could be the inclusion of the construction phase. Many LCA studies applied to UWWS include only the operation phase and neglect the environmental load of the construction and demolition phases. Loubet *et al.* (2014) reviewed eighteen studies that applied an LCA to the urban water system (UWS) scale and indicated that eleven of these studies included the material used in the inventory to construct all of the UWS, and only three studies considered the pipe materials (either in sewers or in drinking-water distribution networks). However, none of these studies considered the civil works involved in the construction of sewers.

Two further drawbacks from the inventory phase in current studies of WWTPs can also be identified. The first limitation is that WWTP equipment is usually missing in LCA studies. A typical WWTP may have more than 200 devices, such as diffusers, pumps and blowers. Foley *et al.* (2010) provided estimates on the equipment but with little detail. The seconddrawback is that when an LCA is applied to WWTPs, it does not normallyshow the contribution of the individual units involved in the wastewater treatment to the overall impact. Normally only the inputs and outputs of the plant are shown, without distinguishing the different unit processes of the plant (pumping + pre-treatment, primary treatment, secondary treatment, the sludge line, and buildings and services). From an environmental point of view, it is interesting to identify which elements of a WWTP are generating or mitigating most of the environmental effects.

The life span of the infrastructures is a key element when an LCA study is applied in environmental studies of a UWWS, even though it is not always systematically applied. The life span of pipes is highly variable as it depends on the material used, along with the characteristics of the water and soil, for concrete tubes the life span can vary from 15 years when concrete tubes are exposed to sulphide emissions to 100 years when they are not exposed to sulphide emissions (www.waterworld.com), or 30 years for pipes made of PVC and 50 years for those made of HDPE (Blosser *et al.*, 2003). In addition WWTP life span is not always considered and, when it is considered, it ranges from 10 to 30 years depending on the study carried out (Mels *et al.*, 1999; Dixon *et al.*, 2003; Renou *et al.*, 2008). The life spanof the equipment used in the sewer system and the WWTP also has to be taken into consideration. Lundin *et al.* (2000), for example, considered 15 years as the life span for pumps and tanks. Subsequently, the contribution of the renovation phase will depend on the life span considered for the infrastructure and WWTP equipment.

Therefore, the first obstacle this PhD thesis attempts to overcome is the fact that, in order to improve the application of LCA in UWWS, more detailed and less uncertain inventories for the construction and renovation of sewer systems and WWTPs need to be developed. Besides this, improved inventories should distinguish between the different steps or processes needed in the construction of sewer systems and WWTPs.

Challenge 1: Improving data quality and reducing inventory uncertainty in the construction and renovation phases of UWWS infrastructure

1.5.2.-FACILITATE THE INTEGRATION OF LCA RESULTS INTO WASTEWATER TREATMENT DECISION-MAKING

An effort should be made to achieve wider acceptance of LCA results amongst decision-makers through continuous stakeholder participation (Guest *et al.*, 2009), so that these results provide greater value to the decision-making process. Not only is communicating the outcomes of LCA studies a difficult task (as mentioned earlier), but explaining the environmental processes and mechanisms on which the LCA methodology relies is particularly challenging given that they are highly complex and interactive and the models that describe them rely on assumptions that remain hidden in databases. As a result, nowadays LCA and other life cycle methodologies are normally not used by the stakeholders for decision making in UWWS infrastructure management. Engaging utility personnel early in the process may achieve greater buy-in among the decision-makers as to the validity of the LCA and its underlying assumptions. Finally, LCA methodology should be linked to economic (Life Cycle Costing -LCC) and social (Social Life Cycle Assessment -SLCA) evaluations completing the whole picture of sustainability (Life Cycle Sustainability Assessment -LCSA) (Kloepffer, 2008). Thus, within the scope of this PhD we approached the Besòs River Basin Water Authority about incorporating LCA (both environmental and economic aspects) into their decision-making through two environmental impact assessment studies. The first wasto evaluate the integrated management of two neighboring WWTPs, while the second was to estimate the positive impact WWTPs can make in reducing the water footprint the urban wastewater treatment.

Recently, LCA studies have demonstrated the importance of assessing freshwater use by quantifying water consumption from wastewater treatment, once current LCIA methods were expanded (Kounina *et al*., 2012). Risch *et al.* (2014)evaluated the direct water consumption from three different operating wastewater treatment technologies located in three different regions and considered regional factors to account for the water scarcity of the different geographical regions. The water footprint (WF) of a product/process was introduced for the first time in 2003 and is defined as the volume of freshwater consumed and polluted to produce a product (Hoekstra, 2003). A strong point of the WF is that it accounts not only for the direct water use of a consumer or producer, but also for the indirect water use which depends on the WF of those activities related to the studied product/ process that go beyond the boundary of the process (Hoekstra *et al.*, 2011).

Therefore, the second challenge that this PhD thesis addresses is overcoming barriers to the use of LCA and other environmental assessment methodologies in the decision-making processes in UWWS management. We aim to perform a proper application of these methodologies in real case studies and show how they can facilitate the decision-making process.

Challenge 2: Promote the use of LCA and other environmental assessment methodologies by stakeholders during the decision-making processes in UWWS management

1.6.- THESIS STRUCTURE

This thesis is developed according to the following structure:

Chapter 1 presents an introduction to the UWC and the UWWS. Next there is a summary of the history of the application of LCA methodology. Following the historical background, there is an explanation of the state-of-the-art of the application of the LCA methodology in the wastewater field and finally Chapter 1 ends by outlining the challenges that will be addressed in this PhD thesis.

In **Chapter 2** the objectives of the PhD are presented.

Chapter 3 presents the specific tools and case studies used to achieve each one of the objectives presented in the previous chapter.

Chapter 4 includes the main results and the corresponding discussion of the research work carried out.

Subchapter 4.1. outlines the procedure proposed to obtain highly detailed inventories for the construction of sewers; the first component of an UWWS. It also presents a tool developed to automate part of the proposed procedure and, finally, subchapter 4.1. shows its usefulness through the environmental analysis of different types of sewers with different life spans and surrounds characteristics.

Subchapter 4.2. details the procedure proposed to obtain detailed inventories of WWTP construction. Initially it provides an explanation of the procedure's application in first obtaining a detailed inventory for the construction of a full scale WWTP based on activated sludge technology, analyzing civil works and equipment in detail, along with the entire WWTP and the different units found inside a WWTP. Following on from this, the comparison of the environmental impacts from a WWTP's construction and operation are made.

Subchapter 4.3. provides the regression equations obtained for the material and energy consumed during the construction phase of four WWTPs based on activated sludge technology of different capacities ranging from 1500 to 21000 $m^3 \cdot d^{-1}$.

Subchapter 4.4. details the results obtainedin the analysis of the economic and environmental effects of an integrated management of two neighboring WWTPs, which were able to be connected through a sewer pipe.

Finally, **Subchapter 4.5.** illustrates a procedure proposed to estimate the WF in WWTPs, and its application to a real full-scale WWTP.

Chapter 5 provides a general discussion of all the results obtained.

Finally, **Chapter 6** outlines the main conclusions drawn in this PhD thesis.

2 OBJECTIVES

The goal of this PhD thesis is to improve the application of environmental impact assessment methodologies in UWWS. Firstly, by improving the data quality of the construction phase of sewer systems and WWTPs and secondly, by showing how applying LCA methodology in a real case workscan be useful for stakeholders when defining UWWS management strategies. The final aim is to show how WF methodology can be applied to a real case scenario to evaluate one of the most important environmental impacts: freshwater consumption in WWTPs.

To achieve these general objectives it is necessary to fulfill the following specific objectives in accordance with the motivation presented in the previous chapter:

1. To develop an Excel® based tool to perform comprehensive LCA studies of sewer construction and renovation. The tool should allow evaluating multiple typologies of sewers including several pipe materials,site-specific conditions (e.g. type of soil) and lifespans.
2. To characterizethe relative importance of WWTP construction and operation in LCA after conducting a detailed and comprehensive inventory of materials, energy and processes required in the construction (civil works and equipment) and operation of a full-scale WWTP.
3. To obtainempiricalrelations between treatment capacity and construction inventories of small and medium WWTPs.
4. To propose a methodology based on life cycle assessment to evaluate the integrated management of neighboring WWTPs including economical and environmental (local and global) criteria.
5. To provide a procedure to estimate a WWTPs’ water footprint. To provide a working example of this procedure applied to a real WWTP.

3 MATERIAL AND METHODS

3.1.- CASE STUDIES

3.1.1.- GIRONA WWTP

The Girona WWTP is located in Girona City (Catalonia, NE of Spain). It treats the wastewater from the city and different towns located around the WWTP, and the effluent is deposited in the Ter River. The plant has a capacity of 206,250 population equivalent (PE) or considering the volume of wastewater per day, 55,000 $m^3 \cdot d^{-1}$. The plant consists of a pumping station, pre-treatment, primary treatment, secondary treatment (with the biological reactor and the secondary clarifier) and the sludge line. The biological treatment consists of an activated sludge system with Modified Ludzack-Ettinger (MLE) configuration with biological nitrogen removal and chemical removal of phosphorus with ferric chloride. The sludge line consists of thickening, anaerobic sludge digestion with electricity production from the biogas, dewatering with the addition of polyelectrolyte and the deposition of the sludge in a composting plant. Fig. 3-1 shows a scheme of the plant with all the units. A couple of relevant specificities of this plant are that when the water enters it is necessary to pump the water more than 5 vertical meters, and also, that aluminum compounds are introduced in the secondary treatment to avoid problems with some bacteria.

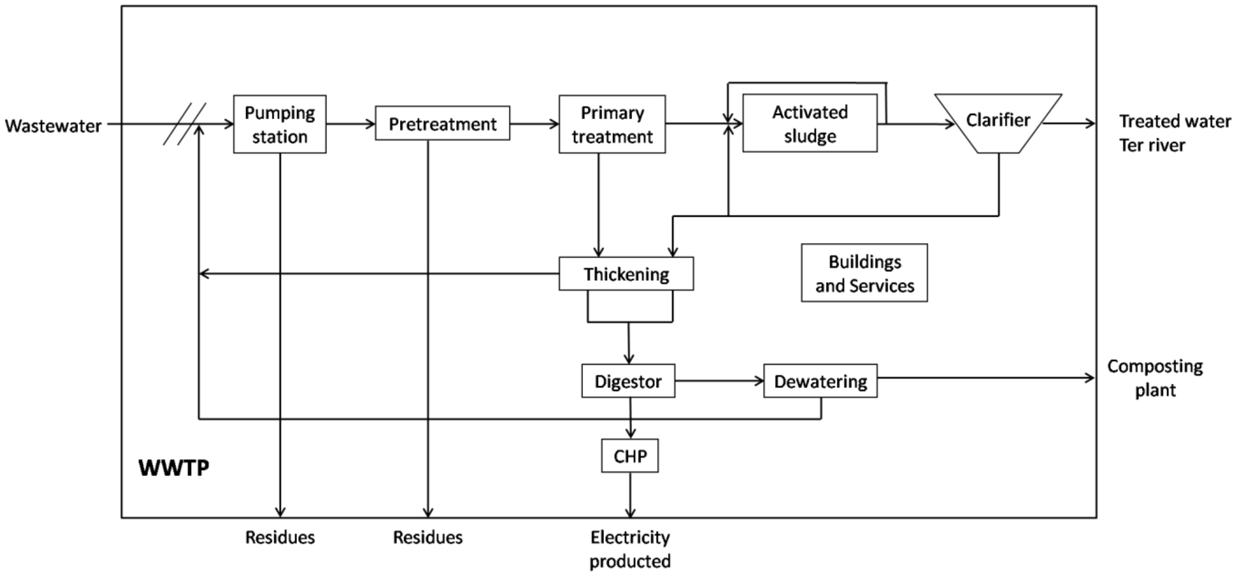


Fig. 3-1: Scheme of the Girona WWTP.

3.1.2.- LA GARRIGA AND GRANOLLERS WASTEWATER TREATMENT SYSTEM

The system studied is located in the Congost sub-catchment, which is part of the Besòs River catchment (NE Spain). The system consists of two different WWTPs: La Garriga and

Granollers connected by a sewer pipe(Fig. 3-2). La Garriga is a 29,000 PE (or 7,000 $m^3·d^{-1}$) WWTP able to remove organic matter and nitrogen with a MLE configuration(Tchobanoglous*et al.*, 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 is a 112,000PE (or 30,000 $m^3·d^{-1}$)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 connection between La Garriga and Granollers WWTPs consists 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.

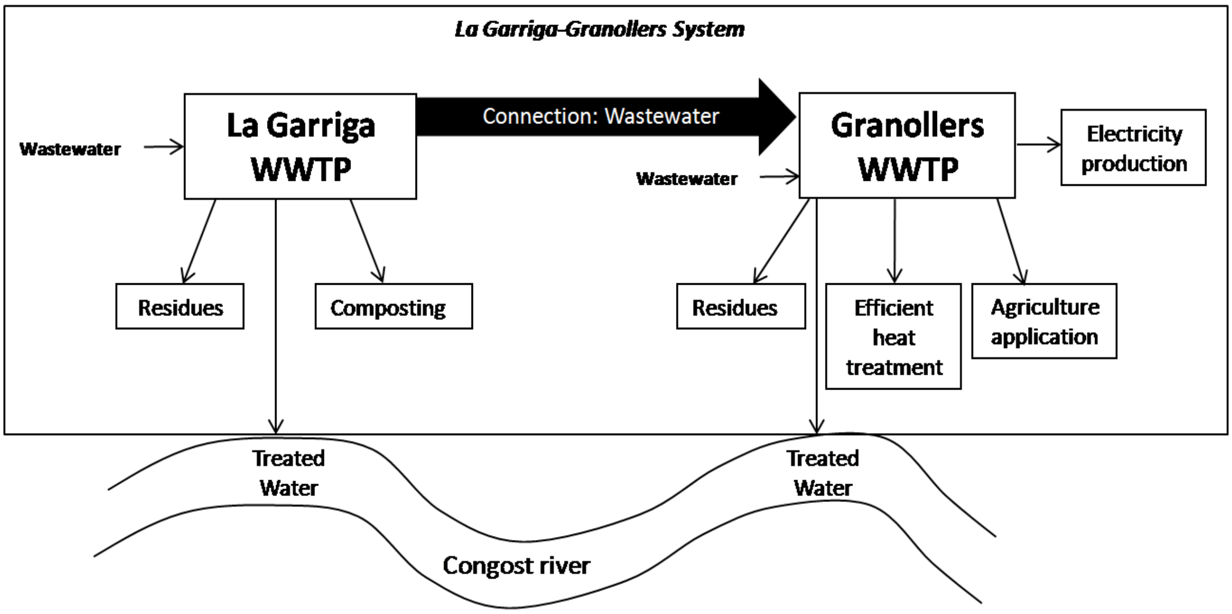


Fig. 3-2: Description of the La Garriga-Granollers system.

3.1.3.- WWTPs OF CAPACITY RANGING FROM 1,500 $m^3·d^{-1}$TO 21,000 $m^3·d^{-1}$

Four WWTPs of capacity ranging from 1,500 $m^3·d^{-1}$to 21,000 $m^3·d^{-1}$were studied to find the relationship between the massof materials and energy used and the capacity of the plant, for each WWTP construction These four plants are located in different municipalities of

Catalonia (Navàs, Balaguer, Manlleu and L'Escala),they have the same process configuration and the same units to carryout the wastewater treatment. The four plants are activated sludge plants with a MLE configuration to eliminate biologically organic matter and nitrogen. The water line consists, as is shown in Fig. 3-3 of a pumping station, pretreatment and, secondary treatment, with a biological reactor followed by a secondary settler.The sludge line is composed by thickening and dewatering, and finally the dewatered sludge is deposited in a composting plant.Table 3-1shows the location and the most important characteristics of each plant. The smallest plant has one line of pretreatment and secondary treatment. The secondary treatment consists in a concentric reactorwith the settler in the middle part surrounded by the biological reactor. On the other hand, the second smallest plant has also one line of pretreatment and secondary treatment, but the secondary treatment consists in an oxidation ditch. On the other hand, the third one, has one line of pretreatment and two lines for the secondary treatment with two different oxidation ditch reactors and two settlers. Finally, the largestone, has two lines of pretreatment and three lines for the secondary treatment.

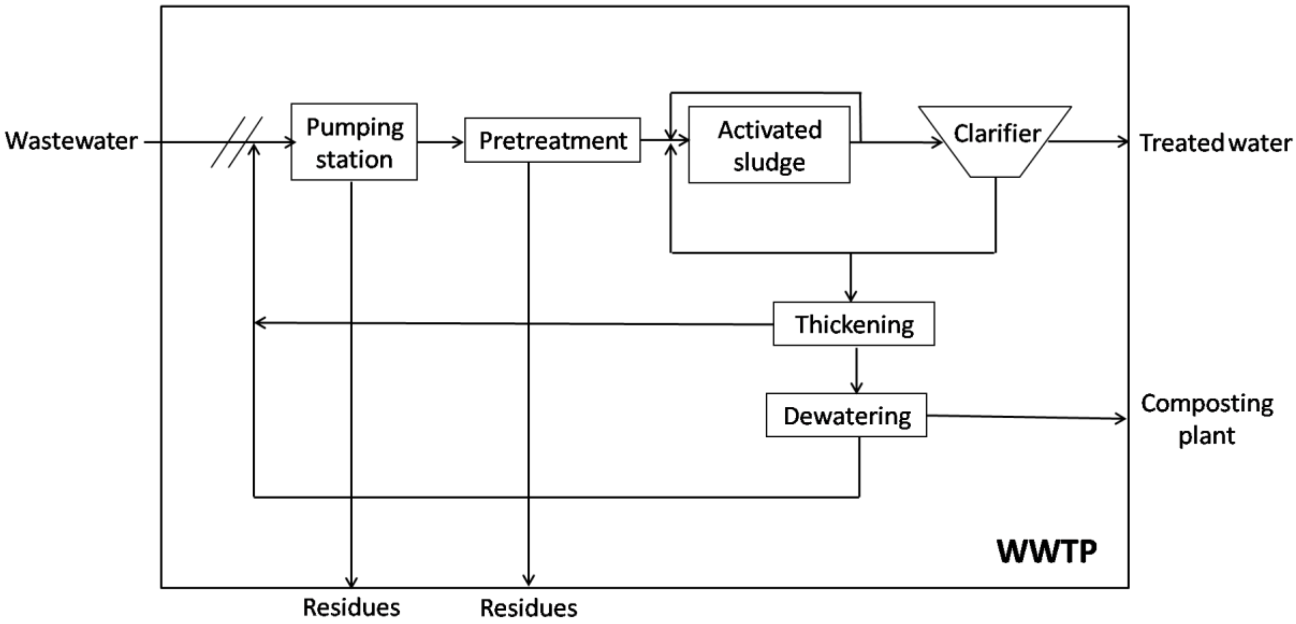
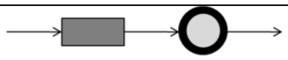
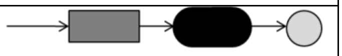
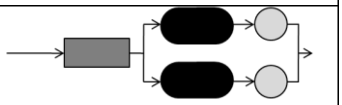
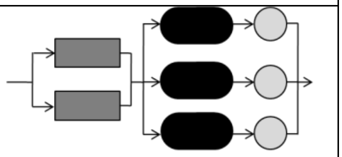


Fig. 3-3: Typical scheme of the studied WWTPs.

Table 3-1: Location, capacity and water line composition of the water line of the studied WWTPs. Dark greyfor pretreatment. Black for the biological reactor and light grey for the secondary settler.

Location (Region)	Capacity ($m^3 \cdot d^{-1}$)	Capacity (PE)	Water line composition
Navàs (Bagès)	1,500 $m^3 \cdot d^{-1}$	8,750 PE	
Balaguer (La Noguera)	3,750 $m^3 \cdot d^{-1}$	18,750 PE	
Manlleu (Osona)	14,400 $m^3 \cdot d^{-1}$	44,153 PE	
L'Escala (Alt Empordà)	21,000 $m^3 \cdot d^{-1}$	105,000 PE	

3.2.- LCA SOFTWARE

A computer software is normally used to carry out the impact assessment phase of LCA studies. Although there are different commercial softwares, in this case only the SimaPro software was used in two different versions, SimaPro 7.3.3 and SimaPro 8.0.3.

SimaPro was created and developed by the PréConsultants Company, a Dutch company specialized in LCA studies since more than 20 years, with a worldwide reputation as one of the most important companies working in environmental impact assessment.

SimaPro is a user-friendly tool that combines different LCI databases together with the most important calculation methods. SimaPro permits to model and analyze complex systems. SimaPro can calculate the environmental impacts, and also permits to detect hot-spots in a systematic and transparent way. SimaPro allows to obtain the results in midpoint or endpoint impact categories and also to analyze only single impacts as carbon footprint or water use.

SimaPro is used in industry, consultancies, universities and research centers of more than 80 countries.

3.3.- BEDEC BANC DATABASE

The *BEDECbanc* is a database that contains very detailed information related with the material and energy used to carry out all needed operations to construct any civil infrastructure. Italso contains information about the cost for each operation, distinguishing between human and material resources needed for each operation. This database is widely used for engineers and architects to do their constructive budgets.

The *BEDEC banc* database has been used in this thesistogether with the real constructive budgets in order to obtain the inventories for each WWTP construction and sewer system construction, since the budget contains the quantity of each constructive operation while the database provides the information of the material and energy used for each operation, as an example, to excavate one cubic meter of compact soil is necessary 0.05 hours of personnel work, also 0.1654 hours of a backhoe with a consumption of 432.12 MJ of diesel per hour.

3.4.- IMPACT METHODS USED

A calculation method must be applied to transform the information from the inventories to environmental impacts. The calculation method contains all the characterization factors necessaries to do this calculation. CML and ReCiPe were the methods used, CML because was the most used method according to the review presented in section 1.4., and ReCiPe because is the most recommended method nowadays.

3.4.1.-CML

CML is a calculation method developed by the Institute of Environmental Science of the University of Leiden(Guinée, 2001). CML contains characterization factors for different impact categories and also contains normalization data for all impact categories with different factors depending on the place and time.

There are different versions of the CML.On one hand CML, baseline versions (CML 2000 baseline and CML-IA (baseline)), which develop the problem-oriented approach obtaining a list of midpoint impact categories, recommended to do basic LCA studies. The list of impact categories obtained can be divided in three different groups: 1.- Obligatory impact categories (category indicators used in most LCAs); 2.- Additional impact categories (operational indicators that exists, but are not often included in LCA studies); 3.- Other impact categories (no operational indicators available, therefore impossible to be included quantitatively in

LCA). These baseline methods are recommended for simplified studies. On the other hand, CML non-baseline methods (CML 2001 (all impact categories) and CML-IA non-baseline) are extended versions of the baseline methods. These methods contain the baseline categories and also alternative impact categories recommended for extended LCA studies.

3.4.2.- RECIPE

ReCiPe is a calculation method created by RIVM, CML, PRé Consultants and Radboud Universiteit Nijmegen(Goedkoop *et al.*, 2013). This method was created with the combination of two older methods; CML and Eco-indicator 99. This method differentiates between two levels of indicators, the 18 midpoint categories and the 3 endpoint categories. This method contains characterization factors for different substances, as well as, factors for normalization from Europe and from all over the world.

ReCiPe method can be calculated from three different perspectives:

- Individualist: short term, optimism that technology can avoid many problems in the future.
- Hierarchist: as often encountered in scientific models, this is often considered to be the default model, consensus model.
- Egalitarian: long-term based on precautionary principle thinking.

4 RESULTS

4.1.-LIFE CYCLE ASSESSMENT OF CONSTRUCTION AND RENOVATION OFSEWER SYSTEMS USING A DETAILED INVENTORY TOOL

Human activities in households and industries consume large amounts of water which have to be treated before being returned to the freshwater ecosystems. Above 80% of population in 14 of the EU Member states are connected to urban wastewater treatment plants (WWTPs) (European Environment Agency, 2013), which have the function of removing contaminants from the used water (i.e. wastewater). Sewer systems are the elements that collect and transport wastewater from households and industries to the WWTPs. Despite the important role they have, their construction and renovation generates environmental impacts associated to the direct emissions generated on-site and to the production of energy and resources required.This chapter presents a detailed example of LCA methodology used in sewer systems construction, analyzing all the different aspects influencing its construction through the use of an Excel®-based tool created to facilitate its application.

In summary, the chapter, through the use of the developed tool, shows contribution to the impact of the renovation of sewers, and the high contribution to the impact of the material deposition during the renovation. The chapter also shows good environmental results of HDPE tubes compared with other materials, and analyze all the aspects that can influence the construction of sewer systems.

Redrafted from:

Morera, S.; Comas, J.; Remy, C.; Corominas Ll. Life cycle assessment of construction and renovation of sewer systems using a detailed inventory tool

Submitted

4.1.1.- MOTIVATION AND OBJECTIVE

Life cycle assessment (LCA) is a widespread tool to assess the environmental impacts from urban water systems (UWS) (Loubet *et al.*, 2014), including drinking water treatment, distribution systems, sewer systems and WWTPs. Many of the studies published so far include the operation but neglect (or partially consider) the environmental load of the construction and end-of-life phases. The review from Loubet *et al.*(2014) concluded that only three out of eighteen studies included the pipe materials (either in sewers or in drinking-water distribution networks) in the inventory phase and none considered the civil works involved in the construction of sewer systems. Risch*et al.*(2015) is the first study that compared in detail the environmental impacts from the construction and operation of a case-study which included a sewer system and a WWTP. Risch*et al.*(2015) provided a detailed inventory including pipe materials and civil works for the construction of one specific sewer system.

Focusing on pipe networks (either for sewers or for drinking-water distribution), three studies have addressed in detail their construction following a life cycle approach. Piratla *et al.* (2012) compared four pipe materials (molecular oriented polyvinylchloride (PVC-O), polyvinylchloride (PVC), high-density polyethylene (HDPE) and ductile iron) in terms of CO_2 emissions from their manufacturing and assumed a lifespan of 50 years for all materials evaluated. Du *et al.*(2013) compared six pipe materials (PVC, ductile iron, concrete, HDPE, reinforced concrete and cast iron) in terms of global warming potential (GWP) and considered pipe production, transport, installation and use phases and assumed a service life of 30 years for all pipe materials. Petit-Boix *et al.*(2014) followed a multi-criteria LCA approach (involving several potential impact categories) to evaluate pipes made from PVC, concrete and HDPE and assumed that plastic pipes had to be replaced once every 100 years. The three studies differ in the phases and processes considered in the construction of the pipe networks, did not model in detail renovation of the infrastructure and made different assumptions regarding their life span.

Construction and renovation (particularly for sewers) are not systematically included in LCA studies of UWS due to the limited availability of comprehensive life cycle inventories which account for different diameters, a variety of characteristics of the site, multiple materials with varying life span and several options for pipe disposal. Hence, the objective of this study is to provide comprehensive life cycle inventories for the construction and renovation of sewer systems. This inventory was embedded into an Excel®-based tool, which allows for effective life cycle evaluation of different sewer typologies. By using the tool it was possible to determine which are the most important phases, processes and related parameters involved in the construction and renovation of sewers from an environmental and economical point of view.

4.1.2.-METHODOLOGY

Description of sewer pipes construction and renovation phasesand processes

The sewer system construction process can be divided into six different phases (Fig. 4-1a): (1) the working area is cleaned; (2) the trench is excavated and underpinned; (3) the pipe is laid at the bottom of the trench above a layer of draining material; (4) the trench is backfilled with granite sand until 30 cm above the pipe and normal sand, which is taken from the same workplace, or sand taken from elsewhere; (5) if there is a road on top of the trench, a layer of asphalt is included, and (6) the unused excavated soil is distributed around the working area or transported and deposited in a landfill.

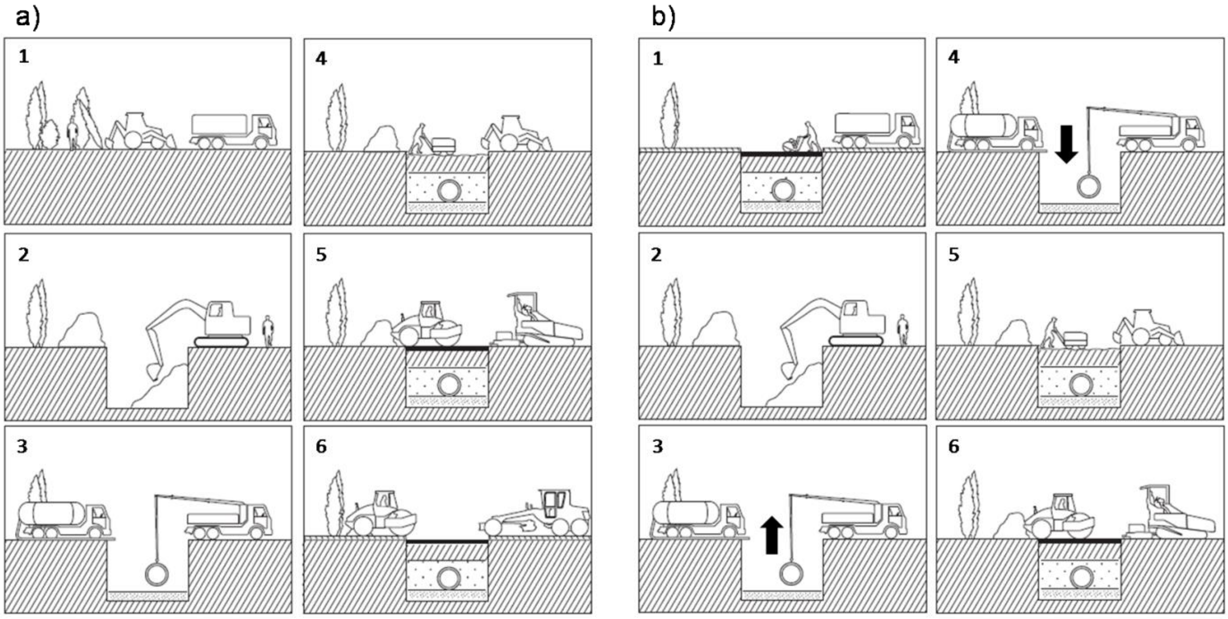


Fig. 4-1: Illustration of the required steps to construct and renovate a sewer pipe located in a non-urban area with traffic: a) Construction. b) Renovation.

Three types of trenches can be considered for the construction of sewers depending on the site characteristics. Rectangular trenches are applied for rocky soils and for most compact soils (Fig. 4-2a and b). When the excavated soil is soft a trapezoidal trench is applied (Fig. 4-2c). If asphalt is placed in the upper part of the trench deeper trenches are needed (Fig. 4-2a). The trench type shown in Fig. 4-2b is the selected for the analysis conducted in this paper, even though the Excel® spreadsheet tool created considers the three options.

