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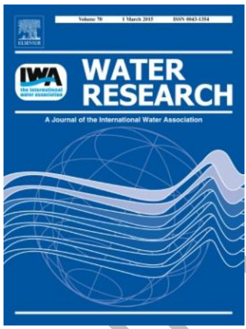

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Life cycle assessment of urban wastewater systems: Quantifying the relative contribution of sewer systems

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Abstract

This study aims to propose a holistic, life cycle assessment (LCA) of urban wastewater systems (UWS) based on a comprehensive inventory including detailed construction and operation of sewer systems and wastewater treatment plants (WWTPs). For the first time, the inventory of sewers infrastructure construction includes piping materials and aggregates, manholes, connections, civil works and road rehabilitation. The operation stage comprises energy consumption in pumping stations together with air emissions of methane and hydrogen sulphide, and water emissions from sewer leaks. Using a real case study, this LCA aims to quantify the contributions of sewer systems to the total environmental impacts of the UWS. The results show that the construction of sewer infrastructures has an environmental impact (on half of the 18 studied impact categories) larger than both the construction and operation of the WWTP. This study highlights the importance of including the construction and operation of sewer systems in the environmental assessment of centralised versus decentralised options for UWS.

Keywords: Construction; inventory; LCA; methane; sulphide; wastewater treatment

Abbreviations: 5-day biochemical oxygen demand (BOD_5); CH_4, methane; COD, chemical oxygen demand; CP, basic components; DIN, dissolved inorganic nitrogen; FU, functional unit; GHG, greenhouse gas emission; H_2S, hydrogen sulphide; H_2SO_4, sulphuric acid; HRT, hydraulic retention

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time; LCA, life cycle assessment; LCI, life cycle inventory; LCIA, life-cycle impact assessment; N, Nitrogen; N_2O, nitrous oxide; PE, population-equivalent; SE, sub-assemblies; SR, sewer subsets; UWS, urban wastewater system; WWTP, wastewater treatment plants.

1 Introduction

Life cycle assessment (LCA, standardised ISO-14044) has become one of the reference methods used to assess the environmental performance of processes over their complete life cycle from raw material extraction, infrastructure construction and operation to final dismantling. Several LCA studies have been conducted since the 1990s to assess the environmental impacts caused by wastewater treatment systems as reviewed in Corominas et al.(2013). **Table 1** complements the review of Corominas et al.(2013) and lists the published LCA studies so far on urban wastewater systems (UWS) which included sewer systems. These are grouped into i) studies based on carbon or energy footprint approaches i.e., with an inventory limited to greenhouse gas emissions (GHG) and/or cumulative or gross energy demand and ii) studies which followed a multi-criteria LCA approach i.e., with an inventory of all resource consumption and pollutant emissions. Table 1 shows for each of the studies the inventoried components of the sewer systems included in the stages of construction, operation and maintenance. The end-of-life stage was not included as there were scarce information in most studies about the chosen options for the dismantling of the used infrastructure and whether recycling was done for some materials.

All the reviewed studies with the exception of Benetto et al. (2009) and Tarantini et al. (2001) included the use of building materials for the sewer pipes, which generally include cement, PVC and metals. For 2 of these studies (Lassaux et al., 2007; Lemos et al., 2013), it is the only element that is taken into account. Only 8 studies out of 19 (Barjoveanu et al., 2014; De Sousa et al., 2012; Doka, 2009; Friedrich et al., 2009; Lundie et al., 2004; Remy et al., 2006; Slagstad and Brattebø, 2014; Venkatesh et al., 2009) included in the inventory the use of materials for other components of the sewer systems such as manholes and connection systems, and only 8 studies included the pumping stations as components (De Sousa et al., 2012; Friedrich et al., 2009; Gagnon et al., 2008; Godskesen et al., 2013; Lundie et al., 2004; Mouri and Oki, 2010; Slagstad and Brattebø, 2014; Uche et al., 2013). The inventory related to the civil works required to build the sewer on-site following the steps of excavation, backfill and compaction, was addressed in 3 papers (Doka, 2009; Herz and Lipkow, 2002; Uche et al., 2013). To a lesser extent, an estimation of energy demand or fuel consumption was accounted in 3 papers (Remy et al., 2006; Slagstad and Brattebø, 2014; Venkatesh et al., 2009) and the use of concrete and aggregates for pipes bedding was included in 7 papers (Borghi and Gaggero, 2008; Doka, 2009; Gagnon et al., 2008; Herz and Lipkow, 2002; Remy et al., 2006; Slagstad and Brattebø, 2014; Uche et al., 2013). Finally, none of the papers included the paving of the roads using bitumen, which is a product of the petroleum refining industry, whose environmental burdens can be significant because it is energy and resource-intensive (Santero et al., 2010). Concerning maintenance operations on the sewer systems, only Barjoveanu et al. (2014) assessed ongoing expenditures in terms of diesel consumption, replacement piping materials and waste generation, while Lundie et al. (2004) estimated additional materials to cope with system upgrades and maintenance. As for operation, electricity consumption in pumping stations was provided in 8 studies (Barjoveanu et al., 2014; Friedrich et al., 2009; Gagnon et al., 2008; Godskesen et al., 2013; Lundie et al., 2004; Mouri and Oki, 2010; Slagstad and Brattebø, 2014; Uche et al., 2013). Direct emissions