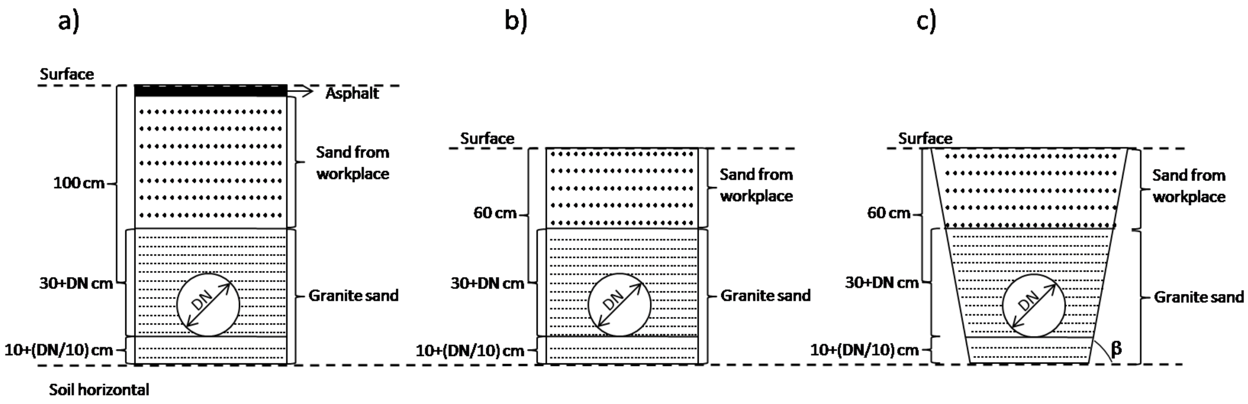


Fig. 4-2: Guidelines to calculate the trench depth, a) with traffic in the upper part in a rectangular trench, b) without traffic in the upper trench in a rectangular trench, c) without traffic in the upper trench in a trapezoidal trench.

To renovate a sewer, six different phasesare considered (Fig. 4-1b): (1) breaking the asphalt layer and deposition of the material; (2) excavation of the trench; (3) extraction of the old pipe; (4) substitution with the new pipe; (5) backfilling the trench and (6) including a layer of asphalt when is necessary.Finally, during the renovation, it is also necessary to include the end-of-life processes, i.e. to extract and deposit/incinerate the pipe, which also includes its transport.

Each phase comprises different processes such as materials production and transport, consumed diesel from machinery work and disposal (incineration or landfilling). Work area cleaning phase includes the energy consumption process. Excavation phase includes diesel consumption by the machines and transportation of the excess material to a landfill. Pipe laying phase includes the production of the pipe, its transport to the workplace, the diesel consumed during the pipe laying and water consumed to proof its reliability. Backfilling phase considers the granite sand extraction/production, its transport to the workplace and diesel and water consumed during its placement. Asphalt placement phase includes the asphalt production, its transport to the workplace and its placement. The soil distribution around the work accounts for the diesel consumed.

Life Cycle Assessment

The environmental assessment was conducted following the ISO 14040 and 14044 standards (ISO 14040, 2006; ISO 14044, 2006) which define four stages: (1) goal and scope definition; (2) inventory analysis; (3) environmental impact assessment; and (4) interpretation. A process-based LCA approach was followed because the goal was to evaluate the specific process of construction and renovation of sewers, with detailed results and being able to quantify the environmental impact from specific process stages. Although process-based LCA tends to be time consuming there are databases available for the construction sector which provide the required information for this study.

Goal and scope definition

The goal of this life cycle assessment was to compare the environmental impacts from the construction and renovation of several sewer system typologies and to determine which are the phases, processes and related parameters contributing the most to the environmental impacts. As a starting point a hypothetical sewer system with a length of 1 km and a PVC pipe with a diameter of 40 cm was evaluated (this is the initial system from now on). It was considered that the sewer is located in a non-urban area without traffic (no asphalt placement in the upper part of the trench). The pipe was installed in a compact soil zone within a rectangular trench with no underpinning(Fig. 4-2b). Distances of 50, 30 and 25 km were selected for the transport of granite sand and sand, asphalt and pipe distributors (Personal communication with Voltes S.L.U. company), respectively, which also coincides with the assumptions taken in Petit-Boix *et al*. (2014). It was assumed that the surface to be cleaned was the double of the trench surface in the upper part. Because an average life span of 25 years for PVC pipes, in the evaluation, the construction of the sewer plus two renovations were considered. The functional unit of the entire study was the construction and regular renovation of a sewer system of 1 km length during 70 years of operation. The system boundaries are shown in Fig. 4-3 and include direct emissions generated on-site (e.g. air emissions to the ecosphere from diesel combustion) and indirect emissions related to diesel and material production, pipe material deposition and transport. Even though the Excel®-based tool provides estimations of water consumption during the construction process, it has no effects in this study since the water is considered that is directly extracted from the nature.

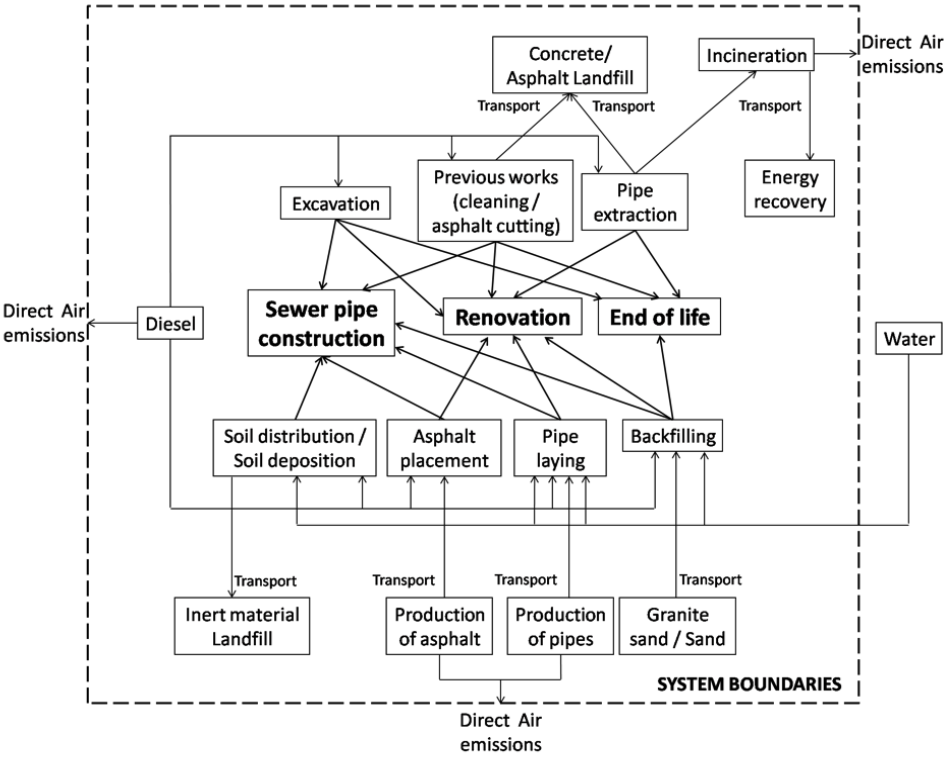


Fig. 4-3: System boundaries, phases and processes considered.

After evaluation of the environmental impacts of the initial sewer system defined above, a sensitivity analysis was conducted to evaluate which parameters involved in the sewer construction and renovation (parameters in grey in Table 4-2) have the highest influence on the different environmental impact categories. The parameters included in the sensitivity analysis are the type of pipe material (PVC, HDPE, precast concrete and reinforced concrete), diameter of the pipes (ranging from 20 to 160 cm), transport distances for materials (ranging from 0 to 100 km) and the characteristics of the working area (location, type of soil and asphalt placement). Special emphasis was put in analyzing the influence of pipe renovation, which is directly related to the life span of the materials. In the analysis, variability related to the life span of pipes was included. For PVC, an average lifetime of 25 ± 5 years was assumed. For HDPE, a lifetime of 40 ± 10 years was considered, and finally, for precast concrete and reinforced concrete pipes, a lifetime of 70 ± 20 years was assumed. Even though pipe suppliers normally specify longer life span ranges, construction companies and water agencies experience shorter life spans in practice (Blosser *et al.*, 2003). Hence, the ranges assumed in this paper were defined after personal communication with the construction company Voltes S.L.U. (Catalonia) with more than 60 years of experience in the field. Precast concrete and reinforced concrete pipes have the same weight. Certain materials that are used, such as ductile iron, or pipe configurations, such as oval pipes, were not considered here. Finally, transportation was considered for the environmental analysis but not for the economic analysis.

With regards to renovation, the excavation process was considered as the excavation of compact soil. In addition, the energy consumed during pipe extraction from the trench was considered to be the same as during its laying. Additionally, during pipe extraction and laying during renovation, granite sand losses of 10% were considered. Finally, it was assumed that concrete pipes and excess soil are disposed of in landfills, located at 30 km., whereas plastic pipes are incinerated (a process that involves energy recovery).

Inventory analysis

The inventory was carried out following the steps identified in Fig. 4-4. Comprehensive life cycle inventories for sewers construction and renovation were obtained after interviewing construction experts and reviewing sewer construction budgets from the Catalan company Voltes S.L.U. (Catalonia). The construction budgets include in detail the amount of resources (materials, energy, machinery, etc.) required to execute the work. The public database BEDEC from the Construction Technology Institute of Catalonia (Banc BEDEC, accessed in August 2013) was also used to obtain detailed information of each material or element (a pipe is for instance an element included in the database). The Banc BEDEC database supplies technical and economic information regarding all kind of elements used in the construction market. It includes detailed information of 2,026 construction items including prices (before taxes). For example, the database provides information from a “concrete pipe” of a specific diameter. The information includes the weight and the price per unit (in this case, linear meter). Since concrete pipes are heavy, the database also adds the right handling machinery, in this case a crane, assuming the cost of the rental, the estimated time of use of the machinery and the diesel consumption per hour.

The calculations related with the trench characteristics and the volumes to be excavated and backfilled were estimated using the guidelines proposed in “Installing pipes for distribution, irrigation and sanitation according to current legislation” (Adequa-GrupoUralita, 2007).

Table 4-1 shows the rules used to calculate the width of the trenches, and Fig. 4-2 provides guidance on to calculate the depth of the trenches.

Table 4-1: Rules to calculate the trench width at the bottom. Trench width has to be large enough to place the tube and has space to work. The trench width depends on the pipe diameter (because more extra space will be needed as bigger is the diameter), the necessity to underpin the trench or not and the angle between the trench wall and the soil horizontal. Information from Adequa-Grupo Uralita, 2007.

Pipe diameter (mm)	Minimum trench width (OD + x), meters		
	Underpinned trench	No-underpinned trench	
		β > 60º	β ≤ 60º
≤ 225	OD + 0.40	OD + 0.40	
> 225 to ≤ 350	OD + 0.50	OD + 0.50	OD + 0.40
> 350 to ≤ 700	OD + 0.70	OD + 0.70	OD + 0.40
> 700 to ≤ 1,200	OD + 0.85	OD + 0.85	OD + 0.40
> 1,200	OD + 1.0	OD + 1.0	OD + 0.40
OD is the outside diameter of the pipe in meters. β is angle of the no-underpinned trench wall measured from the horizontal.			

Environmental impact assessment

The types of materials and energy sources from the inventories were matched to their corresponding equivalents in the Ecoinvent database (Weidema *et al.*, 2013). The potential environmental impacts were calculated through the use of LCIA characterization factors related to four impact categories from ReCiPe (H) 1.09 (Goedkoop *et al.*, 2013). The climate change (CC) category (measured as emissions of CO_2equivalent) evaluates the emission of greenhouse gases that capture part of the irradiation reflected on the earth from the sun, which increases the temperature of the surface. The human toxicity (HT) category (measured in kg 1.4-dichlorobenzene (DB) equivalents) takes into account the environmental persistence and accumulation in the human food chain and toxicity of toxic substances related to human activities. The particulate matter formation (PM) category (measured as PM10 equivalents) evaluates the emission of small particulates that can enter into the human body and negatively affect human health. Finally, the fossil depletion (FD) category (measured in kg of oil equivalent) considers the depletion of fossil fuels from hydrocarbons. All inventories used for the materials and energy production processes in this study were taken from Ecoinvent 3 (Weidema *et al.*, 2013) except the inventories related to the materials deposition, which were taken from Ecoinvent 2.1. (Frischknecht *et al.*, 2005).

4.1.3.-RESULTS AND DISCUSSION

Inventory tool for sewer systems

To facilitate the creation of material and energy inventories and the assessment of LCA impacts for the construction and renovation of sewers, an automatic tool was created. This tool automates steps two to four described in Fig. 4-4.

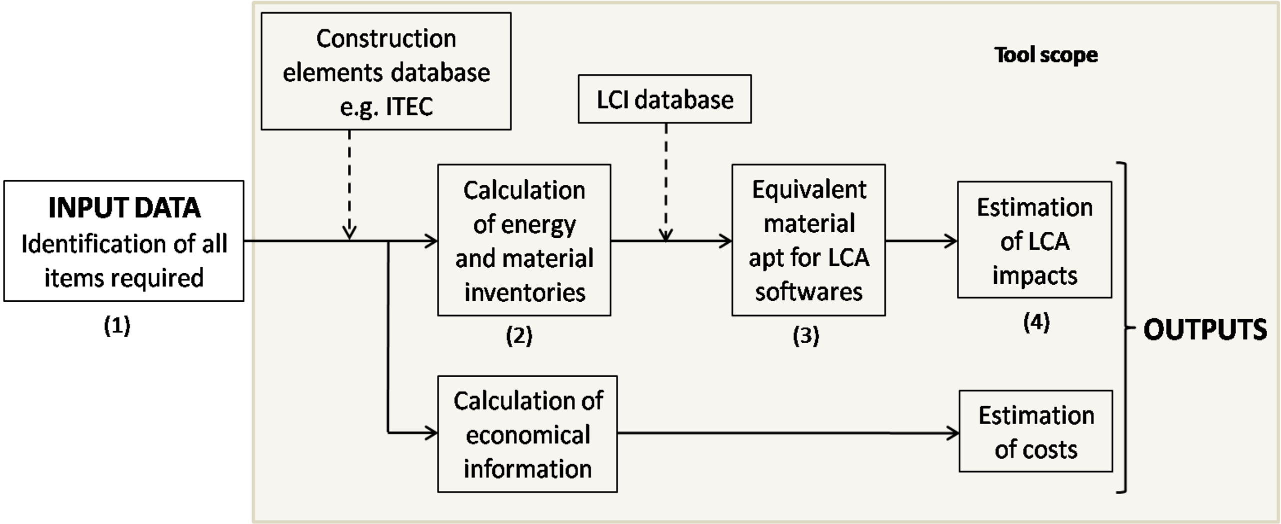


Fig. 4-4: Tool scope and all of the necessary steps to calculate the impacts of a sewer system. The Excel®-based tool automates steps 2 to 4.

The tool was implemented in an Excel® spreadsheet and incorporates all parameters and options required for sewer system construction, renovation and end-of-life of sewer systems (Table 4-2). Once the required input data are introduced, the tool automatically estimates the material and energy inventory, the LCA impacts (CC, HT, PM and FD) and costs. The environmental impacts can be estimated either per considered materials or per considered processes. A prototype version of the tool, which is not intended to be used for commercial purposes, is provided as supplementary information.

Table 4-2: Parameters, options and their effects considered in the inventory tool for the sewer system construction, renovation and end-of-life. All the parameters considered in the sensitivity analysis performed in the work are colored in grey.

Parameter	**Options considered**	**Phase affected / Practical effects**
Location	Urban	Excavated soil to landfill
	Non-urban	Distribution of excavated soil near the construction site
Work area cleaning	Yes	Cleaning may be required to prepare the surface for further work, which will double the trench surface in the calculation
	No	
Traffic	Yes	If there is a road above the trench, it is necessary to construct deeper trenches and install asphalt
	No	
Trench underpinning	Yes	For urban area, underpinning is considered in soft and compact soils For non-urban area, underpinning is not considered because it is preferable to construct trapezoidal trenches
	No	
Surface to be cleaned before the work	Automatic calculation	Is calculated automatically considering 2 times the trench surface in the soil surface
Surface to be underpinned	Automatic calculation	Is calculated automatically considering the surface of the trench walls
Pipe material	PVC	Each material has different characteristics (e.g., weight, longevity)
	HDPE	
	Reinforced concrete	
	Concrete	
Pipe diameter	From 20 to 250 cm	Depending on the material
Trench shape	Rectangular	Angle between trench and soil β=90°
	Trapezoidal	Angle between trench and soil β<90°
Angle	Between 90º and 30º	The angle selected determines the trench shape
Trench length	Case specific	Determines the length of the trench and useful to calculate the volume of excavation
Type of soil	Soft	Depending on the hardness of the material to be excavated, more diesel is consumed during excavation. In addition, rocky soil must be transported to the landfill for disposal
	Compact	
	Rocky	
Distances from material distributors	Case-specific	Transport distances between the workplace, distributors and deposition facilities can be defined

Deposition of the trench material	Yes	To calculate the environmental impact of the deposition of the trench material after its use and when the renovation is not included in the analysis, renovation automatically includes the deposition of the old one
	No	
Renovation inclusion	Yes	Renovation of the sewer includes regular exchange of pipes after their life span and all relevant work related to it
	No	
Years of operation	Case specific	Total time frame for the analysis in relation to the lifetime of the pipes will determine the number of renovation events
Nº of renovations	Automatic calculation	Is calculated automatically when the renovation is considered. The calculation depends on the years of operation and the tube material selected, each tube material has different life span
Distances to deposition treatments	Case specific	Distance in km between the workplace and the deposition infrastructure

Results of the inventory analysis stage are summarized in Table S-1 from supplementary information.

Environmental impact profile and costs for the initial hypotheticalsewer system

The construction and renovation of a 1 km PVC pipe with a diameter of 40 cm generates environmental impacts (Fig. 4-5). For CC the overall impact represent $3.11 \cdot 10^5$ kg CO_2 eq, for HT $5.63 \cdot 10^4$ kg 1.4-DB eq, for PM kg $5.03 \cdot 10^2$ PM-10 eq and for FD $1.14 \cdot 10^5$ kg of oil depletion (in all categories this number is the sum of the contribution of both construction and renovation phases). Renovation of the sewer has a larger impact compared with that of construction, which is 2.2 times higher for CC, 3.2 higher for HT, 1.4 higher for PM and 1.6 higher for FD (this accounts for two renovations). Except for CC, impacts from one renovation do not equal those from one construction, being larger for HT (renovation includes incineration of the PVC pipe which generates emissions of Arsenic, Barium, Manganese, Selenium and Vanadium into water, amongst others, associated with the combustion or the production of chemicals used during the incineration process) and smaller for PM and FD (e.g. 90 % of the granite sand is reused during renovation).

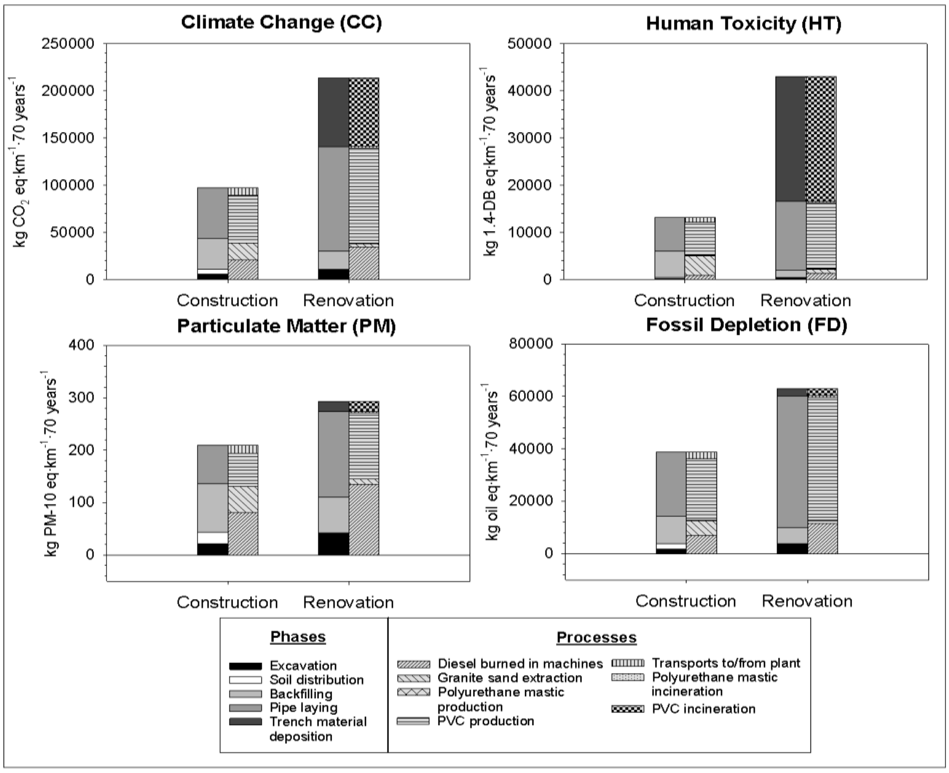


Fig. 4-5: LCIA results for the initial hypothetical sewer system with a length of 1 km and a PVC pipe with a diameter of 40 cm (analysis includes construction and renovation). The results include a single construction and two renovations over 70 years of operation. For each impact category, the results are split into the construction and renovation phases. Left part of each bar (construction or renovation) relates to the phases and the right part of each bar relates to the processes. Total impact for each category is the sum of construction and renovation bars.

With regards to the construction phase (left side of double bars for construction and renovation in Fig. 4-5), pipe laying (which also includes PVC pipes production) is the major contributor to the CC, FD and HT categories, with a 55%, 63% and 54% share respectively. Backfilling represents 44% and 42% of the PM and the HT impacts, respectively. With regards to the renovation phases, besides pipe laying, with a contribution to the impact of 52% in CC, 56% in PM and 80% in FD categories, the deposition of trench materials significantly contributes to the impacts (particularly for CC and HT, with a share of 34% and 61% respectively).

When analyzing the contribution of the processes (right side of double bars for construction and renovation in Fig. 4-5, the production of PVC (both for construction and renovation) is the primary source of impact for CC (around 50% for both construction and renovation), FD (60% for construction and 74% for renovation) and for HT (53% share in the construction and 33% in the renovation). Trench material deposition impacts are primarily driven by PVC incineration. Diesel burned in machines is the major contributor to the PM impact category (39% contribution on the construction and 46% on the renovation) together with the production of PVC (30% for construction and 43% for renovation). Either looking at the phases or processes, the non-inclusion of the renovation phase results in underestimation of the environmental impacts between 58 and 77% depending on the category.

Fig. 4-6 shows that the sewer pipe renovation of the initial sewer system (90,480 €) (two renovations are included) is more expensive than its construction (73,970 €). The increase of costs is related to pipe laying because pipes are changed twice during the life span of the sewer. Analyzing the different phases, it is possible to see that for construction, backfilling, which includes the price of the granite sand, machines, water used and labor force, is the most expensive phase followed by pipe laying, which includes the pipe, machines, water and labor force. In addition, during the renovation phases, pipe laying is the most expensive process followed by backfilling and excavation because only a small part of new granite sand is replaced, whereas new pipes must be acquired each time. From a life cycle cost point of view, costs for renovation should also be included in the infrastructure asset management because they are higher than that for construction. Hence, the phases contributing the most to the environmental impacts are also the most expensive ones.

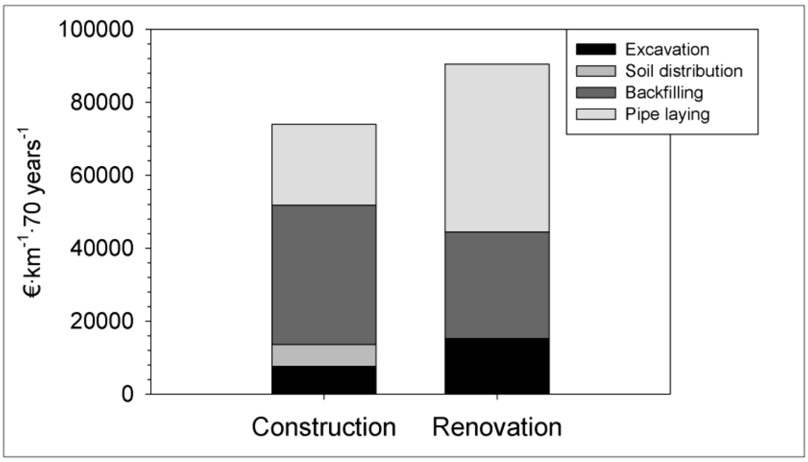


Fig. 4-6: Single construction and two renovations costs over 70 years of operation for the studied reference sewer.

Influence of different parameters on the environmental impacts

Influence of pipes (materials and diameters)

Different pipe materials were evaluated (PVC, HDPE, precast concrete and reinforced concrete) for diameters ranging from 20 to 160 cm (Fig. 4-7), while maintaining the remaining characteristics of the initial sewer system. Regarding CC, PVC sewers always have a larger impact than concrete (reinforced concrete and precast concrete) and HDPE sewers. PVC results in 40 to 55% larger impacts compared with that of HDPE depending on the impact category. The large differences between PVC and HDPE are explained by their different life spans (25 years implying 2 renovations against 40 years implying 1 renovation) and because for all of the studied categories except for FD, the impact generated per kg of tube produced is larger for PVC (it is worth noting that weight for PVC and HDPE were assumed to be the same). Comparing PVC and concrete pipes, the relative differences are the largest and increase with diameter (up to 299% for the FD impact category for a 150 cm diameter PVC pipe).

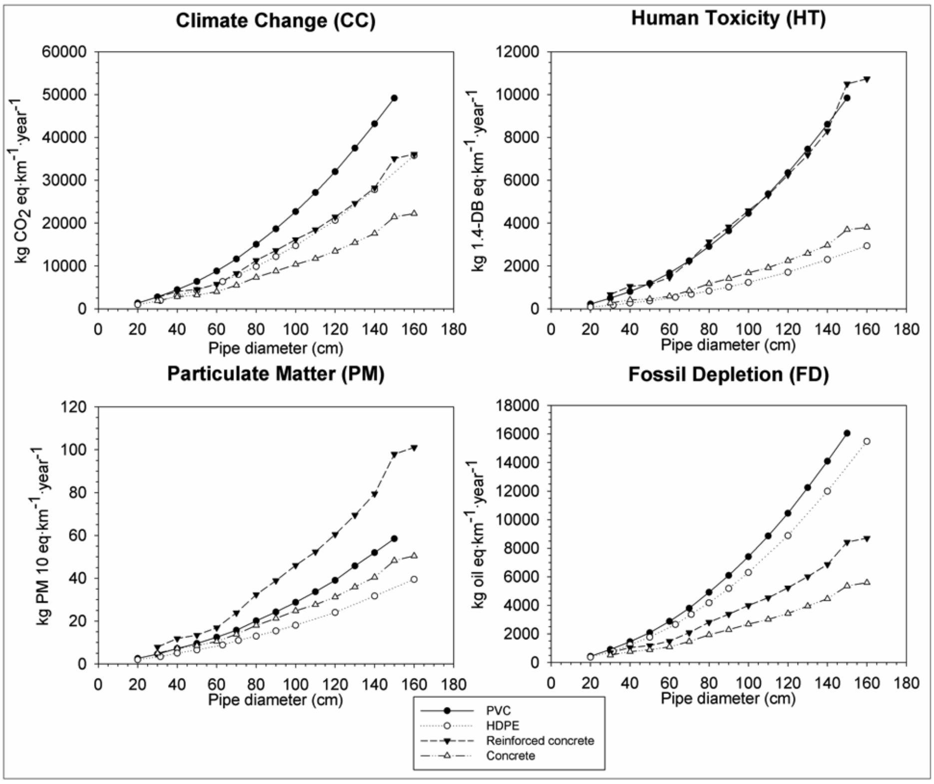


Fig. 4-7: Environmental impacts for the construction and renovation of a 1 km sewer pipe using different materials (PVC, HDPE, reinforced concrete, precast concrete) and diameters (from 20 to 160 cm). The initial hypothetical sewer system corresponds to the PVC pipe of 40 cm diameter.

For HT, two different groups of pipe materials can be distinguished. Significantly larger impacts are estimated for PVC and reinforced concrete, whereas smaller impacts are obtained for HDPE and precast concrete. Larger impacts are associated with materials production because the emissions to the air of mercury during PVC production and reinforcing steel contribute mostly to the HT impact. This difference becomes more evident as the diameter increases. For small diameters (< 50 cm) the difference between these groups is less than 100% and for large diameters (> 90 cm) increases up to 150%.

For PM, reinforced concrete has the highest impact followed by PVC, precast concrete and HDPE. Differences between PVC and reinforced concrete are constant and have a higher impact by approximately 40% for reinforced concrete. However, when comparing PVC against the other materials, differences appear with larger diameters (> 90 cm., between 134-155% for HDPE and 58-100% for precast concrete) because the impact per kg of PVC is higher than HDPE in addition to the lower life span for PVC.

For FD, there are two types of materials that follow different trends. The first type includes concrete-based pipes, and the second type is plastic pipes. Plastic sewers have a 1.5 to 3 times higher impact compared with that of concrete sewers because plastic requires energy during its production and transport phases and also includes the embedded (fossil) energy in the form of crude oil.

Overall, the obtained results show that environmental impacts are lower for precast concrete and HDPE pipes. This fact is due to the longer life of concrete and HDPE compared with that of PVC and also because the production of PVC pipes (per kg of material) has a greater impact than other materials. In terms of CC, this statement is in agreement with Du *et al.* (2013), where it was also shown that concrete and HDPE pipes have the lowest contribution to CC. However, Du *et al.* (2013) obtained higher CO_2eq emissions than the ones obtained in this study. For instance, for a ≈30 cm PVC pipe, Du *et al.* (2013) estimated 3600 kg $CO_2eq \cdot km^{-1} \cdot year^{-1}$ and this study obtained 2500 kg $CO_2eq \cdot km^{-1} \cdot year^{-1}$, and still Du et al. (2013) did not consider incineration which would result in even 38% higher emissions. In fact, the emission factors used in Du *et al.* (2013) for the production of PVC result in 19 kg $CO_2 \cdot (kg\ PVC)^{-1}$ compared to 2.72 kg $CO_2 \cdot (kg\ PVC)^{-1}$ applied in this study using the Ecoinvent database. In contrast to our statement, Petit-Boix *et al.*(2014) concluded that PVC pipes have the lowest environmental impacts. Their results differ from ours mainly because they did not include the end-of-use processes of the renovation phase. In this study incineration of PVC and HDPE pipes were modeled, and more energy is recovered during the incineration process for the HDPE pipe since it has a much higher heating value than PVC (41.84 MJ·kg^{-1} and 20.92 MJ·kg^{-1}, respectively). Piratla *et al.* (2012) concluded as well that HDPE pipes production and installation result in lower CO_2 emissions than PVC pipes.

Influence of transport distances

As shown in Fig. S-1, varying the transport distances (from 0 to 100 km) of excess materials from the construction site to landfill and from suppliers to the construction site result in less than 4% change for all impact categories compared to the initial hypothetical sewer system. The influence of PVC pipe transportation was even lower (results not shown). By looking intoTable S-2, it can be seen that the influence of transport distances is even lower as pipe diameter increases.

Site-specific characteristics

The influence of changing site-specific characteristics (soil type in construction area, asphalt placement need, and urban or non-urban setting) on the initial hypothetical sewer is shown in Fig. 4-8. For the initial hypothetical sewer (with PVC pipes) changing from compact to soft soil does not make a difference on any of the impact categories, whereas changing to rocky soil increases the impacts between 9 to 34 % depending on the impact category. With increased diameter size (80 and 140 cm) the percentage of change decreases because the contribution of the tube laying and backfilling increases. When covering the trench with asphalt the impacts increase by around 20% for CC and HT, and up to 35% and 55 % for PM and FD, respectively. Again, this influence decreases as the diameter increases. The environmental burden from constructing the sewer on an urban or a non-urban setting does not show a significant difference.

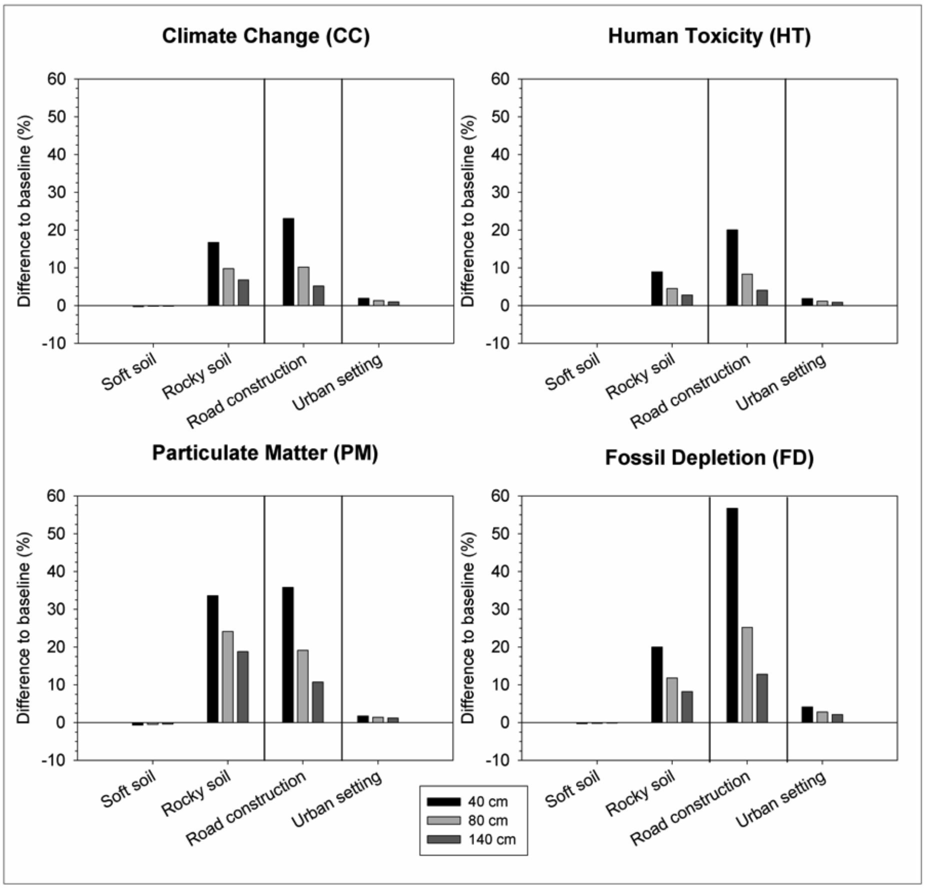


Fig. 4-8: Influence of site-specific characteristics (soft and rocky soil vs compact, asphalt placement when a road is constructed vs no asphalt, and urban vs non-urban setting) on the environmental impacts. The impact of each site-specific characteristic is referred to a baseline, which corresponds to the initial hypothetical sewer system but with 3 different diameters (40, 80 or 140 cm).

Pipe deposition

Considering the disposal of pipes at the end of their life enables the inclusion of both the additional impacts of disposal (e.g., transport, incineration) and also the recovery of feedstock energy from plastic material. The effect of taking into account the disposal process (incineration for PVC and HDPE with electricity production and a specific landfill for construction materials for precast concrete and reinforced concrete) is shown compared with the exact same sewer but without considering disposal (0%) (Fig. 4-9).

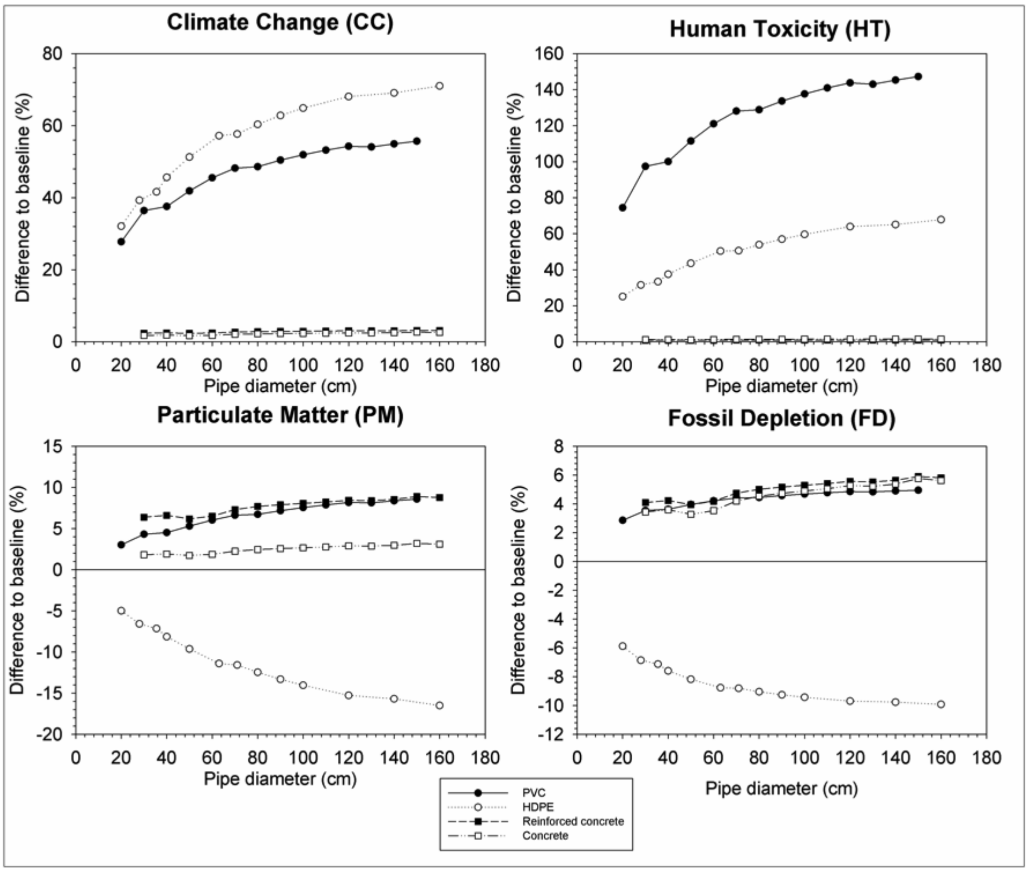


Fig. 4-9: Effect of including deposition on the LCIA of a 1 km sewer pipe (positive percentages mean increased impacts whereas negatives percentages correspond to decreased impacts). Different materials and diameters are evaluated. Baselines (no deposition included) are different for each material and pipe diameter and the percentages of change after including deposition are calculated compared to these baselines.

As shown in Fig. 4-9, including the disposal process adds between 28 to 71% of the impact to CC for plastic pipes, which is mostly due to CO_2 emissions from incineration. The partial recovery of electricity from the heating value of plastic materials in incineration does not offset the negative impacts from incineration emissions. For HT, the additional impact of disposal is even more pronounced, with an increase of 74-147% for PVC compared with the baseline. For particulate matter and FD, including the disposal phase is less important and adds only 1-8% for PVC to the impacts, and in the case of HDPE, the impact decreases between 5 and 15% because fewer resources are used and more energy is obtained in the HDPE incineration. For concrete-based materials, the impact of including disposal is marginal (< 5%) for all four impact categories, which is essentially because disposal only includes additional transport to the landfill and no subsequent emissions or energy recovery.

Influence of life span

Given the defined life span ranges for each material, the selection of the highest or the lowest values (see section goal and scope definition) (compared to the average value assumed) greatly affects the obtained results (Fig. 4-10). PVC increases between 20% and 40% of the impact depending on the category when using the lowest life span. The increase is even larger for HDPE, between 40 and 60% (but still lower absolute values compared to PVC pipes).

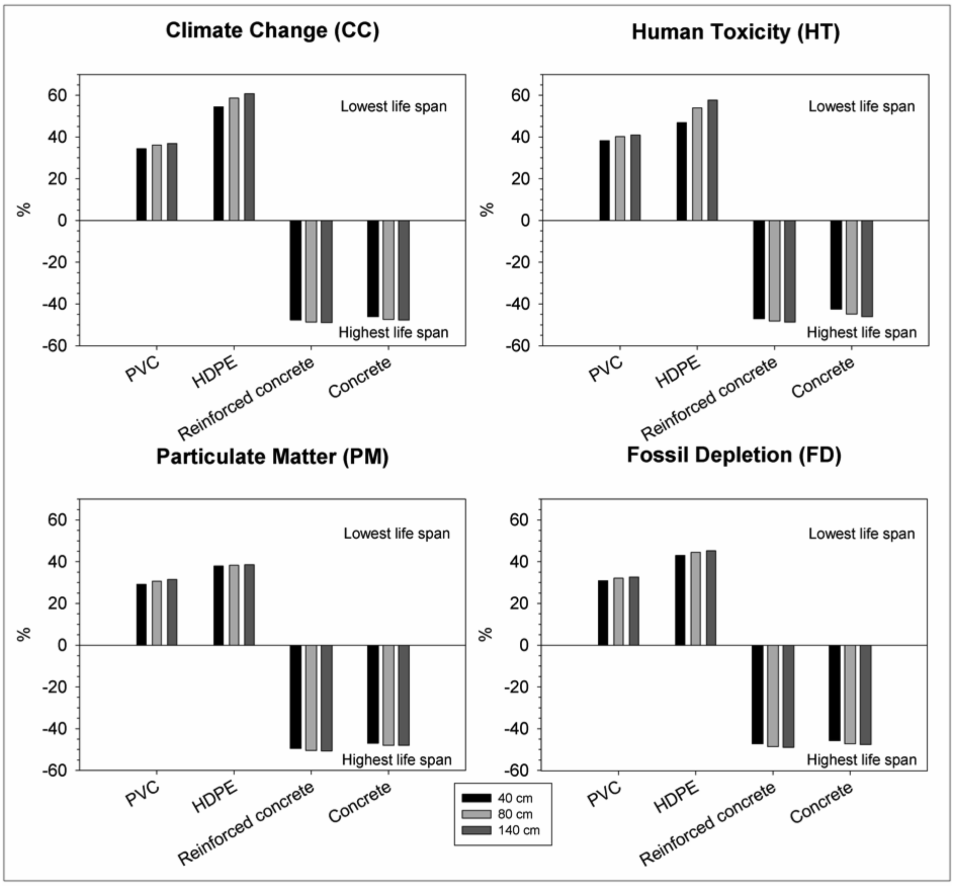


Fig. 4-10: Influence of the pipe material life span to the environmental impacts from the construction and renovation of 1 km sewer system. The results are obtained after calculating the impacts on the initial sewer system typology and changing from the average life span (the baseline) to the highest and the lowest value (results show the maximum difference obtained).This evaluation is conducted separately for each pipe material (except for the material and its corresponding life span the remaining characteristics from the initial sewer are applied).

For concrete materials the selection of the highest life span value represents a decrease in the environmental impacts between 40 and 50% depending on the category. The combination of the effect of the diameter together with the life span results in differences lower than 12 % (differences for each studied characteristic between the black, light grey and dark grey). This means the influence of the selection of life span is large no matter the pipe diameter.

Influence of including renovation or not

The results presented in section "Environmental impact profile and costs for the initial hypothetical sewer system" already indicate that including renovation for PVC pipes has a significant contribution. Table S-2, including a summary of all the sensitivity analysis, shows how the non-inclusion of renovation would underestimate the impacts from 40 to 80% for different pipe materials and diameters.

4.2.- COMPARISON OF THE CONSTRUCTION AND OPERATION PHASES ON THE LIFE CYCLE ASSESSMENT OF A LARGE WWTP BASED ON A DETAILED INVENTORY

Wastewater treatment plants (WWTPs) are complex processes designed to reduce the impact of wastewater generated in urban systems before it is discharged to the receiving water bodies. Despite their beneficial contribution to the environment, they also generate environmental impacts during their construction and operation.

Although the application of the LCA is well-known in the operational phase of the life cycle of WWTPs, its application in the construction phase is not as common as in the operation. Some LCA practitioners justify the no-inclusion of this phase in older works where the contribution of the construction is considered as negligible.

In this chapter the procedure to obtain very detailed inventories is explained, followed by its application in a real case study analyzing the contribution of the construction against the operation.

In short, construction contribution represents an impact 0.4% and 10% for marine and freshwater eutrophication impact categories, respectively. 11% for ozone depletion and climate changecategories, 24 % for fossil depletion, 28% for human toxicity and, finally, 74% for metal depletion category.

Morera, S.; Corominas, Ll.; Rigola, M.; Poch, M.; Comas, J.Comparison of the construction and operation phases on the life cycle assessment of wastewater treatment plants based on very detailed inventories

In preparation

4.3.- CONDUCTING EASY, FAST AND MODULAR CONSTRUCTION INVENTORIES FOR LIFE CYCLE ASSESSMENTS OF SMALL TO MEDIUM WWTPs

Construction inventories are not systematically included in Life Cycle Assessment (LCA) studies of wastewater treatment plants (WWTPs). In the review of Corominas *et al.*(2013), only 22 of the 45 LCA studies applied to WWTPs included the construction. It is normally not considered due to the difficulties to obtain specific information about WWTPs construction and, if there is any information available, it is extremely time-consuming to obtain construction inventories from it.

In this chapter a comparison between the detailed inventories for four small and medium full scale WWTPs and four of the WWTPs included in Ecoinvent database is carried out. Besides, a set of equations and ranges are provided to conduct easy, fast and modular inventories for the civil works of activated sludge WWTPs between 1,500 and 21,000 $m^3 \cdot d^{-1}$. The usefulness of these equations is demonstrated by comparing the environmental impact based on real (complete) inventories and the impact based on inventories obtained with these equations and factors are facilitated.

In summary, the chapter shows that a revision and update the current inventories of WWTP construction in Ecoinvent would be necessary. Equations provided enable to easily estimate reliable inventories of materials consumed for the construction of small to medium WWTP in a fast way.

4.3.1.-MOTIVATION AND OBJECTIVE

Emmerson*et al.*(1995) was the first study in this field which included a construction inventory and concluded that in activated sludge plants its contribution to the overall environmental impacts was less than 5%, against other stages such as operation which represented more than 90% of the impacts.

After the work of Emmerson*et al.*(1995), several studies conducted their own construction inventories (Machado *et al.*, 2007; Ortiz*et al.*, 2007) obtaining data from the real system. In parallel, the results from Doka (2007) were incorporated into the Ecoinvent databases. That inventory has been widely used as the basis to create inventories for construction of WWTPs without necessity to obtain real data. One example is Foley*et al.*(2010), which calculated the volume of reinforced concrete in the main civil structures for each scenario analyzed. The concrete volume was then used as a multiplier for the consumption of other materials and processes in the construction phase of each scenario, as defined by previously catalogued construction inventory data from Swiss WWTPs (Doka, 2003).However, these data was obtained from studies carried out more than 20 years ago, thus some information could be outdated.

Unfortunately, many studies did not consider construction in their inventories justifying that decision based on the outcomes from Emmerson*et al.*(1995) and following LCA guidelines. As is explained in annex A of the ILCD Handbook (European Comission, 2010) to have studies with very good level of quality they have to explain at least a 95% of the environmental impacts using adequate inventories, with good technological, geographical and time-related representativeness, good precision of the data and use of correct LCI methodologies. Despite this, there are articles that indicate a larger contribution of the construction to the impact than the contribution obtained in Emmerson *et al.*(1995). As an example in Renou*et al.*(2008) a contribution of 10% of the construction in global warming potential impact is described as well as a 11.5% in abiotic depletion.

To the best of our knowledge, besides the work from Doka there is no other works in literature that brings to the community detailed inventories from WWTPs that can be used in LCA.However, materials and practices applied to the construction of WWTPs have evolved during the years. In addition, better reporting is available now in the budgeting, and better information of the items can be obtained thanks to the existence of complete databases (with information of materials and energy consumption, information of labor force, residues generated and their expenses).

Hence, the objective of this chapter is to present detailed construction inventories from four WWTPs with capacities ranging from 1,500 to 21,000 $m^3 \cdot d^{-1}$. In the analysis of the results we provide a comparison against the inventories from Doka, 2007 introduced in Ecoinvent and, as a compendium of good practices, we provide equations to conduct easy, fast and modularconstruction inventoriesfor any activated sludge WWTP with capacities ranging within the studied boundaries.

4.3.2.- METHODOLOGY

Detailed WWTP inventories (unit processes classification)

The functional unit of the study is the construction of aWWTP. Detailed inventories for the four WWTPs with capacities ranging from 1,500 to 21,000 $m^3 \cdot d^{-1}$ described in section 3.1.3 were conducted. The WWTPs are all of similar configuration (oxidation ditch) to remove carbon and nitrogen and with simple sludge treatment (thickening and dewatering). The construction inventories were obtained following the methodology described in Chapter 4.2. As a summary, the items from the construction budget were transformed, through the use of Banc BEDEC database to a detailed list of materials and energy for each WWTP process unit (pre-treatment, secondary treatment, sludge line, connections, buildings, urbanization and power station). Pre-treatment includes the receiving waters well, the pumping station, screening, grit removal and degreasing operations. Secondary treatment includes the biological reactor and the secondary settler. Sludge line includes the thickener and dewatering. Connections include all the tube connections to transport the wastewater inside the plant. Buildings include the control and services building together with buildings that hold key elements from the system that cannot be outside (e.g. building for blowers). Urbanization includes the process of asphalting inside the WWTP, sidewalks construction, the construction of green zones and the placement of metallic fences around the WWTP. Finally, power station includes the placement of the needed buildings for the electricity transformer. Fig. 3-3 shows the division of the plants in different units.

Detailed WWTP inventories (materials classification and grouping)

Materials, energy consumed as well as the excess soil generated were distributed into different items in order to facilitate the subsequent analysis of the results. These items were: diesel used for machines, diesel used for electricity generators, excavated soil deposited in an inert waste landfill and its transport, concrete, reinforcing steel, steel used in formworks, other metals (galvanized steel, stainless steel, cast iron, copper, aluminum, etc.), PVC used in formworks, other plastics (HDPE, polypropylene, polystyrene, extruded polystyrene, etc.), mortars, precast pieces, wood for formworks and other used wood (particle board, sawn timber), other materials (includes materials that cannot be classified in the previous items, as sand, bitumen or paint), and finally, transport of materials, that was calculated considering the mass of material to transport and 40 km of transport distance.

Simple equations to conduct easy, fast and modular WWTP construction inventories

For each one of the items of material and unit processes defined in the previous section, the relation between WWTP capacity and the quantity of material/energy used was evaluated. The equations are linear regressions forcing the line to exactly match the value for the smallest WWTP to avoid negative values for capacities closest to the smallest WWTP. The linearity can be explained by the difference in complexity of the civil construction, more simple for plants of small size and the modular construction of bigger plants. These equations are only valid for WWTPs with capacities between 1,500 and 21,000 $m^3 \cdot d^{-1}$ and the configuration described in Table 3-1. Note that the increasing capacity of the studied WWTPs is related to an increase in the number of treatment lines from 1 (WWTP of Balaguer) to 3 (WWTP of l'Escala). We considered useful equations those with a r^2 higher than 0.7. For the groups of materials where lower correlation was obtained (r^2 lower than 0.7) a fixed value was provided which should be added on top of the calculated values for each material.

Assumptions

Several assumptions were taken in this approach. Particular specificities from each WWTP were not considered for the purpose of comparing 4 plants as similar as possible.Each plant had some specificities that could significantly contribute to the LCA results.For example, sometimes the tanks are buried or not depending on the soil hardness, water stored in the soil and plant location, which lead to different excavation and transport necessities, or for example, the type and capacity of thickening can be different. Some assumptions were madeto exclude specificities from the analysis and hence, find good correlations between WWTP of same configuration (but different sizes) and their corresponding inventories.

There are some differences when the inventories obtained in this work are compared with the Ecoinvent inventories. While in Ecoinvent a specific process for the excavationexists, in this studythe excavation is considered as the consumption of diesel needed for the construction machines to excavate the needed volume of soil. Also the electricity consumption is considered in a different way. While in the Ecoinvent inventories, the electricity is assumed to be used directly from the network; in this case we consider that the electricity is generated on site by an electrical generator. In Ecoinventz, transport of the excess excavated soil to the landfill or the transport from the manufacture to the workplace is not considered while in this case they are included. Finally, for comparison purposes, the process considered for the concrete production used in WWTPs construction in Ecoinvent was changed from concrete for high requirement to concrete with non-special requirements. That was made because after personal communication with construction companies, it was assumed that the concrete used for the construction of WWTPs does not need any special requirements.

4.3.3.- RESULTS AND DISCUSSION

Inventory for the 4 studied WWTPs and comparison with Ecoinvent

Fig. 4-18shows a comparison between the inventories calculated from the linear regression obtained from the plant inventories in Ecoinvent with similar capacities to the studied plants and the 4 inventories obtained in this work for the 5 more relevant materials. In general, it can be seen that the inventories facilitated in Ecoinvent use always larger masses of materials than the inventories from this study, except for the category other materials, which include a lot of different materials such as sand, bitumen, paint, gravel, etc. Regarding concrete and mortars, the inventories obtained in this work range from $2.46 \cdot 10^6$ kg to $3.10 \cdot 10^7$ kg for the plants ranging from 1,500 to 21,000 $m^3 \cdot d^{-1}$, while for the Ecoinvent inventories the masses of concrete range from $1.24 \cdot 10^7$ kg for a plant of 1,500 $m^3 \cdot d^{-1}$ to $1.34 \cdot 10^8$ kg for a plant of 21,000 $m^3 \cdot d^{-1}$. Reinforcing steel consumption ranges from $5.14 \cdot 10^4$ to $1.15 \cdot 10^6$ kg in the inventoriescalculated while for the Ecoinvent plants ranges from $3.95 \cdot 10^5$ to $4.37 \cdot 10^6$ kg. The same trend is observed in the consumption of metals and plastics, ranging from $1.17 \cdot 10^4$ and $5.07 \cdot 10^4$ kg for metals in the inventories calculated in this work and $4.07 \cdot 10^4$ to $4.52 \cdot 10^5$ kg in Ecoinvent inventories, and ranging from $8.42 \cdot 10^2$ to $7.13 \cdot 10^4$ kg of plastics, in this case, against $1.70 \cdot 10^4$ to $1.89 \cdot 10^5$ kg for plastics in Ecoinvent inventories, respectively. Finally, in the case of the category other materials, this trend is the opposite, while in this study the masses range between $1.30 \cdot 10^6$ and $1.08 \cdot 10^8$ kg, for the Ecoinvent inventories these masses range from $6.14 \cdot 10^5$ to $8.36 \cdot 10^6$ kg.

Fig. 4-18 also illustrates that exists a linear correlation for the masses of materials and the capacity of the plant for the Ecoinvent plants, since they are calculated from a linear regression previously made in(Doka, 2003). In this study a linear correlation is also observed, with a different slope, between the consumed mass of materials and the capacity of the plants for concrete and mortars and also for reinforcing steel, which are the largest consumed materials for WWTPs construction. For the rest of the materials, this study does not provide linear regressions. However, the mass of metals and plastics do not have a high influence in the inventories of material, because their weight is very low compared with the most consumed materials. Finally, for the other materials items, even though in the inventories calculatedrepresenting a large mass, their influence is low in the computed environmental impacts, since in general they have lower potential impact than other materials as concrete or reinforcing steel.

Compared to Ecoinvent (Doka, 2007), a larger diversity of materials was considered in this study (30 different materials instead of the 15 materials used in Ecoinvent). Specifically, more diversity of metals (low-alloyed steel, galvanized steel, cast iron, brass, stainless steel among others), plastics (polyurethane, PVC, extruded polystyrene, nylon, polyester, among others) and new types of materials (wood, mortars or precast pieces) were considered (Table S-5 of annexes section).

Despite this fact, the total mass of materials for the 4 WWTPs inventoried is lower than the corresponding plantsin Ecoinvent, mainly explained by a larger consumption of concrete and reinforcing steel (Fig.4-18). In this study the consumption of kg of concrete per volume of water that the plant can treat per day ranges from 1,179 kg/($m^3 \cdot d^{-1}$)to 1,701 kg/($m^3 \cdot d^{-1}$), while in the Ecoinvent plants the consumption of concrete is around 6,900 kg of concrete per $m^3 \cdot d^{-1}$ of capacity. Regarding the reinforcing steel, in this study the consumption ranges between 21 and 55 kg of reinforcing steel per $m^3 \cdot d^{-1}$ of capacity, while in Ecoinvent plants the consumption is between 220 and 230 $kg/(m^3 \cdot d^{-1})$. Regarding the consumption of other metals and plastics, it is also much higher in Ecoinvent than in the inventories from this study. Finally, for the item entitled "other materials" the consumption in this study is much higher, mainly due to the sand used during the urbanization process or to refill some excavated parts (between 83 and 99% of the other materials masses). However this group of materials does not have a relevant influence in the environmental results since the sand production process has much lower potential environmental impact than the manufacture of other materials such as concrete.

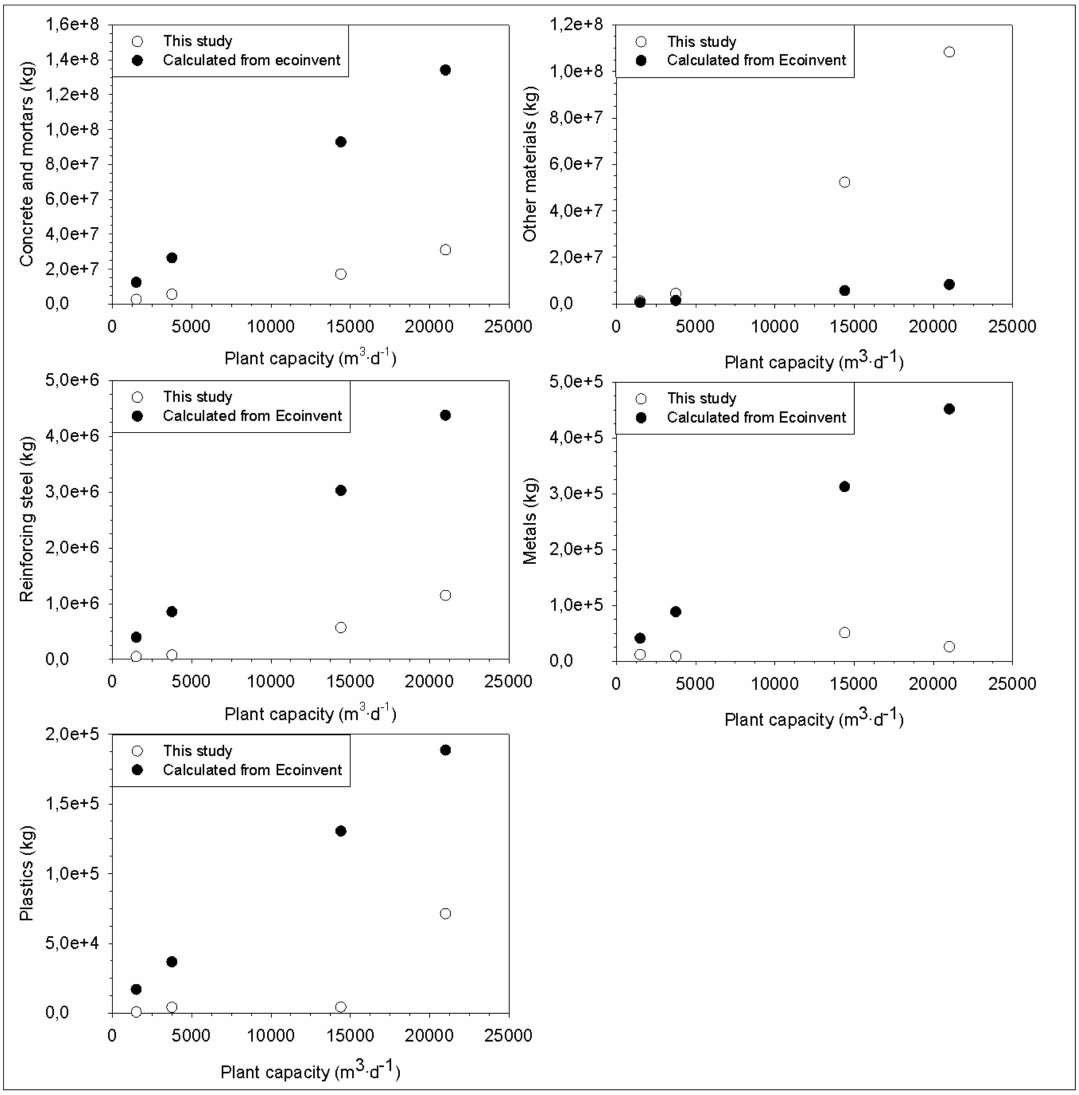


Fig. 4-18: Comparison of the masses of the most important materials considered.

Comparison of environmental impacts

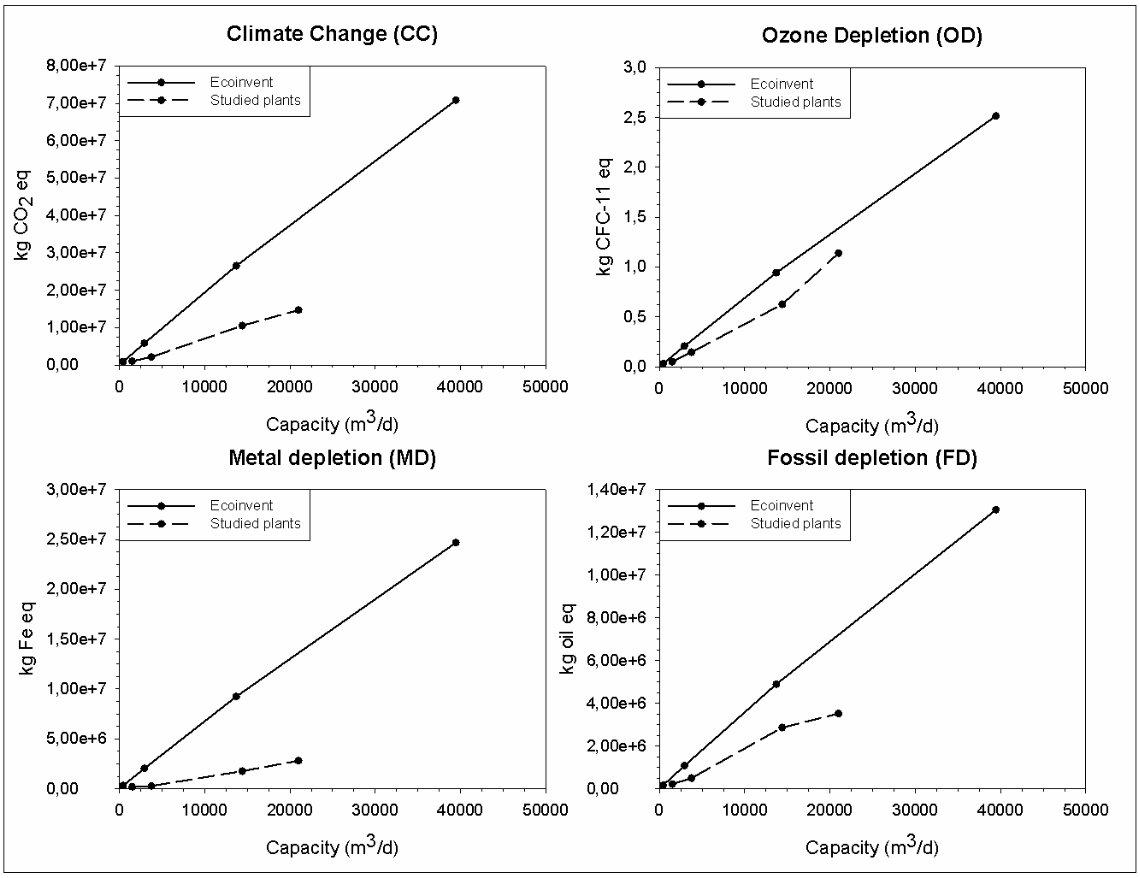


Fig. 4-19: Comparison of the potential environmental impacts of the complete plants.

In order to have better comparable results, the dismantling phase of the inventories of WWTPs from Ecoinvent was removed, because in this study this phase is not considered.

As shown in Fig. 4-19, the environmental impacts generated by using the Ecoinvent inventories are higher than the results using the inventories from this study for all impact categories. In this study, the construction of WWTP have an impact between $1.02 \cdot 10^6$ and $1.47 \cdot 10^7$ kg of CO_2 eq for Climate Change (CC) category; $4.99 \cdot 10^{-2}$ to 1.14 kg of CFC-11 eq for Ozone Depletion (OD) category; $1.89 \cdot 10^5$ to $2.81 \cdot 10^6$ kg of Fe eq in Metal Depletion (MD) category; and $2.20 \cdot 10^5$ to $3.52 \cdot 10^6$ kg of oil eq in Fossil Depletion (FD) category. On the other hand, the impacts calculated for the Ecoinvent plants are always larger ranging from $8.92 \cdot 10^5$ to $7.08 \cdot 10^7$ kg of CO_2eq for CC category; from $3.17 \cdot 10^{-2}$ to 2.52 kg of CFC-11 eq for OD category; from $3.11 \cdot 10^5$ to

$2.47\cdot10^7$ kg of Fe eq in MD category; and finally, $1.64\cdot10^5$ to $1.31\cdot10^7$ kg oil eq in FD category.

In CC, MD and FD categories the difference between the impact generated by the plants in this study and the plants from Ecoinvent increases as the capacity of the plant increases. In OD category the difference between the impact of the studied plants and the plants from Ecoinvent decreases as the capacity of the plant increases, mainly because the biggest studied plant uses one plastic with a high potential of impact in this category.

The higher environmental impacts for Ecoinvent plants are explained by the higher consumption of materials, specially for the enormous consumption of concrete and reinforcing steel compared with the studied plants, but also for the higher consumption of metals and plastics. Finally, even though the mass of materials classified as other materials is higher in this study than in Ecoinvent they have less environmental impact potential than concrete and reinforcing steel.

Detailed analysis of the studied plants

Contribution of the different unit processes to the global impact of the plants

Fig. 4-20 shows the contribution of each one of the units to the global impact of the studied plants for different impact categories (CC, FD, MD and OD). In all the plants, the unit with the highest contribution to the impact is always by far the secondary treatment, followed, to a significant distance, by the urbanization. In comparison with the impacts generated by large WWTPs (previous chapter), secondary treatment is also the highest contributor but, urbanization does not appear to be one of the most important units. Sludge line, the second most relevant unit in large WWTPs, is much more simple in small to medium WWTPs and its relative importance is reduced. Sludge line has a contribution lower than 10% since it only considers the thickeners and the building where the dewatering devices are placed, while anaerobic digesters, which increase a lot the mass of concrete and reinforcing steel, are typically not used in small to medium WWTPs. In Balaguer and L’Escala, sludge line has a bit higher contribution for OD impact category due the use of extruded polystyrene in the dewatering building.The contribution of the other units is much smaller for all plants, even though, as a general rule the contribution of buildings decreases as the plant capacity increases (it was not possible to consider the buildingsin the Manlleu WWTP). The contribution of connections to the impact depends a lot on the material used for the tubes; for this reason each contribution is very case specific.

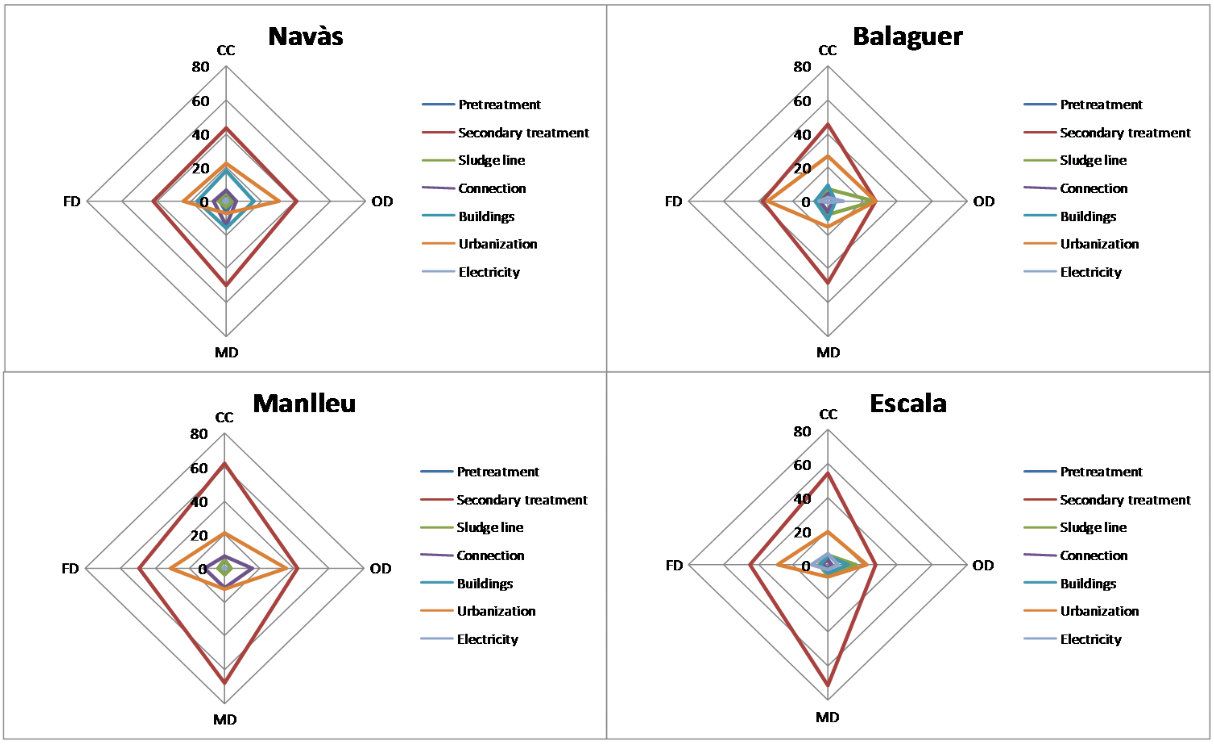


Fig. 4-20: Percentage of contribution of each unit in the environmental impacts of the different studied plants.

<u>Cumulative contribution of the different materials and unit processes to the global impact of the plants.</u>

Fig. 4-21 shows a cumulative graph for materials and unit processes for one of the four WWTPs studied (Navàs). The graph permits to analyze the contribution of each unit process, as well as, the contribution of each material and (deposition and transport) processes used during the construction of each unit to the global impact.

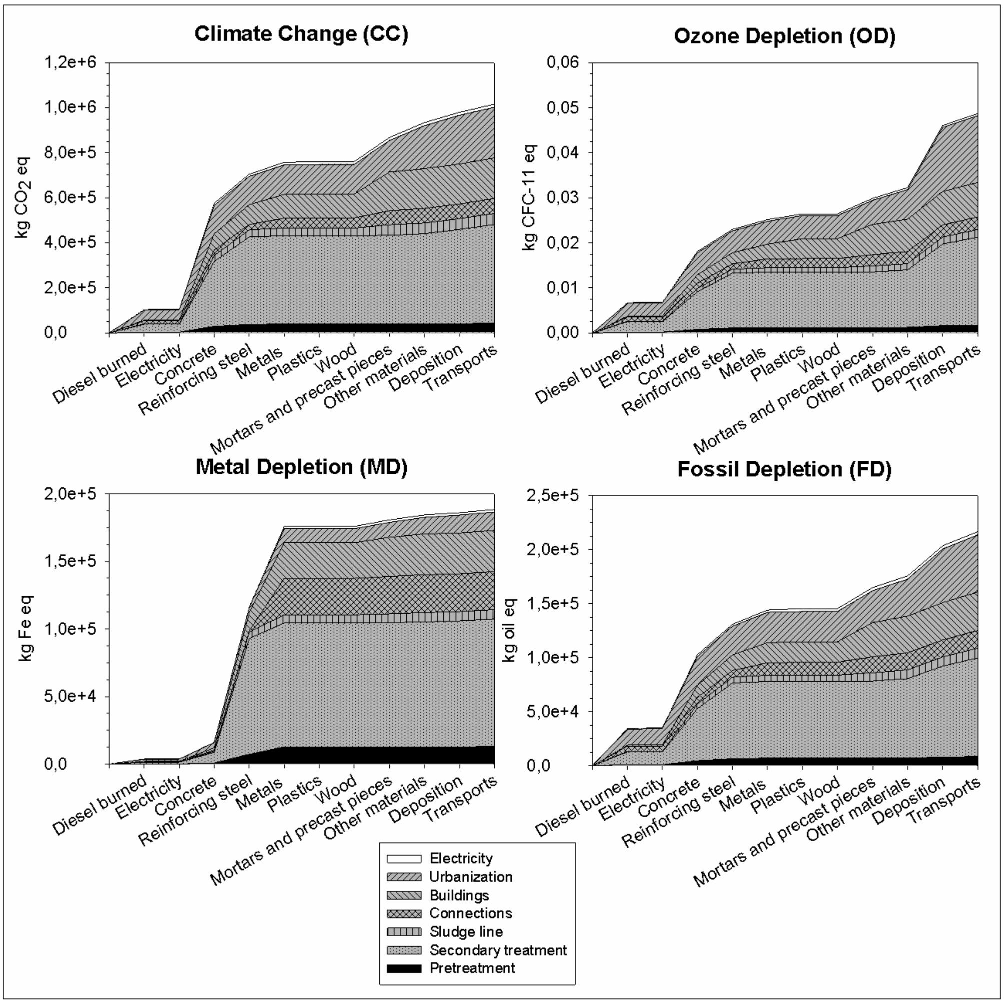


Fig. 4-21: Analysis of the contribution of each material and unit for Navàs WWTP.

In all the plants the secondary treatment is the unit with higher contribution to the global impact for all categories. Concrete has the highest influence to the impact in CC category, especially due to the concrete consumed in the secondary treatment (bioreactor and secondary settler) and urbanization. Secondly, the contribution of reinforcing steel is also important in these two units. Finally, the contribution of mortars and precast pieces consumed in the buildings is also very relevant for CC category. In the OD category the concrete and reinforcing steel consumed during the construction of the secondary treatment as well as the deposition of the excess soil excavated from the secondary treatment have the highest influence. In this case the contribution of the deposition of the excess excavated soil during the urbanization is also important. In MD, the material with the highest contribution to the global impact is the reinforcing steel, especially consumed in the construction of the secondary treatment. The other metals group has also some importance in the secondary treatment but its contribution to the global impact is higher for the connections and buildings units. Finally, in the FD category, the concrete and reinforcing steel consumed during the construction of the secondary treatment have the highest contribution to the global impact, but also the production of the mortars consumed in the buildings and the management of the excess soil deposited from the urbanization have a high contribution to the impact.

Equations to conduct easy, fast and modular inventories

In this section of the results, as a compendium of good practices, the equations to conduct fast, easy and modular inventories for small and medium WWTPs construction are presented. Table 4-6summarizes all equations for the linear regressions (together with r^2) obtained between consumption of materials and unit processes, and the range of materials used when no good correlations were found ($r^2<0.7$).

For the units directly related with the wastewater treatment (i.e. pre-treatment, secondary treatment and sludge line) it was easier to find linear regressions with good correlation (blank cells in Table 4-6) compared to the unit processes not directly related with wastewater treatment (i.e. connections, buildings, urbanization and external electrical installation). Good correlations were found for the energy consumed by machines, soil excavation and transport to landfill, concrete and reinforcing steel with a r^2 higher than 0.85 and formworks for the concrete structures (steel, plastics and wood) with a r^2 higher than 0.72. There was also a good correlation for mortars and precast pieces for the pre-treatment and sludge line (with a r^2 higher than 0.87). In the biological treatment, a good correlation (r^2 of 0.728) was found for other plastics group probably due to particularities or common practices of each construction company. For the rest of materials and electricity no good correlations were found (grey cells in Table 4-6). Although there is high number of grey cells, a good correlation was found for the most important materials consumed of the main units (pre-treatment, secondary treatment and sludge line). Finally, transport had also a good correlation because it only depends on the materials considered.

Table 4-6: Equations describing the material and energy consumption, as well as, the excess soil deposited per unit of treatment with the r^2. When good correlations were not found (r^2 lower than 0.7, cells in grey), a range of materials consumed is provided. Eq.: Equation. Parameter "x" in the obtained equations is the plant capacity of the studied plant in $m^3 \cdot d^{-1}$.

Material	Unit	Pretreatment	Secondary treatment	Sludge line	Tube connections	Buildings	Urbanization	Power connection
Diesel burned in machines (MJ)	Eq.	$1.74\cdot10^{1}x-5.33\cdot10^{-3}$	$1.59\cdot10^{2}x+1.39\cdot10^{5}$	$8.76x+1.57\cdot10^{3}$	$2.22\cdot10^{1}x+1.20\cdot10^{5}$	2.97 to $1.97\cdot10^{1}$ MJ/m^{3}	$1.67\cdot10^{2}$ to $2.92\cdot10^{2}$ MJ/m^{3}	0 to $4.92\cdot10^{1}$ MJ/m^{3}
	R^2	1	0.999	0.991	0.953			
Soil excavation (Ton)	Eq.	$1.16\cdot10^{-1}x-1.55\cdot10^{-5}$	$1.06x+9.30\cdot10^{2}$	$5.76\cdot10^{-2}x-1.36\cdot10^{-1}$	0 to 1.51 ton/m^{3}	$1.08\cdot10^{-2}$ to $7.15\cdot10^{-2}$ ton/m^{3}	$2.19x+3.20\cdot10^{2}$	0 to $1.22\cdot10^{-2}$ ton/m^{3}
	R^2	1	0.999	0.967			0.990	
Soil transport to landfill (tkm)	Eq.	$4.65x+5.99\cdot10^{-4}$	$4.24\cdot10^{1}x+3.72\cdot10^{4}$	$2.31x-5.43$	0 to $6.04\cdot10^{1}$ tkm/m^{3}	$5.39\cdot10^{-2}$ to $7.22\cdot10^{-1}$ tkm/m^{3}	7.60 to $4.07\cdot10^{1}$ tkm/m^{3}	0 to $2.46\cdot10^{-2}$ ton/m^{3}
	R^2	1	0.999	0.967				
Concrete (kg)	Eq.	$6.52\cdot10^{1}x+4.39\cdot10^{4}$	$1.11\cdot10^{3}x-2.98\cdot10^{5}$	$9.27\cdot10^{1}x-6.56\cdot10^{3}$	$3.61\cdot10^{-5}$ to $3.64\cdot10^{1}$ kg/m^{3}	$3.75\cdot10^{1}x+3.16\cdot10^{5}$	5.53 to $2.93\cdot10^{2}$ kg/m^{3}	0 to $2.90\cdot10^{1}$ kg/m^{3}
	R^2	0.901	0.997	0.960		0.995		
Reinforcing steel (kg)	Eq.	$2.54x-5.74\cdot10^{2}$	$4.27\cdot10^{1}x-2.41\cdot10^{4}$	$2.93x-2.29\cdot10^{3}$	0 to 1.40 kg/m^{3}	$1.73x+3.42\cdot10^{3}$	0 to 1.16 kg/m^{3}	0 to $6.60\cdot10^{-2}$ kg/m^{3}
	R^2	0.886	0.971	0.873		0.999		
Metals for formworks (kg)	Eq.	$9.14\cdot10^{3}x+4.25\cdot10^{1}$	$1.65\cdot10^{-1}x+1.05\cdot10^{2}$	$1.01\cdot10^{2}x-7.01$	0 to $2.48\cdot10^{-3}$ kg/m^{3}	$1.38\cdot10^{-2}$ to $3.76\cdot10^{-2}$ kg/m^{3}	0 to $6.14\cdot10^{-3}$ kg/m^{3}	0 to $9.55\cdot10^{-5}$ kg/m^{3}
	R^2	0.766	0.944	0.733				
Other metals (kg)	Eq.	$4.26\cdot10^{-2}$ to $3.12\cdot10^{-1}$ kg/m^{3}	$3.13\cdot10^{-2}$ to $2.31\cdot10^{-1}$ kg/m^{3}	$5.20\cdot10^{-2}$ to 3.02 kg/m^{3}	$1.62\cdot10^{-1}$ to 3.60 kg/m^{3}	$2.43\cdot10^{-1}$ to 2.65 kg/m^{3}	$1.51\cdot10^{-2}$ to $8.66\cdot10^{-1}$ kg/m^{3}	0 to $1.96\cdot10^{-1}$ kg/m^{3}
	R^2							
Plastics for formworks (kg)	Eq.	$3.94\cdot10^{-4}x+1.83$	$7.11\cdot10^{-3}x+4.54$	$4.29\cdot10^{-4}x-3.11\cdot10^{-1}$	0 to $1.07\cdot10^{-4}$ kg/m^{3}	$8.09\cdot10^{-4}$ to $5.65\cdot10^{-3}$ kg/m^{3}	0 to $2.62\cdot10^{-4}$ kg/m^{3}	0 to $4.11\cdot10^{-6}$ kg/m^{3}
	R^2	0.766	0.943	0.723				
Other plastics (kg)	Eq.	$4.00\cdot10^{-3}$ to $9.30\cdot10^{-2}$ kg/m^{3}	$7.95\cdot10^{-1}x-1.19\cdot10^{3}$	$1.47\cdot10^{-2}$ to $1.18\cdot10^{-1}$ kg/m^{3}	$5.30\cdot10^{-2}$ to 2.11 kg/m^{3}	$6.23\cdot10^{-2}x+7.01\cdot10^{1}$	0 to $7.34\cdot10^{-2}$ kg/m^{3}	0 to $2.41\cdot10^{-1}$ kg/m^{3}
	R^2		0.729			0.988		

Wood for formworks (kg)	Eq.	$7.30\cdot10^{-3}x+3.40\cdot10^{1}$	$1.56\cdot10^{-1}x-1.41\cdot10^{2}$	$3.87\cdot10^{-2}x+5.26\cdot10^{1}$	0 to $2.49\cdot10^{-3}$ kg/m^3	$1.11\cdot10^{-2}$ to $3.00\cdot10^{-2}$kg/m^3	0 to $5.03\cdot10^{-3}$kg/m^3	0 to $7.63\cdot10^{-5}$ kg/m^3
	R^2	0.766	0.999	0.975				
Other Wood (kg)	Eq.	No	0 to 1.84 kg/m^3	0 to $3.55\cdot10^{-2}$ kg/m^3	0 to $3.29\cdot10^{-2}$ kg/m^3	$1.48\cdot10^{-1}x+2.97\cdot10^{2}$	0 to $1.16\cdot10^{-1}$ kg/m^3	No
	R^2					0.982		
Mortars (kg)	Eq.	$5.58x-8.2\cdot10^{3}$	$4.27\cdot10^{-1}$ to 2.61 kg/m^3	$5.05x+2.62\cdot10^{3}$	0 to 4.81 kg/m^3	9.04 to $4.21\cdot10^{1}$ kg/m^3	$5.38\cdot10^{-1}$ to 4.20 kg/m^3	0 to $1.30\cdot10^{-1}$ kg/m^3
	R^2	0.911		0.876				
Precast pieces (kg)	Eq.	$1.01\cdot10^{1}x-1.51\cdot10^{4}$	$5.32\cdot10^{-1}$ to $1.80\cdot10^{1}$ kg/m^3	$8.71x+1.31\cdot10^{4}$	0 to $2.94\cdot10^{1}$ kg/m^3	$1.36\cdot10^{1}x+8.29\cdot10^{4}$	1.88 to $2.29\cdot10^{1}$ kg/m^3	0 to 2.27 kg/m^3
	R^2	0.955		0.902		0.999		
Other materials (kg)	Eq.	$2.44\cdot10^{-2}$ to $2.69\cdot10^{1}$ kg/m^3	$5.31\cdot10^{1}$ to $3.31\cdot10^{2}$ kg/m^3	$4.63\cdot10^{1}$ to $9.17\cdot10^{1}$ kg/m^3	$4.58\cdot10^{1}$ to $2.87\cdot10^{2}$ kg/m^3	5.47 to $7.21\cdot10^{1}$ kg/m^3	$2.96\cdot10^{3}x-4.01\cdot10^{6}$	0 to $2.34\cdot10^{3}$ kg/m^3
	R^2						0.958	
Diesel for electricity (MJ)	Eq.	$2.32\cdot10^{-2}$ to 2.58 MJ/m^3	$5.02\cdot10^{-3}$ to $1.23\cdot10^{-1}$ MJ/m^3	$2.35\cdot10^{-2}$ to 2.80 MJ/m^3	0 to $6.26\cdot10^{-1}$ MJ/m^3	$3.53\cdot10^{-1}$ to $8.85\cdot10^{1}$ MJ/m^3	0 to 2.49 MJ/m^3	0 to $1.00\cdot10^{-1}$ MJ/m^3
	R^2							
Material transport (tkm)	Eq.	$2.93x+1.41\cdot10^{3}$	$4.62\cdot10^{1}x-1.29\cdot10^{4}$	$4.38x+2.77\cdot10^{2}$	1.84 to $131\cdot10^{1}$ tkm/m^3	$2.12x+1.61\cdot10^{4}$	$1.20\cdot10^{2}x-1.44\cdot10^{5}$	$1.33\cdot10^{-4}$ to $9.36\cdot10^{1}$ tkm/m^3
	R^2	0.909	0.996	0.953		0.998	0.956	

Regarding the units not directly related with wastewater treatment (i.e. connections, buildings, urbanization and external electrical installation), it was very difficult to find good correlations because they depend a lot on how the different treatment units are distributed inside the plant, on specific location characteristics and on constructive solutions adopted (e.g. type of the tubes or trenches). For the connections unit, it was only possible to find a good correlation with the energy consumed by the machines. The size of the buildings might be more correlated with the plant capacity than connections are. In this case good correlations were found for concrete, reinforcing steel, plastics, wood and precast pieces. For urbanization, which is highly dependent of the distribution of the plant units and particularities of each plant, there is only good correlation with the soil excavated and the group of other materials. Finally, it was not possible to find any good correlationfor the electricity unit.

When linear regressions were not obtained, a range relating the consumption of materials and the plant capacity (maximum volume of water to treat for the WWTP per day) was provided. These ranges (considering the highest and the lowest value obtained) were calculated for each group of materials considering all the plants.

Usefulness of the equations: Comparison of impacts between complete (real) calculated inventories

Fig. 4-22 shows a comparison between the impacts calculated by using the equations (Table 4-6) for material consumption and the impacts estimated with the complete (real) inventory. The overall inventory of materials has been calculated by first estimating the materials consumed/used in each WWTPs unit of by using the corresponding equation and/or range and, then, summing up the contribution from all units. When the equation was found per groups of materials (other metals, other plastics, other woods and other materials), a representative material was chosen. In that sense, Table 4-7 summarizes the material or group of materials and the corresponding material from Ecoinvent used to calculate the impacts.

Table 4-7: Material and process from Ecoinvent databases used.

Material/Process from the inventory	Material/Process selected from Ecoinvent 3 and Ecoinvent 2 databases
Diesel burned in machines	Diesel, burned in building machine {GLO}| market for | Alloc Def, U
Soil deposition	Disposal, inert waste, 5% water, to inert material landfill/CH U
Transport	Transport, freight, lorry >32 metric ton, EURO4 {GLO}| market for | Alloc Def, U
Concrete	Concrete, normal {GLO}| market for | Alloc Def, U
Reinforcing steel	Reinforcing steel {GLO}| market for | Alloc Def, U
Metals for shoring	Steel, low-alloyed {GLO}| market for | Alloc Def, U
Other metals	Steel, chromium steel 18/8 {GLO}| market for | Alloc Def, U
Plastics for shoring	Polyvinylchloride[1]
Other plastics	Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U
Woods for shoring and other uses	Sawn timber, softwood, raw, plant-debarked, u=70%, at plant/RER U
Mortars	Lime mortar {GLO}| market for | Alloc Def, U
Precast pieces	Brick {GLO}| market for | Alloc Def, U
Other materials	Sand {GLO}| market for | Alloc Def, U
Diesel burned in generation devices	Diesel, burned in diesel-electric generating set {GLO}| market for | Alloc Def, U

[1] Polyvinylchloride process used is carried out considering a composition of 90% polyvinylchloride bulk polymerized and 10% emulsion polymerized.

Fig. 4-22 shows in general good correlation between the impacts obtained from the calculated inventories and the impacts obtained from the real inventories except for OD in L'Escala. The results are especially similar for Navàs. In the case of Balaguer and Manlleu, the environmental impacts using the calculated inventory are higher than using the real inventory (negative values in the difference bar of Fig.4-21), except for OD in Balaguer. Finally, for L'Escala, we found the opposite trend; i.e., the impacts for calculated inventories from equations are lower than the impact from complete inventories (positive values in the difference bar of Fig.4-22), except for MD.

For CC and FD categories, the differences between the impacts using the real inventories and the calculated are not very important. For Navàs there is a very small difference; for Balaguer and Manlleu the impact from the calculated inventories are a bit higher; and for L'Escala WWTP the impact calculated from the real inventory is a bit higher than the one calculatedfrom the regressions and ranges. The impacts for OD category are higher for Balaguer and L'Escala when using the real inventory because in this case the real inventory includes the extruded polystyrene, a material with a very high potential impact in this category, while the calculated inventory does not consider this material. For MD category, higher impact results were obtained for the calculated inventory for the cases of Balaguer, Manlleu and L'Escala because, in the calculated inventories, the mass of metals used is higher, and also because the metal used for the calculated mass of metals has a higher environmental potential than the metals of the real inventories.

As can be seenin Fig. 4-22, the difference between the environmental impacts calculated with the real inventories and the inventories obtained using the regressions and ranges are not big. The biggest differences are in the case of OD for L'Escala, but, as mentioned in L'Escala inventory, this difference is due to the factthat extruded polystyrene used. Also the differences are big in MD category, mainly because there are significant differences in the amount of reinforcing steel usedamong the different plants.

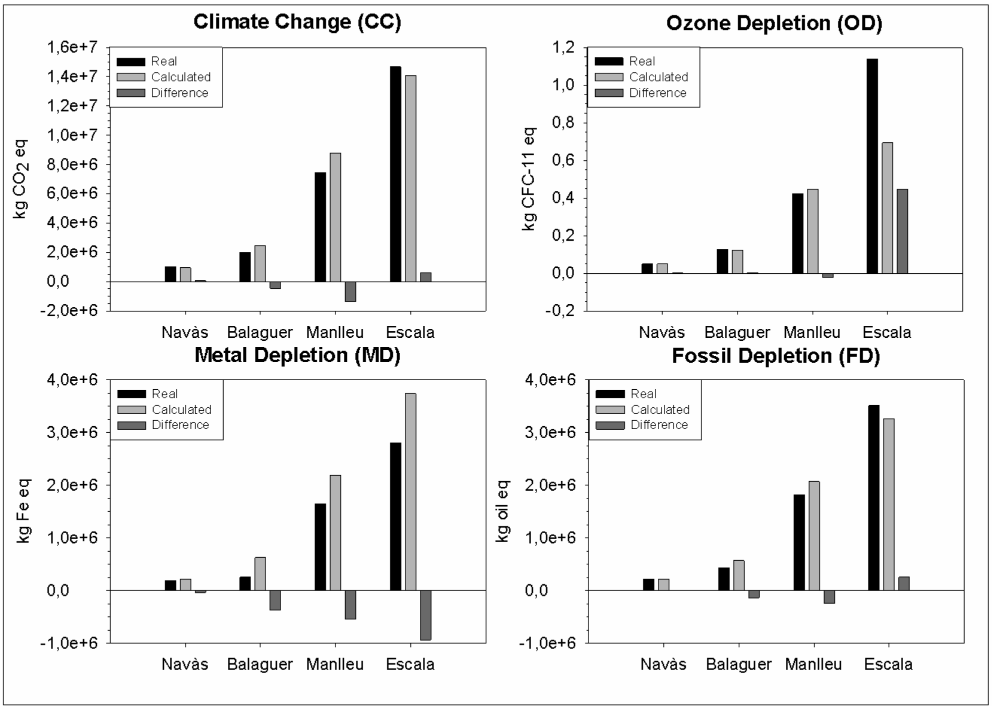


Fig. 4-22: Comparison between the real impact of the plants construction and impact calculated by means of the equations and ranges provided.

4.4.-CONNECTION OF NEIGHBORING WWTPs: ECONOMIC AND ENVIRONMENTAL ASSESSMENT

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 at 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.*, 2013). This is especially relevant in semi-arid regions (such as the Mediterranean) with low river flows and significant contribution of WWTP discharges.The objective of this chapter is to propose a methodology to evaluate the integrated management of neighboring WWTPs including economical and environmental (local and global) criteria.

In brief, the chapter shows the successful application of the consideration of economic and environmental aspects at the same time. The results also show that in this specific case, in 2 years and 11 months the investment to construct a connection between the studied WWTPs is compensated when the minimum ecological flow of the river is maintained. The results also show that the connection would be beneficial economically until a length of 3,2 km or until a length of 50 km considering the savings of CO_2 emissions.

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4.4.1.-MOTIVATION AND OBJECTIVE

Some studies can be found in the literature evaluating the integrated management of multiple facilities from an 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; 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 chapter 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.

4.4.2.-MATERIALS AND METHODS

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 14044 (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. 4-23shows the proposed methodology, which includes environmental local constraints together with global environmental assessment and cost assessment in urban wastewater systems decision-making.

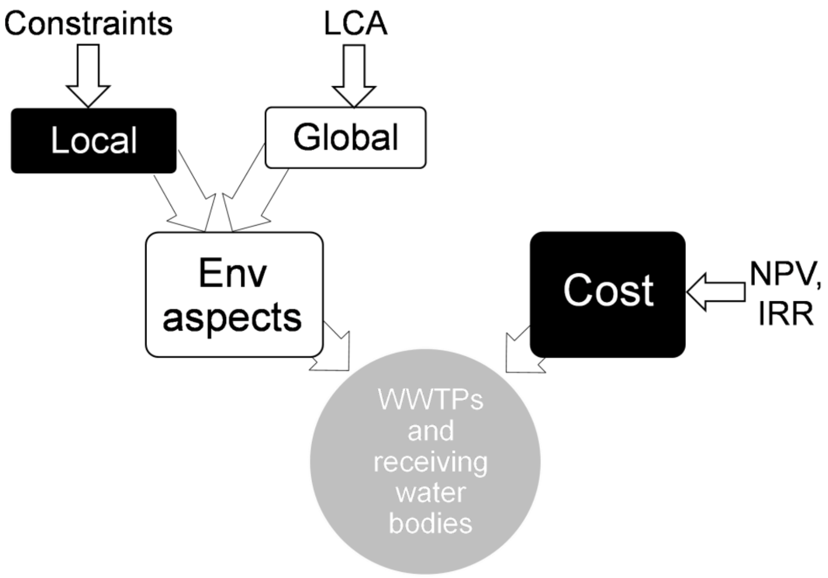

Fig. 4-23: Methodological approach proposed in this paper (the novelty is the inclusion of environmental local constraints and environmental assessment of urban wastewater systems, together with a cost assessment).

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. 4-24).

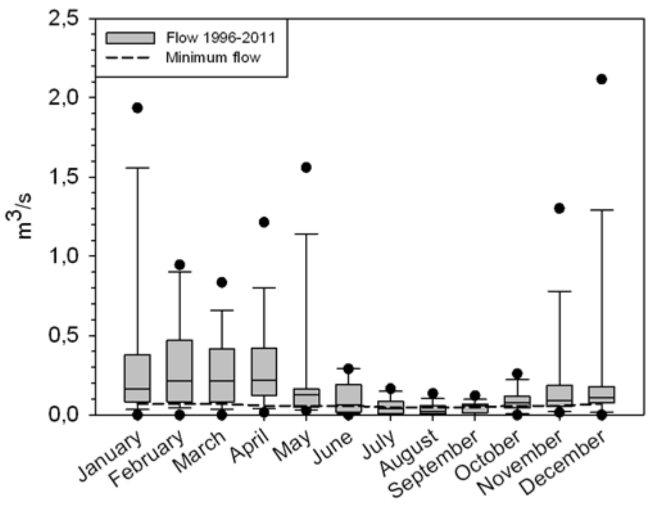

Fig. 4-24: Relationship between river flow and minimum river flow.Dashed line shows the minimum ecological flow required for the river during the year. Grey boxes are made using flow river data from 1996 until 2011. The line inside the boxes represents the median. The variability of the data is shown by the error bars while dots represent data out of the range of the analysis.

Fig. 4-24shows 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$_{\text{ecolflow}}$), which means bypassing 100% of the wastewater flow rate for the entire year, except for the period with low river flow, when the bypass 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.

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. 4-25) 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.

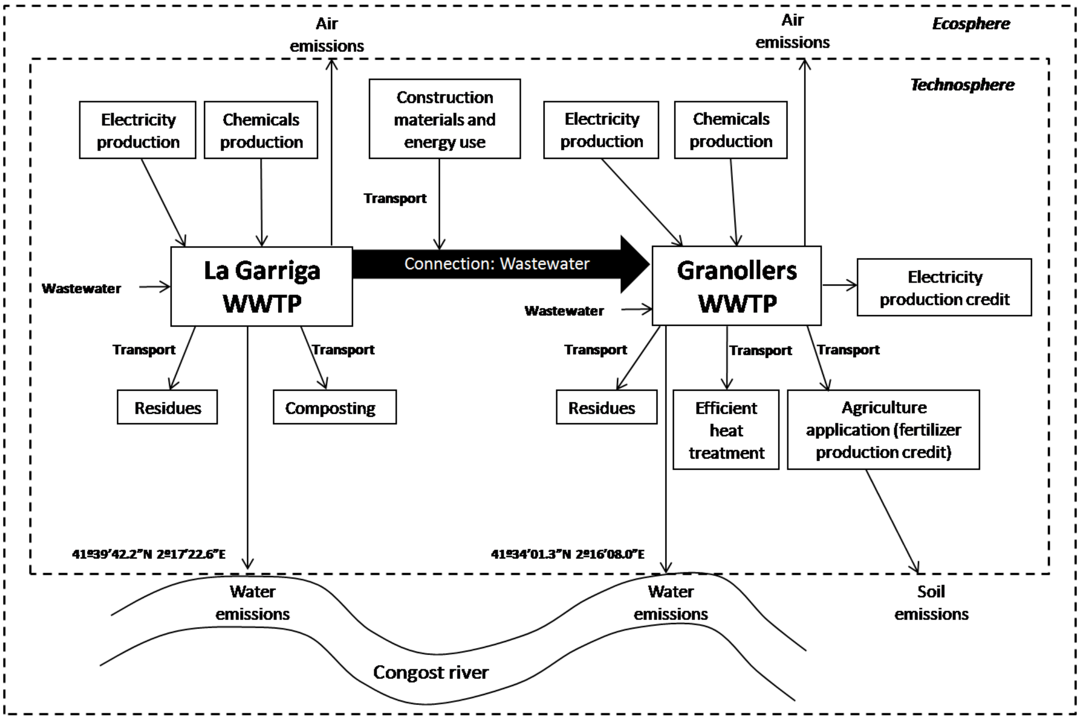

Fig. 4-25: System boundaries of the studies system.

Inventory. The inventory data (see Table 4-8) 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 4-9.

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 LCAs 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 (AD), Acidification (AC), Eutrophication (EU), Global Warming (GW), Ozone Layer Depletion (OLD), Human Toxicity (HT), Freshwater Aquatic Ecotoxicity (FAET), Marine Aquatic Ecotoxicity (MAET), Terrestrial Ecotoxicity (TT), and Photochemical Oxidation (PHO) (Table 4-10).

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.

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 10year 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 inTable 4-8and Table 4-9.

Table 4-8: 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 combustion)	$5.89\cdot10^{-5}$	--	--	
Outputs to further treatment	**kg·m^{-3}**	**€·ton^{-1}**	**kg·m^{-3}**	**€·ton^{-1}**
Municipal solid wastes	$5.29\cdot10^{-2}$	60	$2.81\cdot10^{-2}$	60
Efficient heat treatment of sludge	$7.67\cdot10^{-1}$	10-120	--	--
Agriculture disposal of sludge	$2.18\cdot10^{-1}$	28-30	--	--
Fat wastes	$1.20\cdot10^{-2}$	60	$4.83\cdot10^{-4}$	60
Composting	--	--	$9.17\cdot10^{-1}$	45
Transports	**tkm·m^{-3}**		**tkm·m^{-3}**	

Landfill	$3.18\cdot10^{-3}$	--	$1.69\cdot10^{-3}$	--
Heat treatment	$3.84\cdot10^{-3}$	--	--	--
Agriculture	$2.18\cdot10^{-2}$	--	--	--
Composting	--	--	$3.66\cdot10^{-2}$	--
Fat treatment	$1.20\cdot10^{-4}$	--	$4.83\cdot10^{-6}$	--
Avoided products	**kwh·m^{-3}**	**€·kwh^{-1}**		
Electricity	$2.04\cdot10^{-1}$	0.14	--	--

Table 4-9 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 4-9: Pipeline construction inventory for the 1,139 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 tth 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.

4.4.3.-RESULTS AND DISCUSSIONS

Global Environmental Assessment

The results of the EIA are presented in Fig. 4-26 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 AD, up to 22%; GW, up to 5%; OLD, up to 22%; MAET, 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 AD, OLD and PHO (see Table S-6 on impact categories and processes in annexes section). 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 AC, EU, FAET, HT and TT categories. ACbecomes up to 2.7% and EUup 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 FAET, an increase up to 11.3% in TT and an increase up to 3 % in HT 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.

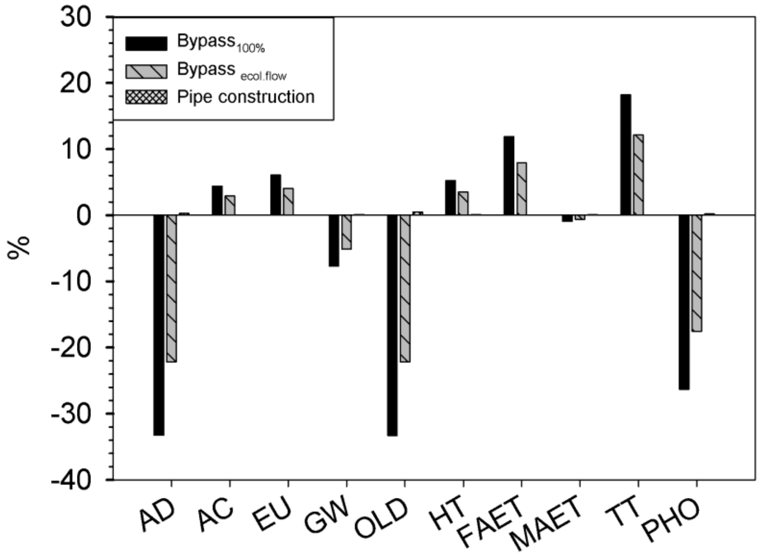

Fig. 4-26: Environmental assessment results for 20 years. Induced impacts compared to reference scenario correspond to positive percentages and avoided impacts are negative percentages. The reference scenario corresponds to 0%.

Table 4-10: Impact categories analyzed, with its name, abbreviation used and meaning.

Name	Abbreviation	Meaning
Abiotic Depletion	AD	Consumption of natural resources, including energetic resources, considered as non-living.
Acidification	AC	Impact of acidifying pollutants in the natural environment, man-made environment, human health and natural resources.
Eutrophication	EU	Potential impacts of excessively high environmental levels of macronutrients.
Global Warming	GW	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	FAET	Impact of toxic substances on freshwater aquatic ecosystems.
Marine Aquatic Ecotoxicity	MAET	Impact of toxic substances on marine aquatic ecosystems.
Terrestiral Ecotoxicity	TT	Impact of toxic substances on terrestrial ecosystems.
Photochemical Oxidation	PHO	Formation of reactive chemical compounds by the action of sunlight in certain primary pollutants.

Economic assessment

Fig. 4-27shows 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 4-8) 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 €.

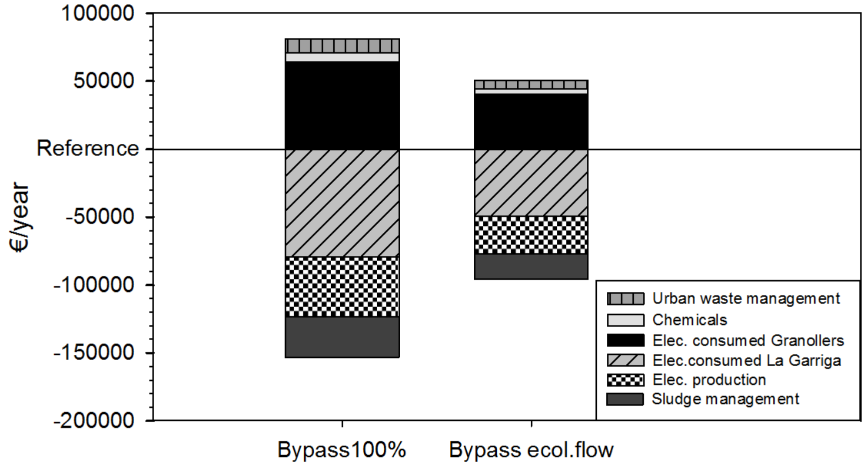

Fig. 4-27: Induced and avoided costs for the different evaluated scenarios compared to the reference scenario. Current situation (0% bypass between La Garriga and Granollers) is the reference scenario and all the changes are compared with the current situation.

Table 4-11 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 4-11: 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

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 (FAET and TT) (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, 2015) 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 (2015)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.

4.4.4.-SCENARIO ANALYSIS

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 GW 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. 4-28a 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. 4-28b 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.

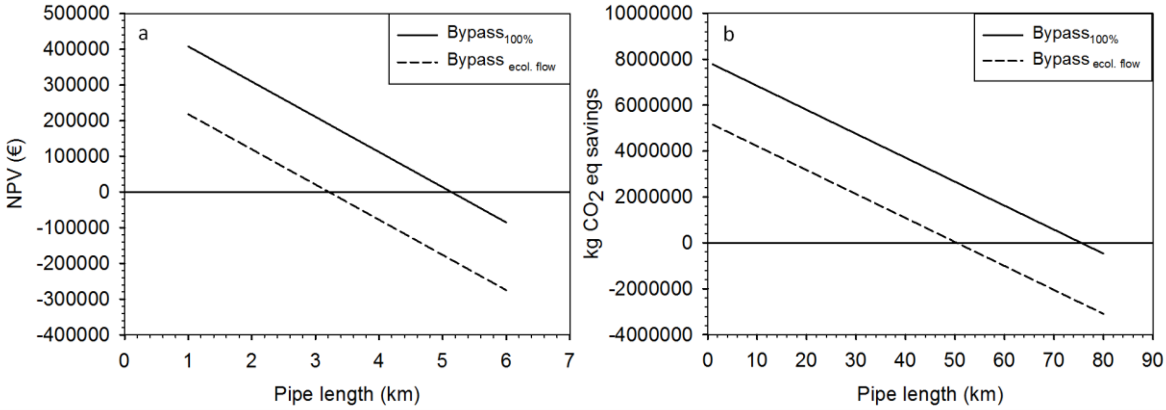

Fig. 4-28: Sensitivity analysis of the pipeline length on a) the VAN and b) the global warming potential.

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. 4-29a 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., AD, GW). The same scenario analysis applied to the *bypass$_{ecolflow}$* scenario (Fig. 4-29b) would lead to even more importance to the price of electricity in Granollers.

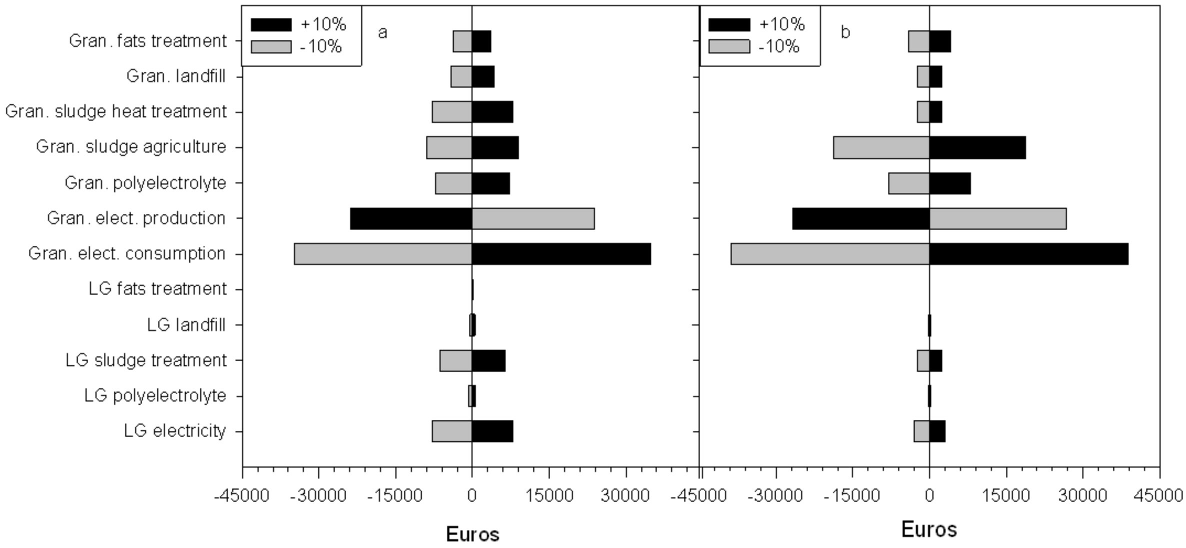

Fig. 4-29: Sensitivity analysis of the tariffs on the operating costs for reference scenario (a) and bypass$_{\text{ecolflow}}$ (b).

4.4.5.-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 greenhouse 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).

4.5.-WATER FOOTPRINT ASSESSMENT IN WASTEWATER TREATMENT PLANTS

Currently, the concern regarding the environmental sustainability of urban development, specifically the use of freshwater resources, has significantly increased due to population growth, which has increased water demand; this problem is exacerbated when combined with water scarcity (which implies limited water availability). Since its formulation the Water footprint (WF) have been applied in many different fields, but since now there are not a complete application of the WF in WWTPs. This chapter presents the adoption of the WF methodology to be applied in WWTPs and finally a real case application of the methodology.

In summary, the chapter shows a successful example of application of WF methodology in WWTPs. The results also show a reduction of 51.5% of WF of the wastewater after the treatment and 72.4% when the phosphorus removal is improved, that indicate that major efforts have to be applied in the removal of phosphorus.

Redrafted from:

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4.5.1.-MOTIVATION AND OBJECTIVE

The urban water cycle (UWC) includes water withdrawal from natural resources, water treatment to satisfy the required quality standards for different uses, water distribution, water consumption (drinking water, water for recreational activities, water for cleaning and irrigation of urban areas, water for agriculture and process water for industries), collection and transport of wastewater via sewer systems, and wastewater treatment. Wastewater is treated in WWTPs, which has the important role within the UWC to improve the water quality before being returned into the natural ecosystems. Traditional WWT is considered an industrial activity where wastewater is transformed by means of different processes, which consume chemicals and energy, into treated water (of higher quality), which generates by-products (primarily solid wastes and gaseous emissions). Hence, the impact of water emissions into the natural ecosystems is reduced; however, there are increased costs and other environmental impacts (Godin *et al.*, 2012)

The water footprint (WF) of a product/process was introduced for the first time in 2003 and is defined as the volume of freshwater consumed and polluted to produce a product(Hoekstra, 2003). The WF accounts not only for the direct water use of a consumer or producer but also for indirect water use, which depends on the WF of the activities related to the studied product/process that goes beyond the boundary of the process(Hoekstra *et al.*, 2011). The WF is divided into three components: blue, green and grey WFs. The blue WF is an indicator of the surface water or groundwater consumption, which includes the evaporated water, water incorporated into the product, and lost return flow, i.e., water that was taken from a catchment and returned to another catchment or the sea or the water that was withdrawn during a period of time and returned in another period of time. The green WF is defined as the consumption of water from precipitation that is stored in the soil and does not run off or recharge the groundwater and thus, is available for evapotranspiration of plants. Finally, the grey WF of a process step indicates the degree of freshwater pollution that can be associated with the process step. The grey WF is defined as the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards(Hoekstra *et al.*, 2011).

Since its formulation, the WF methodology has been applied in many different fields related to human uses of water. For example, applications in agricultural products and the food industry are extremely popular, where several studies have considered different products and countries. For example, (Chapagain and Hoekstra, 2007)assessed the WF of coffee and tea consumption in The Netherlands, which considered the production in the countries of origin. The WF has also been applied to other products consumed or used by people in the consumption of cotton for clothes production (Chapagain*et al.*, 2005; Chico*et al.*, 2013), rice (Chapagain and Hoekstra, 2011) and several industrial products derived from agriculture (Ercin*et al.*, 2012). Finally, the WF methodology has also been applied to account for the water footprint of different diets (Aldaya and Hoekstra, 2010 and Vanham*et al.*, 2013). The WFs of different regions, countries and even all of humanity have also been evaluated (Aldaya *et al.*, 2009 and Hoekstra and Mekonnen, 2011). WFs have also been used to assess the production of hydropower energy (Mekonnen and Hoekstra, 2012) and biofuels (Gerbens-Leenes*et al.*, 2012), amongst other applications.

To the best of our knowledge, the application of the WF assessment methodology to WWTPs is limited to the work of Liu*et al.*, (2012) and Shao and Chen (2013). The first study only estimated the grey water footprint of anthropogenic emissions to major rivers, not specifically from WWTPs, and the second study only accounted for the blue water footprint (the study also did not account for sludge treatment, which is extremely important in LCA).

The objective of this chapteris to adopt the general WF methodology that considers both the blue and grey WFs to assess the water resource consumption of WWTPs. The usefulness of the proposed methodology in assessing the environmental impact and benefits of a WWTP discharging to a river is illustrated with an actual case study.

4.5.2.-METHODOLOGY FOR WATER FOOTPRINT ASSESSMENT IN WWTPs

To evaluate the water footprint of products and consumers, the Water Footprint Network (WFN) developed a methodology for water footprint assessment (WFA) to evaluate the impacts on water consumption caused by an activity (Hoekstra *et al.*, 2011). The WFA methodology addresses freshwater resources appropriation using a four-step approach: (i) set the goals and scope; (ii) account for the water footprint of a process, product, producer or consumer as a spatiotemporally explicit indicator of freshwater appropriation; (iii) evaluate the sustainability of this water footprint and focus on a multi-faceted analysis of the environmental, economic and social aspects; and (iv) formulate strategies to improve the water footprint.

This section introduces the adoption of the WFN methodology for WWTP application and expands the WF accounting phase using a framework for the grey water footprint calculation. As shown in Fig. 4-30, the methodology consists of four phases, which is similar to those in an LCA analysis.

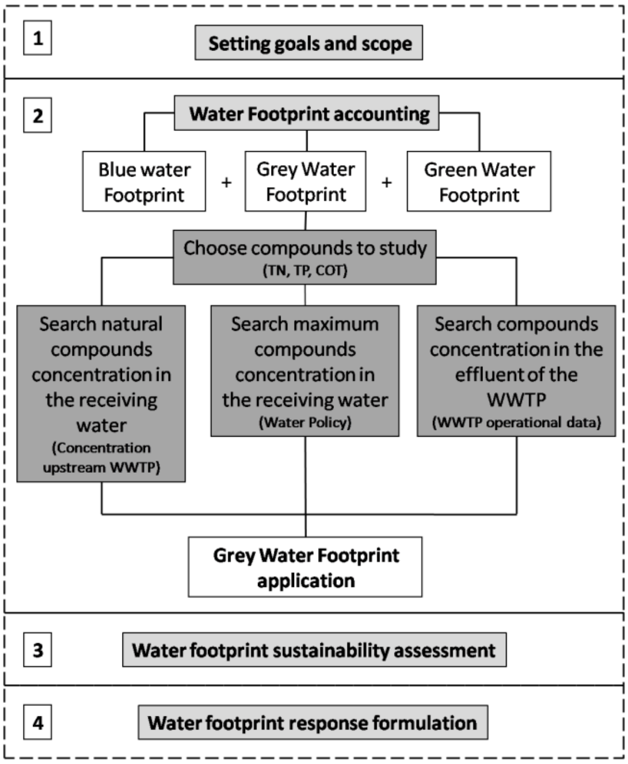

Fig. 4-30: General framework to assess the water footprint in WWTPs. The dark grey boxes explain the proposed development to calculate the grey water footprint of WWTPs.

The first phase consists of defining the goal and scope of the assessment and includes the functional unit, the types of WF to be considered and the data sample. In the second phase, data are collected, and the water footprint is calculated. In the third phase, the water footprint is evaluated from a sustainability point of view, which considers the water availability in the analyzed region or period, and finally in the fourth phase, several recommendations are drawn to reduce the water footprint of the product or system analyzed.

The general equation to calculate the water footprint of a WWTP, which is the volume of water consumed during a period of time and includes the blue (WF_{blue}), green (WF_{green}) and grey (WF_{grey}) water footprints, is defined as the following:

$$WF = WF_{blue} + WF_{green} + WF_{grey} \qquad (2)$$

Eq.2. General equation for the water footprint calculation of a WWTP.

Blue water footprint (WF_{blue}). In WWTPs, the blue water footprint accounts for the water that evaporates during wastewater treatment and the water used for all processes related to the different WWTP unit operations (chemicals, energy consumption, residue management, transportation and sludge treatment) that is incorporated into the final product. For example, the consumption of chemicals and energy has an associated blue water footprint due to the water incorporated during the production of chemicals and energy. However, the lost return flow, which is considered in the blue water footprint, of other processes or products will be zero when the treated WWTP water is discharged into the same catchment. In certain cases, it can be interesting to consider the route of blue water, particularly in processes or products from agriculture (distinction of the water based on if it comes from the surface, groundwater or another source). Water recycled back to the process or used for other applications (e.g., WWTPs that have tertiary treatment and produce reclaimed water) should also be accounted (as avoided water) because it reduces the blue water footprint.

Green water footprint (WF_{green}). In conventional WWTPs, the green WF is not considered because it does not promote the evaporation of water from the soil or from vegetables and does not promote the incorporation of soil water with treated water.

Grey water footprint (WF_{grey}). The proposed calculation for the grey water footprint in the WFA manual (Hoekstra *et al.*, 2011) has been adapted to the specific domain of WWTPs. The new equation is based on a mass balance at the WWTP discharge point (see Equations 3 and 4 and Fig. 4-31). This mass balance-based approach considers that the grey WF is the minimum volume of water required to dilute the pollutant concentration from the WWTP effluent concentration to the maximum pollutant concentration allowed in the river.

$$Q_e \cdot c_{e(p)} + WF_{grey} \cdot c_{nat(p)} = (Q_e + WF_{grey(p)}) \cdot c_{max(p)} \qquad (3)$$

Eq. 3. Mass balance of pollutants at the WWTP discharge point.

$WF_{grey} = max[WF_{grey(p)} = (Q_e \cdot (c_{e(p)} - c_{max(p)}))/(c_{max(p)} - c_{nat(p)})) \ (volume/time)]$ (for p=1 to p)(4)

Eq. 4. Grey WF equation based on the mass balance of pollutants.

where Q_e is the effluent flow rate (volume/time), $C_{e(p)}$ is the concentration of a pollutant *p* in the WWTP effluent (mass/volume), $C_{max(p)}$ is the maximum concentration of a pollutant *p*permitted in the receiving water body, and $C_{nat(p)}$ is the natural concentration of a pollutant *p* in the receiving water body.

Because many pollutants exist in WWTP discharge, a $WF_{grey(p)}$ is calculated separately for each of the compounds. Then, the resulting WF_{grey} is the WF that ensures an adequate dilution capacity for all compounds, and hence, the maximum of the $WF_{grey(p)}$ values is obtained. The compounds included in the assessment depend on the goal of the study.

The sustainability of the blue WF is assessed by comparing the blue WF with the water availability (water ready to be used) in the studied region. However, if the grey WF is less than the river flow rate to assimilate the pollution, then the calculated grey WF is sustainable. It is important to consider the yearly fluctuations in water availability.

4.5.3.-DESCRIPTION OF THE DATA USED TO CALCULATE THE WF

The treated water in La Garriga WWTP is discharged to the Congost river, where its average flow of 0.048 $m^3 \cdot s^{-1}$ represents approximately 16% of the flow; however, this flow can represent up to 25% or 30% in the summer. The inventory data for the WWTP was provided by the *Consorci per la Defensa de la Conca del riu Besòs* (CDCRB), whereas the data from the river were obtained from the Catalan Water Agency (ACA). The WWTP effluent flow and the selected pollutant concentrations (total nitrogen (TN), total phosphorus (TP), and total organic carbon (TOC)) were used to calculate the $WF_{grey(p)}$. The energy consumption, transportation of chemicals and sludge, sludge treatment and consumption of chemicals were used to calculate the WF_{blue} after applying the water consumption factors for these processes obtained from the Ecoinvent 3.0 database (Swiss Centre for Life Cycle Inventories). The evaporated water was calculated from solar radiation data in the area, which was 14.5 $MJ \cdot (m^2 \cdot day)^{-1}$(Generalitat de Catalunya, 2000); the surface area of the WWTP reactors is 1,413 m^2.

Information on the C_{max} concentrations in the Besòs river Basin was obtained from the River Basin Management Plans from Catalonia (ACA, 2007), which were developed for the implementation of the Water Framework Directive (E.U., 2000). Data from a water quality monitoring station located upstream of the WWTP were used to establish the C_{nat} concentrations.

Accounting for the different WF components was calculated using monthly averaged data for the WWTP effluent flow rates and pollutant concentrations during the period from January 2007 to November 2010. Table 4-12 summarizes the inventory data used for the WF assessment.

Table 4-12: Input data for the WF assessment.

	Input data	**TN**	**TP**	**TOC**
WF_{grey}	**C_e**($g\cdot m^{-3}$)	9.66	3.55	11.18
	C_{nat}($g\cdot m^{-3}$)	1.03	0.04	2.07
	C_{max}($g\cdot m^{-3}$)	2.65	0.17	5.05
	WWTP effluent flow (**(**$m^3\cdot month^{-1}$)	123,894		
WF_{blue}	**Energy consumption** ($kwh\cdot m^{-3}$)	0.484		
	Chemicals ($kg\cdot m^{-3}$)	0.026		
	Sludge to treatment ($kg\cdot m^{-3}$)	0.917		
	Other residues ($kg\cdot m^{-3}$)	0.029		
	Evaporation ($m^3\cdot month^{-1}$)	237.200		
	Transport ($tkm\cdot m^{-3}$)	0.040		

WF can also be referred to as the water consumption for 1 kg of pollutant removed (TOC, N and P) and the cost of treating 1 m^3 of wastewater in the WWTP of La Garriga (0.2 €$\cdot m^{-3}$).

4.5.4.-RESULTS AND DISCUSSION

Water footprint assessment for La Garriga WWTP and the Congost river

Goal and scope

The goals of this WF assessment are to identify the relative importance of the blue and grey WFs in WWTPs, to illustrate the positive roles of these installations in reducing the environmental impact and to propose measures for reducing the WF of a WWTP. To achieve these goals, three different scenarios regarding WWT were studied: no-treatment scenario (direct discharge of untreated wastewater into the river), conventional WWT (current operation, i.e., organic matter and nitrogen removal) and WWT with phosphorous removal (Fig. 4-31). The no-treatment option implies only calculating the WF_{grey} assuming that the influent WWTP concentration is C_e from equation 3. In this case, the influent concentrations (50.41 $mg \cdot l^{-1}$ of TN, 6.45 $mg \cdot l^{-1}$ of TP and 181.73 $mg \cdot l^{-1}$ of TOC) were applied. For the phosphorous removal scenario, the water consumed to produce 1 kg of $FeCl_3$ was obtained from the Ecoinvent 3 database and multiplied by the mass of $FeCl_3$ in kg that is consumed to reduce the amount of phosphorous to the legislation limit (2 $mg \cdot l^{-1}$).

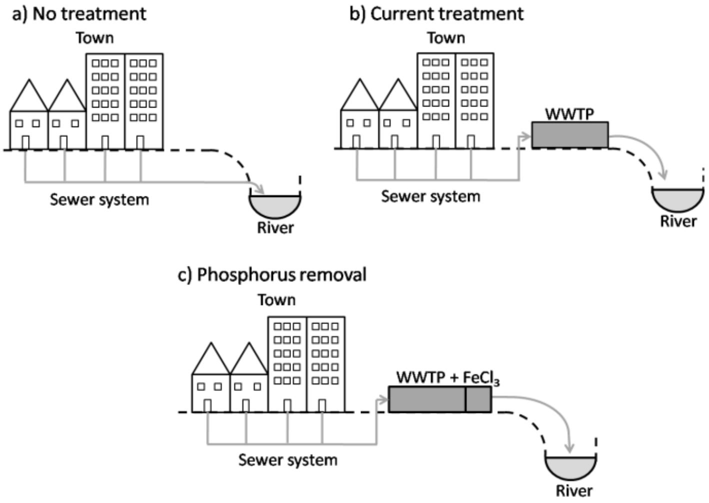

Fig. 4-31: Scenarios considered for the analysis.

As is shown in Fig. 4-32, the system boundaries for the studied system include the different steps of the WWTP (pre-treatment, secondary treatment, sludge thickening and sludge centrifugation), chemical and energy consumption, sludge treatment outside the plant, water evaporation from the plant and pollutants concentration in the effluent water. The functional unit of this case study is the volume of treated wastewater during one month of operation, i.e., 123,894 $m^3 \cdot month^{-1}$.

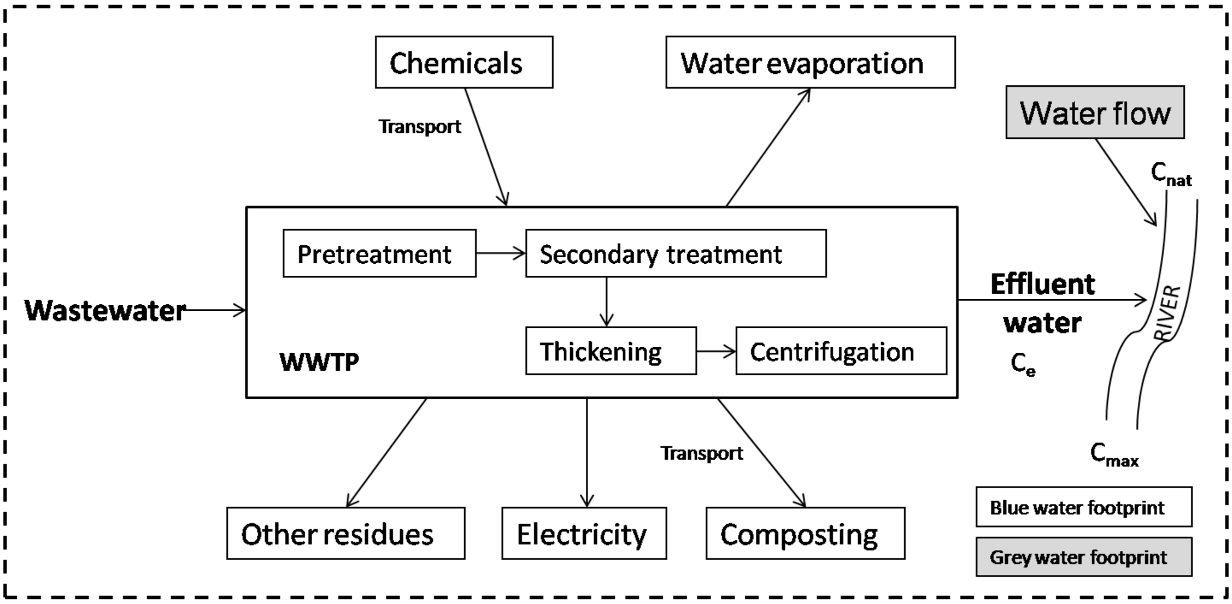

Fig. 4-32: System boundaries for the WWTP under study.

<u>Water footprint accounting</u>

Fig. 4-33a and Table 4-13 shows the total WF for the three scenarios. The highest WF corresponds to the no-treatment scenario (7,479,507 $m^3 \cdot month^{-1}$), the second highest WF corresponds to the current wastewater treatment (3,628,295 $m^3 \cdot month^{-1}$) with a WF_{grey} contribution of 95 % and a WF_{blue} contribution of 5 %, and the smallest WF corresponds to the wastewater treatment with phosphorous removal (2,062,718 $m^3 \cdot month^{-1}$). It can be observed that there is a high reduction of the water footprint when wastewater treatment is applied with (72.4 %) and without phosphorous removal (51.5 %). The grey WF values, i.e., the volume of water required to dilute the WWTP effluent until natural concentrations in the river are reached, were 539,317 $m^3 \cdot month^{-1}$; 3,448,115 $m^3 \cdot month^{-1}$ and 261,779 $m^3 \cdot month^{-1}$ for TN, TP and TOC, respectively, for the current wastewater treatment (Fig. 4-33c and Table 4-13).The WF_{grey} for TP is much greater compared with the other pollutants because the WWTP is not designed to remove TP, and hence, the WWTP effluent concentrations are high. With respect to the no-treatment scenario, the WF_{grey} is reduced by 51.5 % (from 7,479,507 $m^3 \cdot month^{-1}$ to 3,448,115 $m^3 \cdot month^{-1}$) at the expense of a slight increase in the WF_{blue} (180,180 $m^3 \cdot month^{-1}$). TP is the limiting factor for the WF_{grey} calculation for the treated wastewater, whereas TOC is the limiting factor for the no treatment option. For the wastewater treatment with the phosphorous removal scenario, a dosage of 1 mol of $FeCl_3$ per mol of phosphorous (according to the Minnesota Pollution Control Agency) achieves a 72.4

% reduction of the grey WF for total phosphorous while maintaining the same reductions for nitrogen and organic matter (Table 4-13 and Fig.4-34).

The blue WF for the current wastewater treatment scenario was 180,180 $m^3 \cdot month^{-1}$ (Fig. 4-33b and Table 4-13), where the major contributors are the energy consumption (95.85 %) and residues treatment. The residues treatment consist of the treatment of oils and grease and sludge compost and deposition in a landfill of solid residues (3.53 %), both of which account for more than 99 % of the WF_{blue}. Evaporation in the reactors accounted for only 0.13 % of the WF_{blue}. With respect to the wastewater treatment in the phosphorous removal scenario, similar values were obtained for the blue WF, even though there was an increase of 12,337 $m^3 \cdot month^{-1}$ due to the consumption of more chemicals ($FeCl_3$), which increased the phosphorus removal efficiency, and also due to the increase in sludge mass sent to composting. The addition of the $FeCl_3$ increased the WF_{blue} by 6.8 % compared with the current wastewater treatment scenario; however, overall, the results showed a reduction of 72.4 % in the total WF. In agreement with previous studies (Ercin*et al.*, 2010 and Jefferies *et al.*, 2012), the freshwater use associated with supporting activities and materials used in the business (e.g., chemicals, transports), which is not completely associated with the production of the specific product considered, i.e., the overhead water footprint, constitutes a minor fraction of the supply-chain water footprint (0.2–0.3 %).

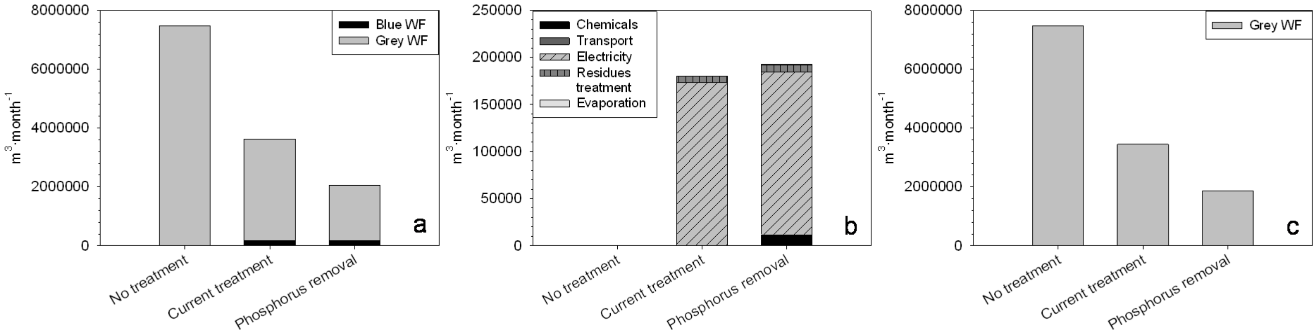

Fig. 4-33:WF results for the three scenarios; a) Total WF, where WF_{blue} and WF_{grey} are distinguished b) WF_{blue} and its contributors, and c) WF_{grey}.

Table 4-13: Comparison between the water footprint for the three scenarios studied.

No treatment			Current treatment			Phosphorus removal		
Grey WF ($m^3 \cdot month^{-1}$)		Blue WF ($m^3 \cdot month^{-1}$)	Grey WF ($m^3 \cdot month^{-1}$)		Blue WF ($m^3 \cdot month^{-1}$)	Grey WF ($m^3 \cdot month^{-1}$)		Blue WF ($m^3 \cdot month^{-1}$)
TN	3,672,231	0	TN	539,317	180,180	TN	539,317	192,517
TP	6,415,114		TP	3,448,115		TP	1,870,201	
TOC	7,479,507		TOC	261,779		TOC	261,779	
Total WF ($m^3 \cdot month^{-1}$)		7,479,507	Total WF ($m^3 \cdot month^{-1}$) (% reduction)		3,628,295 (51.5 %)	Total WF ($m^3 \cdot month^{-1}$) (% reduction)		2,062,718 (72.4%)

The WF obtained in this study for the current wastewater treatment (3,628,295 $m^3 \cdot month^{-1}$) is much larger than the WF obtained in the study by Shao and Chen (2013), which only included the WF_{blue}. Still, comparing the WF_{blue} values from both studies show that a much larger value was obtained in our study (180,180 $m^3 \cdot month^{-1}$, 1.45 m^3 freshwater as $WF_{blue} \cdot m^{-3}$ treated wastewater). The difference is due to the freshwater resource consumption related to electricity generation. In this case, the calculation used the water consumption from the Ecoinvent 3 processes for electricity, chemicals, residues and transport and data from the plant. Differently, in the study by Shao and Chen (2013), the calculation used a hybrid method that considered the operational expenses from the WWTP and the national freshwater consumption for every productive sector in China in 2007, which relates freshwater consumption with the economy. Considering their approach in our case study, the freshwater consumption would be $4.78 \cdot 10^{-3}$ $m^3 \cdot kwh^{-1}$, whereas when considering the Ecoinvent 3 processes for the medium voltage electricity in Spain, the freshwater consumption is approximately 2.88 $m^3 \cdot kwh^{-1}$. It should also be mentioned that the freshwater used to produce the electricity greatly depends on the country and the technologies used to produce it.

The different methods used in this study and Shao and Chen (2013), explains the difference in water consumption. A process-based inventory allows obtaining very specific and detailed inventories but has some limitations such as it is very time-consuming and requires large amount of data (Zhang*et al.*, 2014). On the other hand, Input-Output analysis, is based on economic input-output tables, with information of industrial flows of transactions of goods and services, but the information is not as accurate and specific as in process-based inventories. Finally, an extended method combining both approaches, an hybrid LCA, which is the one used inShao and Chen (2013), allows to overcome these limitations, to increase the completeness of the system boundary and reduce uncertainty (Zhang*et al.*, 2013). However, in this study a process-based inventory is considered to be the most adequate due to the availability of data.

Additionally, the study of Shao and Chen (2013) did not consider residue treatment.

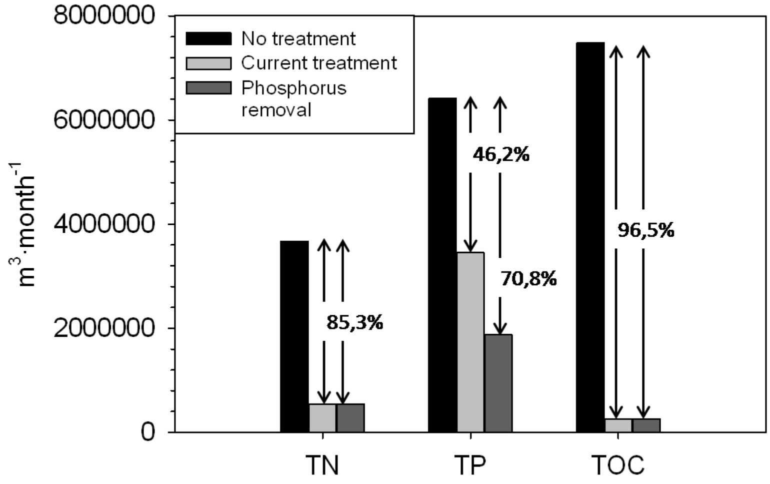

Fig. 4-34: Grey water footprint reduction with wastewater treatment.

Considering the total water footprint for the current wastewater treatment, the intensities for this case study are 171.7 m^3 water·kg^{-1} of TOC removed, 718.7 m^3 water·kg^{-1} of N removed, 10,068.9 m^3 required·kg^{-1} of P removed and 146.4 m^3 water·€$^{-1}$. The blue water footprint of 1 kg of organic matter removed is 8.53 m^3 water (96.5 % removal) in the present study versus 0.01 m^3 water·kg^{-1} COD (86% removal) in the study by Shao and Chen (2013) because, as it is mentioned above, the volume of water consumption for electricity production differs a lot due to the approach used to calculate the water consumption. Despite in both cases, Shao and Chen (2013) and this work, water withdrawal is considered, in our case, using a process-based approach and data from Ecoinvent, we considered not only the water used directly during the electricity production process but also all the indirect water consumption (for example for coal production).

When comparing results, the distinction between water consumption and water withdrawal has to be considered. However, in many cases consumptive use data are not available,thus more efforts should be put to obtain better water consumption inventories.

WF sustainability assessment

Due to lack of specific data, the blue water availability in the studied region (249,100 $m^3 \cdot month^{-1}$) was estimated as the average value (data from 1940 to 2008) of the global water balance of the Catalan catchments. The ratio between the blue water footprint of the process (180,180 $m^3 \cdot month^{-1}$) and the blue water availability (249,100 $m^3 \cdot month^{-1}$) is equal to 0.72 (<1), which indicates that the blue water footprint is sustainable. Additionally, in the case for improved phosphorus removal (with a blue WF of 192,517 $m^3 \cdot month^{-1}$), the blue WF is sustainable with a value of 0.77.

The ratio between the grey WF (3,448,115 $m^3 \cdot month^{-1}$) and the river water flow rate (808,877 $m^3 \cdot month^{-1}$) (4.3>1) indicates that the grey WF is not sustainable. Additionally, in the case when phosphorus is removed to fulfill the legal limit (2 $mg \cdot l^{-1}$ $P\text{-}PO_4^{3-}$), the grey WF is not sustainable because the ratio between the grey WF (1,870,201 $m^3 \cdot month^{-1}$) and the river flow rate is equal to 2.3. This result occurs because the Congost river has a small flow rate with respect to the amount of phosphorous that must be assimilated. The grey WF would become sustainable if the WWTP improved its phosphorous removal to reach an effluent concentration of 0.95 $mg \cdot l^{-1}$ (which assumes a removal efficiency of 85.3 %). Additionally, if phosphorous is not considered in the estimation of the grey WF, then it becomes sustainable because the river has enough capacity to assimilate the pollution generated by nitrogen and organic matter.

Water footprint response formulation

The ratio of required freshwater per unit of treated water (1.45 m^3) is extremely small compared with the water footprint of many other agricultural and industrial products (www.waterfootprint.org, Hoekstra *et al.*, 2011).

After analyzing the water footprint sustainability assessment for the WWTP, it is important to formulate modifications for operational conditions to further reduce the water footprint. In this case, the application of $FeCl_3$ to achieve a greater total phosphorus removal efficiency resulted in a greater reduction in the grey water footprint. In addition to the energy savings, the sludge treatment practices should be further improved by optimizing the operational costs and also by reducing the blue water footprint.

Complements between LCA and WFA

The WFA methodology and its application in agriculture and several industrial products are well known. However, there are a limited number of studies regarding its application in the UWC, particularly in water and wastewater infrastructures. Therefore, a discussion on the possibilities and unclear aspects of its application for WWTPs is required.

Although the goal of LCA is to assess the environmental impacts of a product or activity (a system of products) over its entire life cycle,where water is just one criteria among others (e.g. carbon footprint, land use), whereas the goal of WFA is management-focused, i.e., is focused on the sustainable allocation and use of water. Both methodologies could take advantage of each other and thus complement each other. For example, during the accounting phase for WFA, LCA inventory databases could allow WFA to be more precise, despite, as noted in the section of WF sustainability assessment; a significant amount of uncertainty is associated with the water quantities assigned to electricity generation depending on the data sources. However, the quantitative green and blue footprint indicators for agriculture can be used within the LCA inventory analysis (Boulay*et al.*, 2013), which complements other developed methods (Kounina *et al.*, 2012). Additionally, regarding the blue water footprint, information from many LCA databases is typically related to water withdrawal (or water used) and not to water consumption, which thus implies an overestimation of the blue water footprint. One should be aware of this gap between water consumption and withdrawal. Indeed, (Risch *et al.*, 2014) underlines the need for better estimates of the water consumption and a greater understanding of its impacts during wastewater treatment. In WWTPs, as shown in our case study, although the blue water footprint represents a low value compared with that of the total water footprint (approximately 5% in our case study), the blue water footprint should not be neglected because it is already estimated thanks to the most recent Ecoinvent 3.0 database, which provides water consumption for industrial processes.

The grey water footprint, which is not used in LCA because it represents a theoretical quantification of water pollution, provides complementary information regarding the effluent water quality and WWTP removal efficiencies. During the impact assessment phase, when assessing the sustainability of a WWTP operation, the LCA analysis provides an environmental impact (eutrophication, global warming, etc.), which can be smaller for activated sludge or larger for MBRs; however, in any case, there will always be a certain impact. In contrast, the WF concept demonstrates that the environmental impact of wastewater is reduced when using a WWTP because the grey water footprint is reduced. In the interpretation and response formulation phase, LCA and WFA methods could complement each other in assessing the sustainability of freshwater use and its impact in a more comprehensive way (Boulay*et al.*, 2013). When comparing different technologies for wastewater treatment, sometimes having only one value to compare (i.e., the water footprint) can be an advantage with respect to LCA studies, which always provide different categories; a multi-criteria problem is thus created, where the best solution depends on the weights assigned to each criterion/category.

4.5.5.-SENSITIVITY ANALYSIS

A sensitivity analysis was performed to analyze the contribution on the results of the most important factors. The factors considered were the concentration of phosphorus in the WWTP effluent, the natural concentration of phosphorus in the river, the maximum concentration of phosphorus permitted in the river and finally, the electricity consumption of the plant, since they are the major contributors to the water footprint. The analysis was performed by increasing and decreasing a 25% each one of the factors studied.

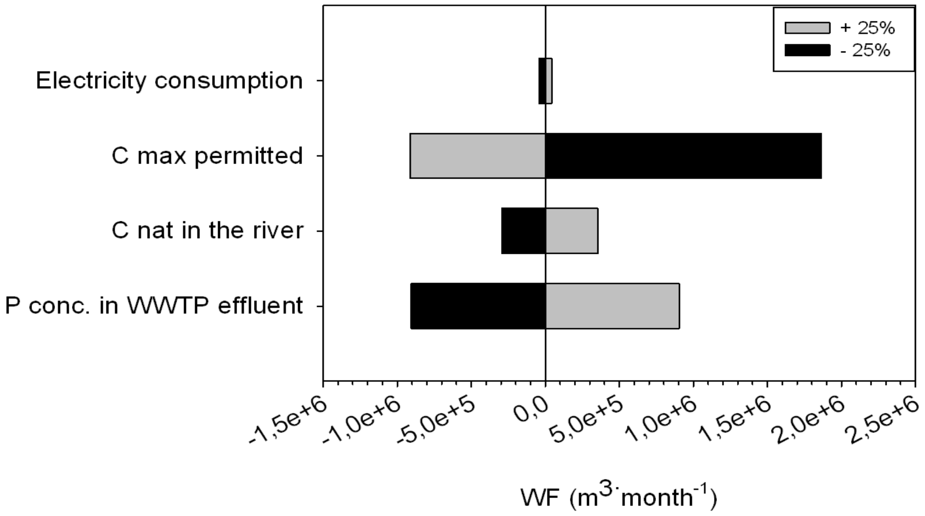

Fig. 4-35: Sensitivity analysis results. The WF with the current treatment is taken as reference (0 $m^3 \cdot month^{-1}$), negative values mean a decrease of the WF, positive values means an increase of the WF.

As is shown in Fig. 4-35, the most sensitive factor is the maximum concentration permitted in the river. If increasing the permitted concentration by a 25%, the water footprint decreases around 912,000 $m^3 \cdot month^{-1}$ (approximately a 25% decrease of the water footprint). On the other hand, if decreasing the maximum concentration permitted in the river by a 25%, the water footprint increases around 1,865,000 $m^3 \cdot month^{-1}$ (approximately a 51% increase of the water footprint). The second most sensitive factor is the concentration of pollutant in the WWTP effluent, with a decrease and increase of the water footprint of 900,000 $m^3 \cdot month^{-1}$ approximately (which represents approximately a 25% increase or decrease, respectively, of the water footprint). The third one is the natural concentration of the pollutant in the river, which increases the water footprint by 10% and decreases about 8%. Finally, the factor with the lowest contribution is the electricity consumption. If increasing and decreasing the electricity consumption in a 25%, the water footprint only increase or decrease about 43,000 $m^3 \cdot month^{-1}$ (+/- 1.2%), respectively. Even though the electricity consumption is the most important contributor to the blue water footprint and considering also that the blue water footprint calculated here is higher than the calculated in Shao and Chen (2013), the increase or decrease of its consumption has not an important effect on the overall results (an increase or decrease by 1.2%, respectively) because the blue water footprint is very low compared with the grey water footprint. The legislation about the maximum concentration permitted of the pollutant in the river together with the level of treatment are the most important factors determining the water footprint of a WWTP, this highlights the importance to develop good normative and to improve the water treatment in order to achieve a lower and more accurate WFs.

5 DISCUSSION

A general discussion of the thesis is presented in this section. Firstly, the main outcomes, which are always related to the challenges that this thesis wants to overcome. Secondly, the potential use of the results and possible limitations are explained, and finally, future work is mentioned.

LCA is a methodology widely used to assess the environmental impacts generated by a process or product during its life-cycle. However, since it is increasing its popularity, its application has some limitations. A UWWS wants to manage and treat urban wastewater so as to minimize the possible environmental impact when that treated water is returned to the natural water system. In accordance with this objective, it is interesting to assess the potential environmental impacts that a UWWS generates and find the most environmentally-friendly option to achieve this objective. LCA can be applied to a UWWS to evaluate its potential environmental impacts, but there are some limitations that this thesis wanted to address.

5.1.- ACCOMPLISHMENT OF THE PhD OBJECTIVES

After analyzing the state-of-the-art of the LCA in a UWWS, two different challenges were detected in section 1.5. Thus, the main objective of this thesis was stated as **to improve the application of LCA methodology in UWWS,** and five different sub-objectives were described as the steps required to achieve the main objective:

1.- *Creation of detailed inventories for sewer system construction*. Although some studies such as Risch *et al.*, (2015) found that the impacts of sewer system construction are comparable to the impacts of WWTPs, LCA is not systematically applied in sewer systems. There are different aspects to consider when a sewer system has to be constructed (type of soil, size and material of tubes and location), each aspect having different possibilities. This fact, together with the tedious process required to obtain the construction inventories, results in sewer system construction receiving very low consideration in LCA studies for UWWS. This thesis contributes to the fulfillment of the first objective through the development of a procedure to obtain detailed inventories and calculate environmental impacts of sewer construction and has created an Excel®-based tool to facilitate these steps. This semi-automated tool also contemplates the possibility of renovating the sewers. To prove its functionality, the tool was applied to a reference case. Finally, a sensitivity analysis was carried out to detect the most significant parameters of sewer construction (material, size and lifetime of pipes, transport distances and site-specific characteristics). Even though the tool permits most of the common sewers to be analyzed, it has some limitations such as the limited number of tube materials and sizes or the typology of the trenches considered.

2.- *Analyze the importance of WWTP construction and operation by conducting a relevant (and detailed) inventory.* When LCA is carried out in WWTPs, the construction phase is not normally considered, in fact, in a recent review of Corominas *et al.*, (2013) only 22 of the 45 studies analyzed took construction into account. When construction is analyzed, the results obtained are highly variable, ranging from the construction phase contributing less that 5% to it contributing more than 20% for a specific impact. This variation depends on the different aspects considered, for instance the lifetime of the WWTPs, materials used during the construction or assumptions considered. As standard practice, some studies where construction is not considered, justify its exclusion by citing the cut-off criteria of LCA guidelines. This second sub-objective is fully achieved through the development of a very detailed study of the construction of a specific WWTP, taking into consideration both civil works and equipment. A procedure to compile comprehensive inventories of the materials and energy consumed to carry out the civil works and manufacture the equipment for WWTP construction was developed. It was then applied in a real case study, allowing the contribution of each material and unit for both civil works and equipment to be analyzed in detail and then compared with the WWTP operation. A contribution greater than 5% for the construction was observed in the majority of the categories analyzed when considering the lifetime of the plant. Finally, different lifetimes for the WWTP are tested to study their contribution to the impacts.

3.- *To provide LCA-wastewater treatment users with equations to facilitate including WWTP construction in LCA studies.* When LCA is applied in WWTP construction, on the whole the material inventory used to perform the assessment is not facilitated. Besides this, sometimes it is simply not possible to obtain information about the materials and energy used in WWTP construction. Inventories not being systematically included in LCA studies and problems in obtaining information result in a very difficult inclusion of the construction phase in LCA studies of WWTPs. This sub-objective is accomplished after applying the procedure explained in subchapter 4.2. to four WWTPs ranging from 1,500 to 21,000 $m^3 \cdot day^{-1}$, and after finding the equations relating the materials and energy consumed during the civil works and the capacity of these WWTPs. Using the equations identified, it is possible to obtain detailed inventories of the materials consumed during the civil works. The use of these equations not only compiles detailed civil works inventories quickly, but also in great detail, allowing them to be included in LCA studies of WWTPs without consuming lot of time. However, these results are only useful for activated sludge plants with a capacity falling within the 1,500 to 21,000 $m^3 \cdot day^{-1}$ range and when the equipment of the plants is not taken into consideration.

4.- *Apply LCA to assessing the integrated assessment of WWTPs.* Although numerous LCA studies are focused on the analysis of single WWTPs, there are very few applications analyzing different management options for two or more WWTPs. In relation to WWTP management, Dennison *et al.*, (1998) applied LCA methodology to sludge management in different WWTPs. There are also some studies, such as that of as Remy and Jekel (2012), which analyze the difference between centralized and decentralized management of wastewater, but to the best of our knowledge, there are no studies that analyze the management of different WWTPs already constructed in the same catchment from an environmental perspective. This may work against LCA as stakeholders might think that while the methodology is useful for academic purposes it is not for real situations. This sub-objective is fulfilled by applying LCA methodology to a real case in agreement with the stakeholders in charge of managing two WWTPs in the “Congost subcatchment”. This real case study applied life cycle methodologies to analyze the environmental and economic performance of different management strategies for two different neighboring WWTPs connected by a sewer, and also considered local specifics such as the ecological river flow (described in the Water Framework Directive (WFD)) as mandatory accomplishments. This application example shows stakeholders the value of LCA as a useful tool for considering environmental aspects during the decision-making process to find the best solution.

5.- *Provide a water footprint assessment for WWTPs.* Although LCA is probably one of the most well-known methodologies for EIA of products or processes, it competes with other environmental assessment methodologies. The final sub-objective applies WF methodology to evaluate the freshwater consumed directly and indirectly during the operation of a WWTP. The last sub-objective of this thesis was fully realized. The WF methodology was adopted and a procedure to calculate the grey water footprint specifically in WWTPs was developed. Thanks to these modifications, the WF was successfully applied in a real WWTP. The methodology was applied before and after treatment to see effortlessly how the WF changes, and also with improved treatment to demonstrate the possibilities of this methodology in evaluating the environmental benefits of WWTPs as well.

Finally, all inventory data and tools developed in the thesis will be publicly available through supporting information of published papers and/or through Researchgate portal.

5.2.- POTENTIAL APPLICATIONS AND POSSIBLE LIMITATIONS

With the main objective of this thesis "to **improve the application of LCA methodology in a UWWS",** the results of this thesis can be very useful for a broader audience. The use of the tools and methods proposed here are interesting for further development within the research community, but they are also directly applicable in practice. Stakeholders can benefit from the outcomes of this thesis through the real case application, which demonstrates the usefulness of environmental impact assessment in decision-making. Consultants, for instance pipeline construction companies wanting to incorporate EIA in their projects, could also directly apply the tools developed in this thesis.

The tool developed in this thesis, described and demonstrated in Chapter 4.1., is extremely useful for research purposes, especially considering the growing concern about integrated management of urban water on a city scale. There are some, albeit, very few tools that can help in obtaining construction inventories for pipelines (ESAT tool – Centre for Water and Waste Technology, University of New South Wales, Sydney 2008-, ACV4E –Irstea, 2014- or Aquaenvec tool –Life-Aquaenvec project, 2015-), but none of these tools are as detailed as the one developed here. This tool is unique because 12 parameters can be combined to describe a particular pipeline hence, a large number of combinations are permitted, along with the ability to analyze and identify options with minimum environmental impacts and costs. The tool is also very attractive for consultancy and construction companies because it enables design and upgrading to be done quickly once the basic information has been introduced. For non-LCA experts, the tool automatically provides EIA for a given impact assessment methodology (ReCiPe). Having said this, it does have some limitations as it only considers one type of trench backfilling and there are normally more tube materials and more tube diameters than the ones considered with the tool. Finally, using this tool in countries other than Spain should be done circumspectly as it has been developed following common practices for sewer construction in Spain, which might differ from other countries.

The results from Chapter 4.2. contribute to establishing good LCA practices after highlighting the importance of including construction inventories for WWTPs. Until now, the study of Emmerson *et al.*, (1995) has been taken as a justification to neglect the construction phase in LCA studies. By conducting the most detailed inventory published so far (including all elements from the construction project) we can guarantee that deviations in the results are not due to oversimplifications. At the same time, this thesis provides some recommendations for conducting simplified LCA studies and identifies the most important materials, units, elements, etc., that should be included in an LCA study. In addition, anyone interested in conducting an LCA inventory from a construction budget has a methodology and a transparent example. This detailed inventory can also be taken as a reference for comparisons. However, the study does have some limitations asparts of the civil works were either estimated (entrance well, one thickener and digesters) or not considered (such as asphalt placement), because they did not appear in the budget or in terms of equipment, not all devices had environmental product declarations and so assumptions had to be made (e.g. helicoidally endless conveyor or filtering screens). The results obtained in the chapter are case-specific and would be transferable to similar case-studies with similar plant configuration, and capacity.

The results from the two previous chapters would be useful forthose construction companies wanting to select construction materials based on EIA and they will be publicly available. Choosing between different materials with less potential impact that the studied materials or trying to reduce its consumption.

Results in sub-chapter 4.3. can be very useful for research purposes and consultancy. Currently, when no real construction inventory data is available for the WWTP being studied,WWTP inventories from Ecoinvent are taken as the reference and normally used (after scaling). The results in sub-chapter 4.3 are the only existing alternative to Ecoinvent examples for the Spanish reality. Most importantly, the results in sub-chapter 4.3 (and those in 4.2) demonstrate that Ecoinvent WWTPs result in increased construction impacts when compared to those obtained in this thesis. The main reasons being a higher consumption of concrete and reinforcing steel, as well as selecting different processes (e.g. use of concrete, which has higher requirements in Ecoinvent and are lower in our case). The results in this chapter provide linear regressions for the most important materials used in and energy consumed by civil works for WWTPs with different capacities and, therefore, facilitate the inclusion of the construction of WWTPs in LCA studies. For construction companies these results can be very useful since, by using the linear equations provided, it is possible to carry out fast, but accurate, studies of environmental impacts produced by the civil works for WWTPs. They also permit the contribution of each unit to the environmental impact to be studied and can be useful during the design process of WWTPs to minimize their environmental impacts. However, these results are only applicable for activated sludge WWTPs between 1,500 and 21,000 $m^3 \cdot day^{-1}$. The regressions do not permit all the materials consumed during the civil works to be considered because it was not possible to find good correlations for all the materials. The equations for metals and plastics were obtained by considering the total quantity of these groups rather than each type of metal or plastic specifically which, as a trade-off, contributes to a loss of sensitivity in the inventories and impacts calculation.

Sub-chapter 4.4. may be very useful for stakeholders. The results show an example of how LCA use can aid the decision-making processes. It could also be very useful for future decision-making processes regarding different options for WWTPs management because it shows how to apply the methodology, how to integrate local considerations to accomplish the WFD and which aspects have to be considered in these types of studies. For research purposes it is very useful because it combines economic and environmental assessment. Furthermore, it shows a possible way to integrate local mandatory accomplishment requirements for the WFD in LCA studies. However, these results are very case-specific and some of the assumptions made in this work would not be useful for future studies like this one.

Sub-chapter 4.5. would be interesting for researchers and environmental consultancies. The results show how to adopt the general methodology of the WF so it is applicable in WWTPs. It also provides a practical example of WF methodology use in assessing the freshwater consumption of WWTPs. The chapter provides a good guideline with all the necessary steps and detailed explanations on how to apply water footprint methodology in WWTPs. However, there are some limitations such as the fact that nowadays water consumption inventories are not very accurate as they change a lot depending on the source of information. Also with the publication of the new ISO 14046:2014 – Environmental Management – Water footprint – Principles, requirements and guidelines, there are some discrepancies in the methodology used in the WFA manual (Hoekstra *et al.*, 2001).

5.3.- FUTURE WORK

Although this thesis accomplished its main objective, there are still a number of aspects that can be studied further.

In relation to the tool that was developed for the sewer system inventories, it could be improved to consider more tube materials, diameters and shapes. Currently the tool considers four different materials (PVC, HDPE, reinforced concrete and concrete), but there are more tube materials such as ductile iron or steel. Although the diameters considered range from 20 to 250 cm, the range of diameters considered can be expanded. Also more tube shapes need to be considered such as oval or rectangular tubes. Another improvement to the tool would be the inclusion of different types of trench backfilling, because for the moment it only covers sand, but it is not uncommon to backfill the trenches (in part) with concrete. The tool could also be improved to take into consideration more shapes for trenches, as currently it only has two types of trenches (rectangular or trapezoidal), but there is at least one other type that is a mix of these two. Finally, the tool can also be improved by adding to it other parts of the sewer system such as pumping stations, the typical equipment used, and incorporating a new module related to sewer system operation.

A more detailed study of the materials and energy consumed during the manufacturing of the equipment of a WWTP is another area to be addressed more fully. Moreover, an in-depth analysis of the end-of-life of a WWTP to really clarify what the common practices during the dismantling of these facilities are and to discern the contribution to the global impact of this phase is required. It would also be interesting to carry out the same type of study in WWTPs which use different technologies.

The equations used in this paper could be expanded to WWTPs of higher capacities and to include WWTPs using different technologies, since currently these equations can only be applied to activated sludge WWTPs. Furthermore, it would be interesting to carry out similar regression analysis also for the equipment installed in the WWTPs and the operation phase. Finally, another improvement could be to develop a tool integrating all this knowledge, to carry out inventories and also EIAs of different WWTPs (technologies and capacities) in a more automated way.

Having the tools and inventories from Thesis as a starting point, a very relevant outcome would be to upgrade current design tools with environmental indicators, based only on basic information provided by engineers during the design phase.

On the other hand, it would be interesting to increase the number of studies applying the WF methodology to compare different treatment technologies, i.e. not only for activated sludge. Additional studies might involve analyzing reducing the WF of WWTPs with different operational strategies or with tertiary treatments.Besides, a comparison of the *classical methodology* for the WF (applied in this work, from the water footprint manual) and the one proposed in the recent ISO 14046:2014 is urgently needed, even though nowadays there is not a general agreement on which one has to be adopted as reference.

Finally, it would be interesting to carry out more studies of EIA in collaboration with stakeholders in order to convince them about the very real possibilities of LCA and other impact assessment methodologies and facilitate their introduction as a common feature considered during the decision-making processes.

6 CONCLUSIONS

The objectives of this thesis have been achieved, being the main contributions: 1) Improve the Life Cycle Inventory phase for the construction of the UWWS, facilitating an easy procedure for obtaining of good and detailed inventories in sewer systems and WWTPs, as well as, through the creation of an excel®-based tool for sewer systems and providing some equations to elaborate the inventory for the civil works of WWTPs between 1,500 and 21,000 $m^3 \cdot d^{-1}$ of capacity. 2) Show real cases with the application of the LCA methodology and water footprint to stakeholders, in order to popularize their application in real cases of decision-making processes.

For the first contribution the following conclusions divided in the different sections of the results can be drawn:

In relation with the improvement of the construction and renovation inventories in sewer systems:

- Renovation of pipes after their technical life span has expired greatly influences all environmental and cost impacts during the lifetime of a sewer system; in the initial hypothetical sewer system, the renovation has an impact between 55 to 77% to the total environmental impact depending on the studied impact.
- The environmental impacts generated during the construction are mainly associated with pipe laying and backfilling of the trench. During the renovation apart from backfilling and pipe laying also the trench deposition phase has a high influence in the results.
- In the initial hypothetical sewer system, the pipe material production process has an impact between 30 and 60% depending on the impact category for construction and between 33 and 74% for renovation.
- A proper life span selection for the pipes is crucial because the results greatly change, ranging from a reduction of the impact of 51% to an increase of 61%.
- Precast concrete and HDPE sewer construction generates lower environmental impacts in the studied categories than PVC pipes because they have a longer life span and the pipe production has a lower impact (per kg of pipe).
- Soil characteristics of the underground have a high environmental impact whereas transport distances have not an important influence.
- Final disposal of pipes affects the final results, particularly for plastic pipes, for which the environmental impacts can increase up to 69% for CC and 145% for HT.

- The influence of the pipe material and its deposition becomes more important when the pipe diameter increases.
- All calculations shown in this paper were obtained thanks to the automatic tool, which was developed to facilitate the development of material and energy inventories for the construction and renovation of sewers and the calculation of environmental impacts and costs. This tool can be easily expanded and adapted to include other processes, which might be relevant in other countries.

In relation with the objective to analyze the importance of WWTP construction and operation by conducting a relevant (and detailed) inventory, the main conclusions are:

- In this study, a systematic procedure to facilitate a framework to do more detailed inventories is proposed. However, during its application, it was necessary to overcome difficulties.
    - In the case of civil works, sometimes, it can be difficult to obtain the budget from the older phases constructed. Furthermore, sometimes, only the drawings are available, in which case it is necessary to estimate the materials and equipment from the drawings.
    - Another difficulty to overcome is that sometimes, the items of the budget are not available in civil work standard databases In this case, it is necessary to search the most similar items or produce by yourself detailed material budgets.
    - The last difficulty is that sometimes, the list of materials obtained during the inventory phase is not available in the LCI database.
- In this study, the impacts of a WWTP dividing the plant into different units were evaluated. This approach allows for a detailed analysis of all the units inside the plant to detect the most important units contributing to the impact.
- This study applied the procedure presented in a specific WWTP of activated sludge higher than 200.00 PE. From this specific application some conclusions can be drawn:

- If a quick but not very detailed analysis is needed for construction, one can consider only secondary treatment and sludge lines, but then, only 75% of each impact category is considered.
- When construction and operation are analyzed together, the buildings and services unit can be ignored, but the other units must be considered. However, for the ME category considering only the secondary treatment, more than 90% of the impact is described. In the CC category, primary treatment can also be ignored because it has an impact of approximately 3%, and primary treatment also has a low contribution, approximately 6%, in FE. In the FE category, pumping + pre-treatment and the sludge line could also be ignored because they contribute less than 5%. The sludge line could also be ignored in HT and FD; thanks to the electricity produced, the impact in these categories is very low (5.5 and 1.4%, respectively), but when there is no electricity production, the sludge line must be considered.
- If the objective is to analyze only the different phases of the life cycle of a WWTP, civil works and equipment can be ignored only in the ME and FE categories. For the other categories, civil works and equipment account for a range between 10 and 70% of the impact, so they must be considered.
- It is important to note the high contribution of construction and equipment in all studied categories, particularly in MD (74% of the impact). This fact highlights the importance of considering different impact categories during environmental analysis because sometimes, one or two impact categories are not enough to get a good idea of the impact of all environmental aspects.
- Related with the materials consumed in all the life cycle of the plant considering the concrete, reinforcing steel, plastics and soil deposition during the civil works together with the operational data between 90 and 99% of the impact is considered in CC, OD, FE, ME and FD categories. On the other hand considering also metals consumed during the civil works and pumps about 91% of the HT impact is counted, finally for MD, metals consumed during civil works and all the equipment has to be considered in order to consider more 90% of this impact.

In relation with the objective to provide new equations to calculate fast and detailed inventories for the construction of WWTPs:

- It is necessary to carry out new inventories, and publish them to be used for other people, for the construction of WWTPs. Nowadays the information available in Ecoinvent databases is limited only to WWTPs constructed at the end of 80s or in the early 90s in Switzerland, and can be differences between the normal practices when that plants were constructed and now or it can be differences also in the type of construction between countries.

- Comparing inventories available in LCA databases and the inventories carried out in this case there are big differences in relation with the diversity of materials used and the mass. Having more diversity of materials in this study, but higher mass in the inventories from Ecoinvent.

- When the construction of WWTPs is considered the analysis have to consider all the plant, not only pre-treatment, secondary treatment and sludge line, also the units not directly correlated with the operation, as connections, buildings and urbanization.

- The equations facilitated in this work permit to do adjusted inventories with good results, when someone wants to do construction inventories of activated sludge WWTPs, knowing only the capacity in $m^3 \cdot d^{-1}$of the plant.

In relation with the second contribution the following conclusions can be drawn:

In relation with the application of LCA in a real case to evaluate different WWTPs management strategies:

- A new methodology that includes economic and both local and global environmental aspects has been proposed for the integrated management of WWTPs and rivers and 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.

Finally, for the application of water footprint methodology:

- The applicability of the water footprint methodology in WWTPs was demonstrated.
- The application to a specific WWTP, which currently treats 4,000 $m^3 \cdot d^{-1}$, resulted in a water footprint of $3.6 \cdot 10^6$ $m^3 \cdot month^{-1}$ for the current operation, with an intensity of 1.45 m^3 required for freshwater$\cdot m^{-3}$ treated wastewater and $2.1 \cdot 10^6$ $m^3 \cdot month^{-1}$ for enhanced phosphorous removal.
- The WWTP under study reduced the water footprint by 51.5 % and 72.4 % when using secondary treatment and phosphorous removal, respectively, to fulfill the legal limits, where blue water footprints of 180,180 and 192,517 $m^3 \cdot month^{-1}$, respectively, were obtained.
- Phosphorous removal should be a priority due to its higher impact after treatment and higher reduction of the water footprint.
- The water footprint illustrates the beneficial role of WWTPs within the urban water cycle.

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ANNEXES

1.- SUPPLEMENTARY INFORMATION OF CHAPTER 4.1.

SUPPLEMENTARY TABLES

Table S-1: Overview of the energy and materials consumed, residues generated and economical information for all the phases involved in the construction and renovation, of the initial hypothetical scenario. Information in the table includes the total amount of each needed phase for the construction and renovation of the initial hypothetical scenario, and the complete inventory of energy, material and residues generated and also the costs to construct and renovate the initial hypothetical scenario.

	Phase	Amount	Unit	Energy (MJ)	PVC (kg)	Polyurethane mastic (kg)	Water (kg)	Granite sand (kg)	Transport (tkm)	PVC to deposition (kg)	Polyurethane mastic to deposition (kg)	Cost (€)
Construction	Excavation compact soil	1,254	m^3	57,156								7,579
	Tube laying	1,000	m	28,648	18,560	42	152,700		465[1]			22,189
	Backfill with granite sand	798.3	m^3	52,776			39,917	1,357,172	67,859[2]			34,078
	Backfill with soil from the workplace	330	m^3	21,271			16,500					4,173
	Distribution excess soil	924	m^3	58,964			46,200					5,951
Renovation	Excavation compact soil	2,508	m^3	115,033								15,158
	Tube extraction and laying of the new one	2,000	m	101,118	37,120	84	305,400		930[1]	37,120*	84*	46,068
	Backfill with granite sand	1,597	m^3	105,552			79,834	271,434	13,572[2]			20,906
	Backfill with soil from the workplace	660	m^3	42,542			33,000					8,346
	Deposition PVC	37,120	kg						742[3]	37,120*		Not considered
	Deposition polyurethane mastic	84	kg						2[3]		84*	Not considered

[1] 25 km distance to tube distributors; [2] 50 km to granite sand distributor; [3] 20 km to deposition treatment

* Is referred to the same material (PVC and polyurethane) but first is accounted to consider the needed energy to extract the tube, and second is considered as mass of material sent to incineration.

Table S-2: Summary of the influence of all the parameters studied in the sensitivity analysis performed in this work, analyzed for three different diameters (40, 80 and 140 cm).

		Climate Change (CC)			Human toxicity (HT)			Particulate Matter (PM)			Fossil Depletion (FD)			Costs (€)		
		40 cm	80 cm	140 cm	40 cm	80 cm	140 cm	40 cm	80 cm	140 cm	40 cm	80 cm	140 cm	40 cm	80 cm	140 cm
Soil characteristics	Type of soil, road construction and urban setting	21	10	7	16	8	4	34	24	19	55	24	12	45	29	25
Life span selection within proposed ranges	PVC	34	36	37	38	40	41	29	31	32	31	32	33	28	28	29
	HDPE	55	59	61	47	54	58	38	38	39	43	45	45	47	46	47
	Reinforced concrete	-48	-49	-49	-47	-48	-49	-50	-51	-51	-47	-49	-49	-42	-43	-44
	Concrete	-46	-47	-48	-43	-4	-46	-47	-48	-48	-46	-47	-48	-40	-42	-42
Distances	Excess soil	3	2	1	2	1	1	4	3	2	3	2	2	-	-	-
	Granite sand	3	2	1	2	1	1	4	3	2	3	2	1	-	-	-
	Sand	1	1	0	1	0	0	1	1	0	1	1	0	-	-	-
	Asphalt	2	1	0	1	0	0	2	1	1	1	1	0	-	-	-
Deposition	PVC	38	49	55	100	129	145	5	7	8	4	4	5	-	-	-
	HDPE	46	60	69	37	54	65	-8	-13	-16	-8	-9	-10	-	-	-
	Reinforced concrete	2	3	3	1	1	1	7	8	9	4	5	5	-	-	-
	Concrete	2	2	3	1	1	2	2	3	3	4	5	5	-	-	-
Renovation (using the average lifespan)	PVC	69	72	74	77	80	82	58	61	63	62	64	65	55	56	57
	HDPE	54	59	61	47	54	58	38	38	39	43	45	45	47	46	47
	Reinforced concrete	48	49	49	47	48	49	50	51	51	47	49	49	42	43	44
	Concrete	46	47	48	42	45	46	47	48	48	46	47	48	40	42	42

SUPPLEMENTARY FIGURES

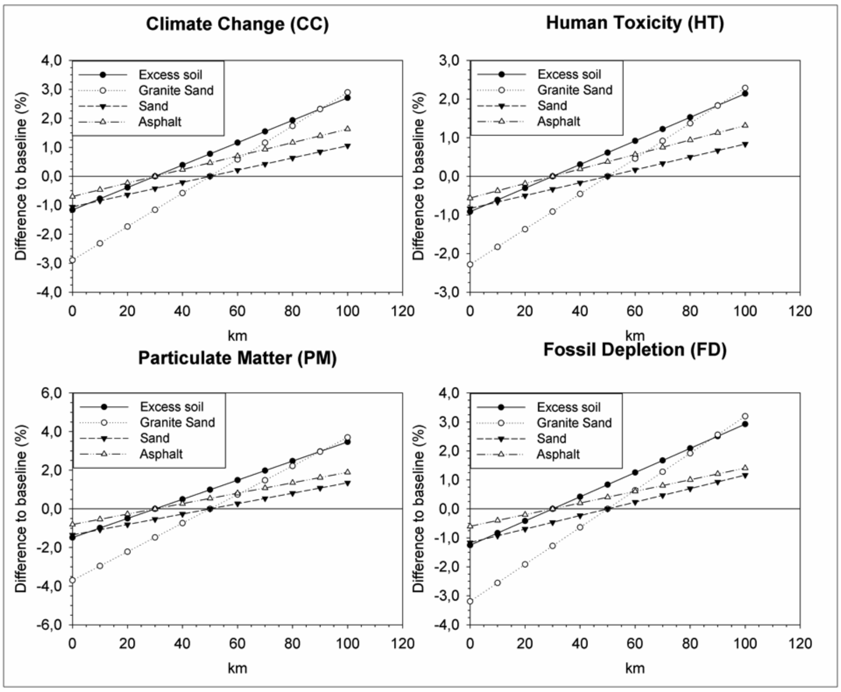

Fig. S-1: Influence of transport of materials to the overall impacts. Includes transport of i) excess material from the construction site to landfill, ii) sand, iii) granite sand and iv) asphalt to the construction site. The baseline corresponds to the distances applied to the initial hypothetical sewer system, which are 30 km for truck transport to the landfill and for asphalt, and 50 km for granite sand and sand for a PVC pipe of 40 cm.

2.- SUPPLEMENTARY INFORMATION OF CHAPTER 4.2.

SUPPLEMENTARY TABLES

Table S-3: Complete material inventory per unit.

Material/Process	Inventory used	Unit	Pumping + pretreatment	Primary tretament	Secondary treatment	Sludge line	Buildings and services
Material deposition in a landfill	Disposal, inert waste, 5% water, to inert material landfill/CH U	ton	$4.59\cdot10^{2}$	$4.03\cdot10^{3}$	$1.13\cdot10^{5}$	$1.23\cdot10^{4}$	-
Diesel burned in mechanical machines	Diesel, burned in building machine {GLO}| market for | Alloc Def, U	MJ	$4.14\cdot10^{5}$	$6.79\cdot10^{5}$	$8.58\cdot10^{6}$	$1.89\cdot10^{6}$	$8.76\cdot10^{5}$
Diesel burned in electrical generators	Diesel, burned in diesel-electric generating set {GLO}| market for | Alloc Def, U	MJ	$1.60\cdot10^{4}$	$2.72\cdot10^{3}$	$5.03\cdot10^{3}$	$5.01\cdot10^{4}$	$1.20\cdot10^{3}$
Transport	Transport, freight, lorry >32 metric ton, EURO4 {GLO}| market for | Alloc Def, U	tkm	$2.82\cdot10^{5}$	$3.35\cdot10^{5}$	$3.57\cdot10^{6}$	$2.14\cdot10^{6}$	$1.43\cdot10^{5}$
Reinforcing steel	Reinforcing steel {GLO}| market for | Alloc Def, U	kg	$1.99\cdot10^{5}$	$1.70\cdot10^{5}$	$1.09\cdot10^{6}$	$5.09\cdot10^{5}$	$8.25\cdot10^{3}$
Wire steel	Wire drawing, steel {GLO}| market for | Alloc Def, U	kg	$2.85\cdot10^{3}$	$2.38\cdot10^{3}$	$1.54\cdot10^{4}$	$7.18\cdot10^{3}$	$1.11\cdot10^{2}$
Steel	Steel, low-alloyed {GLO}| market for | Alloc Def, U	kg	$1.72\cdot10^{3}$	$1.25\cdot10^{3}$	$5.95\cdot10^{3}$	$5.78\cdot10^{3}$	$2.54\cdot10^{2}$
Stainless steel	Steel, chromium steel 18/8 {GLO}| market for | Alloc Def, U	kg	$1.80\cdot10^{3}$	$2.37\cdot10^{3}$	$5.36\cdot10^{3}$	$5.81\cdot10^{2}$	$9.42\cdot10^{1}$

Galvanized steel	Steel, converter, low-alloyed, at plant/RER U	kg	$3.29\cdot10^{3}$	$4.74\cdot10^{3}$	$2.38\cdot10^{3}$	$9.60\cdot10^{2}$	$2.09\cdot10^{2}$
	Zinc coat, pieces {GLO}| market for | Alloc Def, U	m^{2}	$1.14\cdot10^{2}$	$2.27\cdot10^{2}$	$1.22\cdot10^{2}$	$2.43\cdot10^{1}$	$8.61\cdot10^{0}$
Cast iron	Cast iron {GLO}| market for | Alloc Def, U	kg	$9.79\cdot10^{2}$	$8.63\cdot10^{2}$	$1.18\cdot10^{3}$	$2.59\cdot10^{3}$	$5.16\cdot10^{3}$
Aluminium	Aluminium, primary, ingot {GLO}| market for | Alloc Def, U	kg	$3.15\cdot10^{2}$	-	-	$3.21\cdot10^{2}$	$1.52\cdot10^{2}$
Wire copper	Wire drawing, copper {GLO}| market for | Alloc Def, U	kg	-	-	-	$5.40\cdot10^{-1}$	-
PVC	Polyvinylchloride per la construcció *	kg	$8.21\cdot10^{2}$	$6.14\cdot10^{2}$	$7.59\cdot10^{2}$	$1.82\cdot10^{3}$	$8.19\cdot10^{3}$
Elastomeric rubber	Synthetic rubber {GLO}| market for | Alloc Def, U	kg	$2.33\cdot10^{3}$	$3.01\cdot10^{3}$	$5.68\cdot10^{3}$	$1.80\cdot10^{3}$	$2.86\cdot10^{1}$
Nylon	Nylon 6 {GLO}| market for | Alloc Def, U	kg	-	-	-	$3.26\cdot10^{0}$	-
HDPE	Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U	kg	$2.10\cdot10^{3}$	$1.93\cdot10^{3}$	$1.93\cdot10^{3}$	$5.83\cdot10^{3}$	$5.73\cdot10^{2}$
Polyurethane foam	Polyurethane, rigid foam {GLO}| market for | Alloc Def, U	kg	$8.00\cdot10^{0}$	-	-	$8.42\cdot10^{1}$	$1.5\cdot10^{1}$
Extruded polystyrene	Polystyrene, extruded {GLO}| market for | Alloc Def, U	kg	$3.84\cdot10^{2}$	-	$7.88\cdot10^{1}$	$7.21\cdot10^{2}$	$1.18\cdot10^{2}$
Silicone	Silicone product {GLO}| market for | Alloc Def, U	kg	$2.00\cdot10^{0}$	-	-	$1.90\cdot10^{0}$	$5.87\cdot10^{-1}$
Polypropylene	Polypropylene, granulate {GLO}| market for | Alloc Def, U	kg	$7.00\cdot10^{1}$	-	-	$9.07\cdot10^{1}$	$1.87\cdot10^{1}$
Polyester reinforced with glass fiber	Glass fibre reinforced plastic, polyester resin, hand lay-up {GLO}| market for | Alloc Def, U	kg	$7.66\cdot10^{4}$	$7.66\cdot10^{4}$	$7.66\cdot10^{4}$	$2.30\cdot10^{5}$	-
Polystyrene foam	Polystyrene foam slab {GLO}| market for |	kg	-	-	$5.57\cdot10^{1}$	-	-

	Alloc Def, U						
Polyester resin	Polyester resin, unsaturated {GLO}| market for | Alloc Def, U	kg	-	-	-	$4.96\cdot10^{1}$	$1.69\cdot10^{1}$
Anodising pieces	Anodising, aluminium sheet {GLO}| market for | Alloc Def, U	m^{2}	$3.00\cdot10^{0}$	-	-	$3.76\cdot10^{0}$	$1.28\cdot10^{0}$
Enamelled	Enamelling {GLO}| market for | Alloc Def, U	m^{2}	$1.60\cdot10^{-1}$	$1.69\cdot10^{-1}$	$1.69\cdot10^{-1}$	$5.10\cdot10^{-1}$	$1.05\cdot10^{0}$
Antioxidant layer	Tin plating, pieces {GLO}| market for | Alloc Def, U	m^{2}	$2.00\cdot10^{0}$	$4.10\cdot10^{-1}$	$1.19\cdot10^{-1}$	-	-
Wooden plate	Sawn timber, softwood, raw, plant-debarked, u=70%, at plant/RER U	m^{3}	$7.340\cdot10^{0}$	$3.90\cdot10^{0}$	$1.09\cdot10^{0}$	$4.77\cdot10^{0}$	$4.22\cdot10^{-1}$
Wood conglomerate	Particle board, for outdoor use {GLO}| market for | Alloc Def, U	m^{3}	$1.50\cdot10^{1}$	$8.48\cdot10^{0}$	$1.20\cdot10^{1}$	$9.35\cdot10^{0}$	-
Concrete	Concrete, normal {GLO}| market for | Alloc Def, U	m^{3}	$2.82\cdot10^{3}$	$2.47\cdot10^{3}$	$1.21\cdot10^{4}$	$3.72\cdot10^{3}$	$3.06\cdot10^{2}$
Cement mortar	Cement mortar {GLO}| market for | Alloc Def, U	kg	$1.18\cdot10^{4}$	$5.64\cdot10^{3}$	$2.90\cdot10^{5}$	$3.73\cdot10^{3}$	$167\cdot10^{4}$
Precast concrete pieces	Concrete block {GLO}| market for | Alloc Def, U	kg	$1.83\cdot10^{5}$	$2.06\cdot10^{4}$	$2.06\cdot10^{4}$	$2.53\cdot10^{5}$	$2.96\cdot10^{5}$
Lime mortar	Lime mortar {GLO}| market for | Alloc Def, U	kg	$2.25\cdot10^{4}$	$6.01\cdot10^{3}$	$6.51\cdot10^{3}$	$8.93\cdot10^{4}$	$1.01\cdot10^{5}$
Autoclaved aerated concrete	Lightweight concrete block, polystyrene {GLO}| market for | Alloc Def, U	kg	$3.07\cdot10^{4}$	-	-	$7.25\cdot10^{4}$	$9.43\cdot10^{3}$
Brick	Brick {GLO}| market for | Alloc Def, U	kg	$4.46\cdot10^{4}$	$9.30\cdot10^{3}$	$1.183\cdot10^{4}$	$1.16\cdot10^{5}$	$7.60\cdot10^{4}$
Adhesive mortar	Adhesive mortar {GLO}| market for | Alloc Def, U	kg	-	-	$3.84\cdot10^{3}$	$5.14\cdot10^{3}$	$3.01\cdot10^{3}$
High requirements concrete	Concrete, high exacting requirements {GLO}|	kg	$4.41\cdot10^{4}$	-	-	$1.85\cdot10^{4}$	-

	market for | Alloc Def, U						
Roofing tile	Ceramic tile {GLO}| market for | Alloc Def, U	kg	$1.39\cdot10^{3}$	-	$1.39\cdot10^{3}$	$1.88\cdot10^{4}$	$8.44\cdot10^{3}$
Plastering	Cover plaster, mineral {GLO}| market for | Alloc Def, U	kg	-	-	-	$2.05\cdot10^{0}$	-
Synthetic oil	Diesel {Europe without Switzerland}| market for | Alloc Def, U	kg	$4.20\cdot10^{2}$	$3.99\cdot10^{2}$	$1.49\cdot10^{3}$	$3.14\cdot10^{2}$	$2.90\cdot10^{1}$
Mastic asphalt	Mastic asphalt {GLO}| market for | Alloc Def, U	kg	$4.00\cdot10^{1}$	-	$1.46\cdot10^{3}$	-	-
Gravel	Gravel, crushed {GLO}| market for | Alloc Def, U	kg	$1.80\cdot10^{5}$	$1.75\cdot10^{5}$	$1.28\cdot10^{6}$	$5.72\cdot10^{5}$	$1.94\cdot10^{6}$
Adhesive	Adhesive, for metal {GLO}| market for | Alloc Def, U	kg	$3.10\cdot10^{1}$	$7.91\cdot10^{0}$	$7.91\cdot10^{0}$	$4.60\cdot10^{1}$	$1.08\cdot10^{2}$
Cement	Cement, unspecified {GLO}| market for | Alloc Def, U	kg	$1.52\cdot10^{4}$	$6.30\cdot10^{0}$	-	-	-
Paper	Paper, woodfree, coated {RER}| market for | Alloc Def, U	kg	$4.30\cdot10^{-1}$	-	-	$4.15\cdot10^{-1}$	-
Windows	Flat glass, coated {GLO}| market for | Alloc Def, U	kg	$4.58\cdot10^{2}$	-	-	$2.94\cdot10^{2}$	$5.16\cdot10^{2}$
Paint	Alkyd paint, white, without water, in 60% solution state {GLO}| market for | Alloc Def, U	kg	$1.40\cdot10^{1}$	-	-	-	$3.78\cdot10^{1}$
Synthetic resin	Alkyd resin, long oil, without solvent, in 70% white spirit solution state {GLO}| market for | Alloc Def, U	kg	$1.03\cdot10^{2}$	-	$5.67\cdot10^{1}$	$3.26\cdot10^{0}$	$3.46\cdot10^{2}$
Butyl	Butyl acrylate {GLO}| market for | Alloc Def, U	kg	$5.20\cdot10^{-1}$	-	-	$2.88\cdot10^{-1}$	-
Crushed rocks	Rock crushing {GLO}| market for | Alloc Def, U	kg	-	-	$1.20\cdot10^{6}$	-	-
Epoxy resin	Epoxy resin, liquid {GLO}| market for | Alloc	kg	-	-	-	$8.13\cdot10^{2}$	-

	Def, U						
Bitumen	Bitumen adhesive compound, hot {GLO}| market for | Alloc Def, U	kg	-	-	-	$1.16\cdot10^{3}$	$3.94\cdot10^{2}$
Water	Water, unspecified natural origin, ES	kg	-	-	-	$2.00\cdot10^{0}$	$3.79\cdot10^{5}$
Rock wool	Rock wool {GLO}| market for | Alloc Def, U	kg	-	-	-	$8.45\cdot10^{2}$	-
Switch	Switch, toggle type {GLO}| market for | Alloc Def, U	kg	-	-	-	$2.14\cdot10^{0}$	-
Plastic extrusion	Extrusion, plastic pipes {GLO}| market for | Alloc Def, U	kg	$7.96\cdot10^{4}$	$7.91\cdot10^{4}$	$7.91\cdot10^{4}$	$2.37\cdot10^{5}$	-
Plastic moulding	Injection moulding {GLO}| market for | Alloc Def, U	kg	$5.50\cdot10^{1}$	$5.28\cdot10^{1}$	$1.97\cdot10^{2}$	$2.44\cdot10^{2}$	-
Rolling steel sheets	Sheet rolling, steel {GLO}| market for | Alloc Def, U	kg	$9.82\cdot10^{3}$	$1.39\cdot10^{3}$	$4.65\cdot10^{3}$	$4.77\cdot10^{3}$	$8.91\cdot10^{1}$
Rolling stainless steel	Sheet rolling, chromium steel {GLO}| market for | Alloc Def, U	kg	$1.79\cdot10^{3}$	$2.37\cdot10^{3}$	$5.36\cdot10^{3}$	$5.81\cdot10^{2}$	$9.42\cdot10^{1}$
Steel pieces formation	Impact extrusion of steel, cold, 5 strokes {GLO}| market for | Alloc Def, U	kg	$4.24\cdot10^{3}$	$6.66\cdot10^{3}$	$5.75\cdot10^{3}$	$8.48\cdot10^{3}$	$1.82\cdot10^{3}$

Table S-4: Complete list of equipment per unit.

Equipment	Unit	Pumping + pretreatment	Primary treatment	Secondary treatment	Sludge line	Buildings and services
Actuators	p	13	17	27	4	-
Blowers	p	3	1	4	4	-
Burners	p	-	-	-	2	-
Centrifuges	p	-	-	-	3	-
Counters	p	-	-	-	-	2
Diffusers	P	82	-	3714	-	-
Elevation equipment	p	6	-	19	-	-
Emergency lights	p	8	2	6	14	17
Extinguishers	p	4	3	6	11	25
Fans	p	2	3	6	6	-
Frequency variator	p	-	9	8	13	-
Gates	p	14	17	21	3	-
Grids	p	5	-	-	2	-
Heat exchanger	p	-	-	-	4	-
Hydraulic groups	p	2	-	-	16	-
Lighting rod	p	1	-	2	1	-
Mechanical variator	p	-	-	-	6	-
Mixers	p	-	11	19	7	-
Motors	p	31	28	27	8	-
Position detectors	p	18	19	13	31	-
Probes	p	9	4	4	-	-
Pumps	p	7	9	34	30	-
Reducers	p	26	20	11	18	-
Tanks	p	1	3	4	5	-
Transport equiment	p	16	7	5	3	-
Valves	p	60	65	124	220	-

SUPPLEMENTARY FIGURES

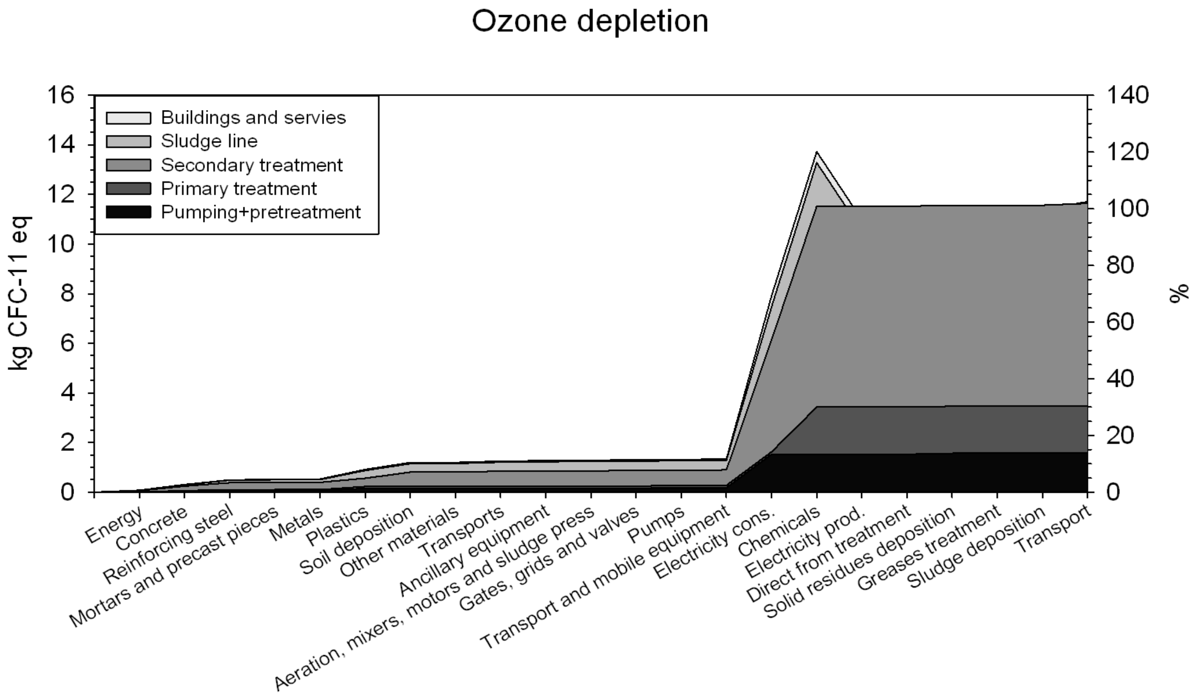

Fig. S-2: Cumulative impact for OD category of civil works, equipment and operation, differentiating between the different units.

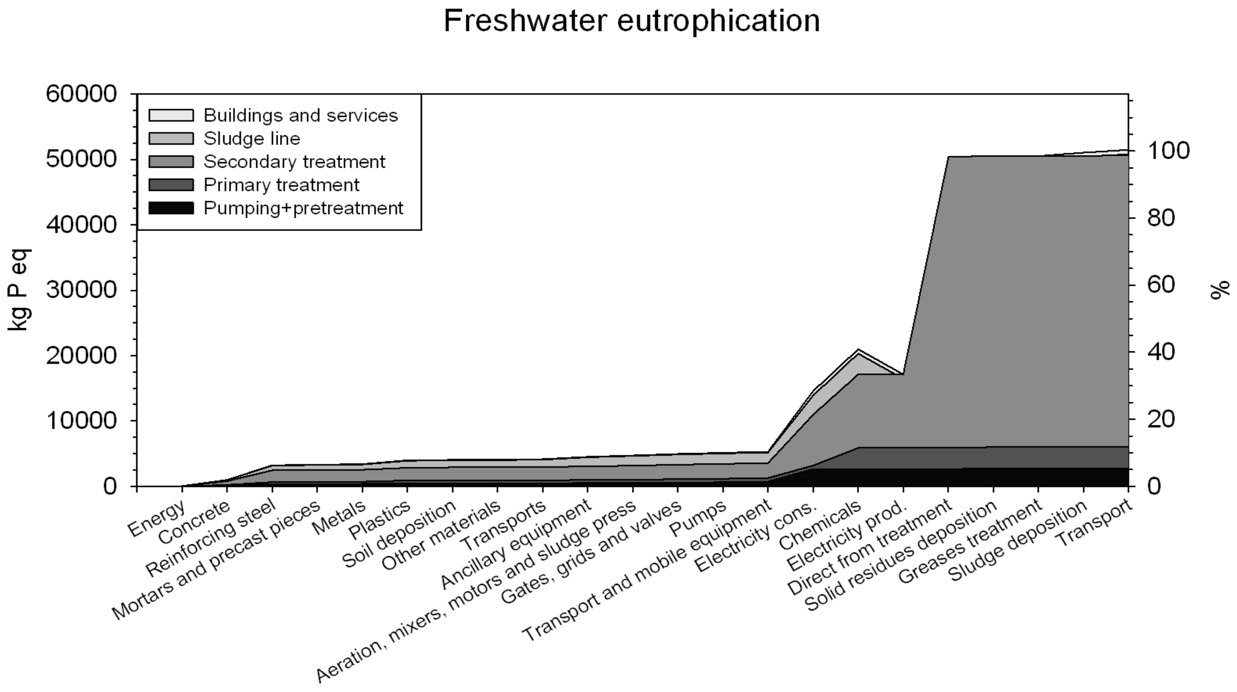

Fig. S-3: Cumulative impact for FE category of civil works, equipment and operation, differentiating between the different units.

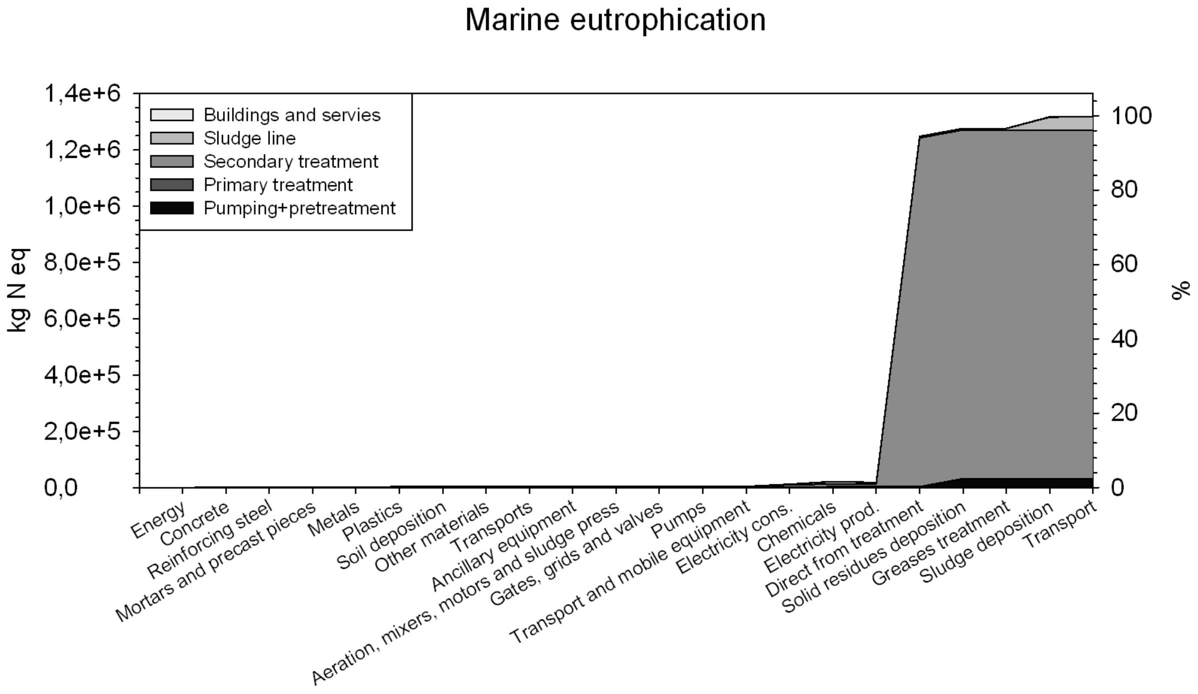

Fig. S-4: Cumulative impact for ME category of civil works, equipment and operation, differentiating between the different units.

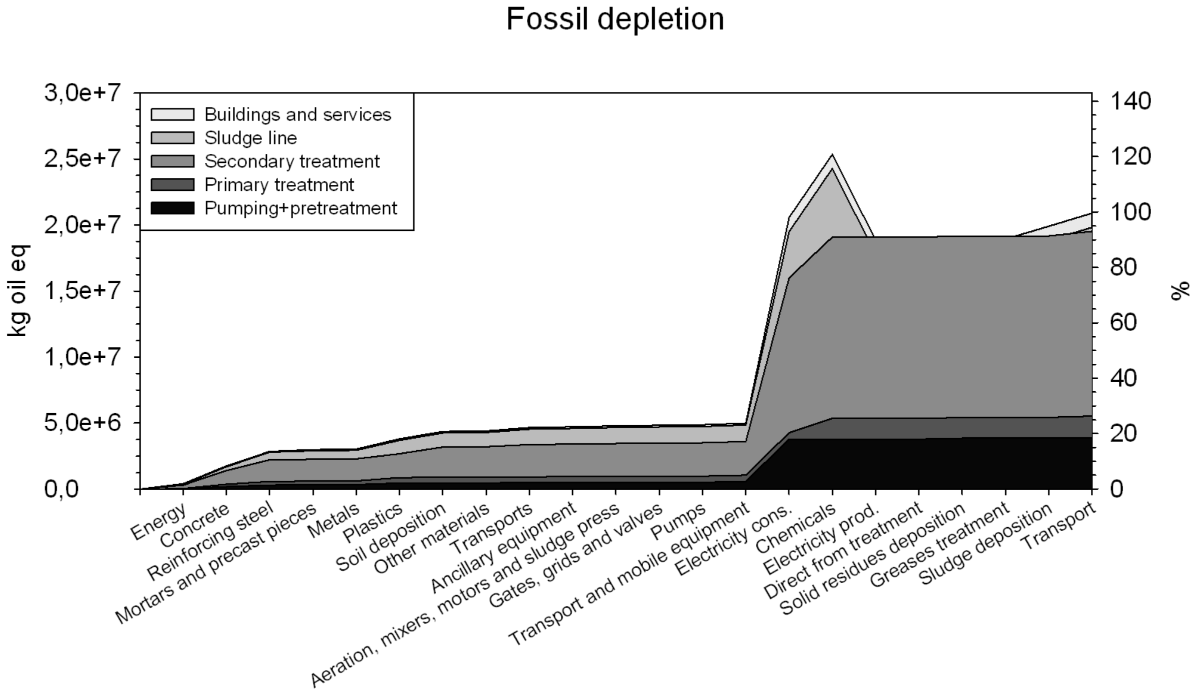

Fig. S-5: Cumulative impact for FD category of civil works, equipment and operation, differentiating between the different units.

ADDITIONAL ANALYSIS

Comparison of the impacts generated by civil works and equipment during the construction phase

In Fig. S-6, the impacts of civil works and equipment for the WWTP are shown. The contribution of each unit to the impact is differentiated. The impact of civil works (left columns in Fig. S-6) is larger than that of equipment (right columns in Fig. S-6) for every impact category analyzed.

For civil works, secondary treatment always makes the highest contribution to the impact. Its contribution is approximately 50% of the total for all categories, due to the huge amount of concrete and reinforcing steel used, which represents between 60 and 90% of the total impact of secondary treatment. The sludge line is the second-highest contributor to the impact, comprising 25 and 30% of the total of all studied categories. The pumping + pre-treatment unit contributes approximately 10-12%. In these cases, although concrete and reinforcing steel are the major contributors to the impact, glass fiber polyester plastic also makes a significant contribution, between 10 and 35%. Primary treatment contributes approximately 10%, and the unit with the lowest contribution is buildings and services, which contributes between 1 and 3%. In this last case, the contribution of concrete and reinforcing steel is lower than in the other cases. It is more important the contribution of other materials, such as bricks, precast concrete and different types of mortars used in the construction of buildings but the amount used is lower than the concrete and reinforcing steel used in the other units.

Considering that all equipment is replaced once during 20 years of operation, in the CC, OD, ME and FD categories, its impact compared with civil works is between 5 and 10%. Pumping + pre-treatment secondary treatment and the sludge line make similar contributions. In contrast, in FE, equipment contributes 26% to the total impact; in HT and MD, the equipment makes an impact of approximately 46% compared with civil works. In FE and HT, the unit that makes the highest contribution to the impact is the sludge line, primarily because the production of copper has a high impact in these categories, and the equipment in this line has a higher quantity of copper than the equipment used in other units. For MD, the unit that makes the highest contribution is pumping + pretreatment, primarily because in the pretreatment, much of the equipment contains a high quantity of chromium steel, a material that makes a high contribution to the impact in this category.

Foley *et al.*(2010) also analyzed part of the equipment of a WWTP separately from the civil works. In that case, not all the equipment was taken into account. For this reason, the weight of the equipment analyzed in our work is higher than that for the most similar WWTP in their work.

Foley *et al.*(2010) also considered civil works. In that work, the materials used are calculated estimating the volume of concrete used and relating it with the factors presented by Doka (2007). The quantity of the construction material used in our case is clearly larger and more diverse. Whereas in Foley *et al.*(2010), there are 15 different materials used for construction, in our case, there are more than 30 (see Table S-3). In our case, there are also higher quantities of materials used, particularly in the case of concrete and reinforcing steel. The material calculated in our work is more than 2 times higher, although the scale factor is considered. There are other materials as aluminum, chromium steel and copper, where the quantities calculated by Foley *et al.*(2010) are larger than in our case. In our case, we also have different materials, such as galvanized steel or cast iron, which shows that every case has constructive specificities and differences. In relation to plastic materials, in our case, we also have more diversity of materials and a generally higher weight of common plastic materials. Finally, different operations related to civil works such as excavation and transport are also larger in our case: The excavation volume is more than 3 times larger, and transports is even larger than that. Another difference is related to energy consumption. Foley *et al.*(2010) consider electricity as that consumed from the network. In our case, we considered that electricity is produced in diesel-electric generators at the same place of work, and we did not consider electricity consumption; we considered only diesel burned in electric generators.

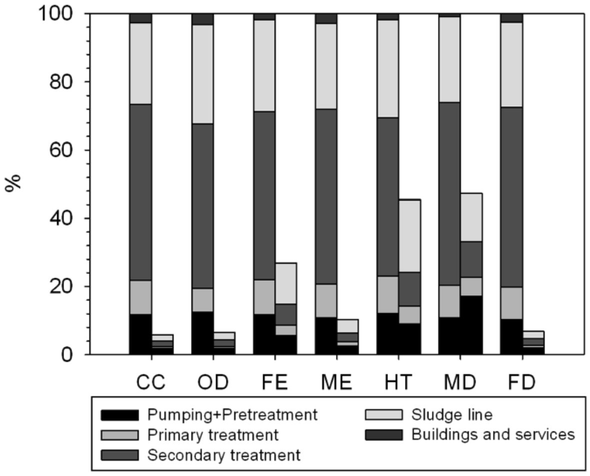

Fig. S-6: Comparison of the impact of civil works (left column) and equipment (right column), distinguishing all different units of the plant.

3.- SUPPLEMENTARY INFORMATION OF CHAPTER 4.3.

SUPPLEMENTARY TABLES

Table S-5: Complete inventory for the materials used for the construction of the 4 studied plants.

Concept	Navàs	Balaguer	Manlleu	L'Escala
Diesel burned in building machines (MJ)	1,06·10^{6}	1,78·10^{6}	6,87·10^{6}	9,30·10^{6}
Soil deposition (ton)	6,49·10^{3}	1,14·10^{4}	7,03·10^{4}	7,51·10^{4}
Soil transport (tkm)	1,24·10^{5}	2,47·10^{5}	2,20·10^{6}	1,29·10^{6}
Concrete (m^{3})	1,07·10^{3}	2,28·10^{3}	7,13·10^{3}	1,28·10^{4}
Reinforcing steel (kg)	5,06·10^{4}	7,83·10^{4}	5,61·10^{5}	1,13·10^{6}
Wire, steel (kg)	7,53·10^{2}	1,01·10^{3}	8,01·10^{3}	1,63·10^{4}
Steel, low-alloyed, for formwork (kg)	4,74·102	8,57·102	2,10·103	5,06·103
Steel, low-alloyed (kg)	3,92·10^{3}	9,48·10^{2}	4,50·10^{3}	8,93·10^{3}
Galvanized steel (kg)	5,96·10^{3}	5,18·10^{3}	3,54·10^{4}	1,98·10^{3}
Stainless steel (kg)	8,85·10^{2}	3,41·10^{2}	8,12·10^{3}	2,25·10^{3}
Brass (kg)	4,02·10^{0}	1,08·10^{2}	3,62·10^{0}	4,41·10^{1}
Aluminium (kg)	3,65·10^{2}	8,98·10^{2}	6,50·10^{2}	6,95·10^{3}
Cast iron (kg)	9,92·10^{2}	0	0	3,67·10^{3}
Copper (kg)	1,25·10^{1}	6,19·10^{1}	0	5,35·10^{1}
Wire, copper (kg)	4,22·101	6,29·101	0	3,60·102
Bronze (kg)	8,50·10^{-1}	1,97·10^{0}	0	8,67·10^{0}
PVC for formworks (kg)	2,04·10^{1}	5,58·10^{1}	9,02·10^{1}	2,17·10^{2}
PVC (kg)	6,60·10^{2}	7,94·10^{2}	2,05·10^{0}	1,28·10^{4}
Synthetic rubber (kg)	1,22·10^{2}	1,79·10^{3}	3,48·10^{3}	6,68·10^{2}
Polyurethane (kg)	1,29·10^{1}	3,30·10^{1}	2,33·10^{1}	5,31·10^{1}
Polystyrene for general purposes (kg)	3,95·10^{0}	1,37·10^{0}	0	1,23·10^{1}
Nylon (kg)	7,64·10^{-1}	1,38·10^{2}	0	2,99·10^{0}
Polyester (kg)	0	3,94·10^{1}	0	2,12·10^{1}
Polyethylene terephthalate (kg)	9,76·10^{-1}	3,39·10^{-1}	0	2,65·10^{2}
Extruded polystyrene (kg)	6,38·10^{0}	1,81·10^{2}	0	2,17·10^{3}
Polystyrene foam (kg)	0	2,99·10^{2}	0	0
HDPE	3,44·10^{0}	6,38·10^{1}	7,62·10^{2}	1,96·10^{3}
Expanded polystyrene (kg)	0	0	0	3,10·10^{2}
Silicone (kg)	2,83·10^{0}	9,15·10^{0}	6,39·10^{0}	1,10·10^{1}
Glass fibre reinforces polyester (kg)	7,52·10^{0}	7,92·10^{2}	0	5,20·10^{4}
Wood for formworks (kg)	2,94·10^{2}	7,95·10^{2}	2,73·10^{3}	4,74·10^{3}
Wood (kg)	7,22·10^{2}	9,07·10^{2}	3,12·10^{3}	4,20·10^{4}

Lime mortar (kg)	$3{,}46\cdot10^{4}$	$5{,}05\cdot10^{4}$	$8{,}58\cdot10^{4}$	$3{,}60\cdot10^{5}$
Cement mortar (kg)	$3{,}86\cdot10^{4}$	$3{,}29\cdot10^{4}$	$1{,}98\cdot10^{4}$	$1{,}12\cdot10^{5}$
Adhesive mortar (kg)	$5{,}53\cdot10^{3}$	$5{,}98\cdot10^{3}$	$1{,}01\cdot10^{4}$	$7{,}09\cdot10^{4}$
High requirements concrete (kg)	0	0	0	$1{,}57\cdot10^{2}$
Cover plaster (kg)	$4{,}51\cdot10^{3}$	$2{,}45\cdot10^{3}$	$7{,}03\cdot10^{2}$	$3{,}12\cdot10^{4}$
Concrete block (kg)	$1{,}56\cdot10^{5}$	$3{,}07\cdot10^{5}$	$2{,}43\cdot10^{5}$	$5{,}64\cdot10^{5}$
Brick (kg)	$6{,}26\cdot10^{4}$	$8{,}30\cdot10^{4}$	$3{,}15\cdot10^{4}$	$5{,}88\cdot10^{5}$
Lightweight concrete block (kg)	$1{,}81\cdot10^{2}$	$2{,}21\cdot10^{4}$	0	$1{,}62\cdot10^{5}$
Gypsum plasterboard (kg)	$3{,}36\cdot10^{2}$	$1{,}18\cdot10^{3}$	0	$5{,}05\cdot10^{3}$
Sand (kg)	$1{,}04\cdot10^{6}$	$1{,}89\cdot10^{6}$	$4{,}60\cdot10^{7}$	$1{,}07\cdot10^{8}$
Gravel (kg)	0	$1{,}76\cdot10^{6}$	$6{,}30\cdot10^{6}$	0
Release agents (kg)	$8{,}04\cdot10^{1}$	$2{,}92\cdot10^{2}$	$6{,}85\cdot10^{2}$	$1{,}70\cdot10^{3}$
Epoxy resin (kg)	$4{,}78\cdot10^{1}$	$3{,}50\cdot10^{0}$	$8{,}93\cdot10^{-1}$	0
Glass (kg)	$1{,}26\cdot10^{3}$	$6{,}04\cdot10^{1}$	$2{,}60\cdot10^{2}$	$1{,}03\cdot10^{3}$
Water (kg)	$8{,}66\cdot10^{3}$	$5{,}95\cdot10^{5}$	$3{,}25\cdot10^{4}$	$8{,}43\cdot10^{4}$
Paint (kg)	$1{,}17\cdot10^{2}$	$2{,}21\cdot10^{2}$	$2{,}04\cdot10^{2}$	$2{,}75\cdot10^{4}$
Varnish (kg)	$2{,}62\cdot10^{0}$	0	0	$6{,}48\cdot10^{1}$
Acrylic filler (kg)	0	$4{,}84\cdot10^{1}$	0	$1{,}78\cdot10^{2}$
Alkyd resin (kg)	0	0	0	$2{,}36\cdot10^{2}$
Asphalt (kg)	$1{,}17\cdot10^{3}$	$2{,}01\cdot10^{4}$	$1{,}06\cdot10^{4}$	$5{,}29\cdot10^{4}$
Organic solvents (kg)	$2{,}02\cdot10^{-1}$	$2{,}88\cdot10^{1}$	$6{,}15\cdot10^{-1}$	$1{,}82\cdot10^{2}$
Sanitary ceramics (kg)	$6{,}71\cdot10^{1}$	$6{,}06\cdot10^{1}$	0	$2{,}56\cdot10^{2}$
Switch (kg)	$1{,}85\cdot10^{1}$	$6{,}44\cdot10^{0}$	0	0
Rock wool (kg)	$2{,}91\cdot10^{1}$	$3{,}09\cdot10^{0}$	0	$2{,}36\cdot10^{3}$
Sealing compound (kg)	$3{,}89\cdot10^{1}$	0	0	0
Adhesive for metals (kg)	$2{,}15\cdot10^{0}$	0	0	$7{,}15\cdot10^{-2}$
Printed paper (kg)	0	$1{,}69\cdot10^{0}$	0	$3{,}02\cdot10^{1}$
Crushed rock (kg)	$2{,}27\cdot10^{5}$	$2{,}30\cdot10^{4}$	$2{,}36\cdot10^{2}$	$7{,}76\cdot10^{5}$
Polycarbonate (kg)	0	0	0	$1{,}28\cdot10^{-2}$
Compost (kg)	$2{,}35\cdot10^{4}$	0	0	$1{,}80\cdot10^{4}$
Cement (kg)	0	$1{,}07\cdot10^{5}$	0	0
Diesel burned in generators (MJ)	$2{,}15\cdot10^{4}$	$1{,}31\cdot10^{4}$	$5{,}02\cdot10^{3}$	$1{,}81\cdot10^{5}$
Material transport (tkm)	$1{,}69\cdot10^{5}$	$4{,}08\cdot10^{5}$	$2{,}83\cdot10^{6}$	$5{,}67\cdot10^{6}$

4.- SUPPLEMENTARY INFORMATION OF CHAPTER 4.4.

SUPPLEMENTARY TABLES

Table S-6: LCA results for the three different scenarios analyzed based in the CML 2 baseline 2000 v2.05

		Reference scenario		Bypass$_{100\%}$		Bypass$_{ecolflow}$	
Category	Unit	La Garriga	Granollers	La Garriga	Granollers	La Garriga	Granollers
Abiotic Depletion	kg Sb eq	121,093.17	156,349.04	0	185,189.13	40,364.39	175,575.76
Acidification	kg SO$_2$ eq	154,226.6	1,144,993.6	0	1,356,198.7	51,408.9	1,285,797
Eutrophication	kg PO$_4$--- eq	421,398	3,612,176	0	4,278,477	140,466	4,056,377
Global Warming (GWP100)	kg CO$_2$ eq	22,570,478	79,626,480	0	94,314,355	7,523,493	89,418,396
Ozone Layer Depletion	kg CFC-11 eq	0.93	1.20	0	1.42	0.31	1.35
Human Toxicity	kg 1,4-DB eq	7,845,675	62,542,642	0	74,079,237	2,615,225	70,233,705
Fresh Water Aquatic Ecotoxicity	kg 1,4-DB eq	9,298,599	158,110,330	0	187,275,310	3,099,533	177,553,650
Marine Aquatic Ecotoxicity	kg 1,4-DB eq	13,553,940,000	69,341,575,000	0	82,132,300,000	4,517,979,900	77,868,725,000
Terrestrial Ecotoxicity	kg 1,4-DB eq	215,971	102,709,860	0	121,655,680	71,990	115,340,410
Photochemical oxidation	kg C$_2$H$_4$	5,974.38	9,830.41	0	11,643.7	1,991.46	11,039.29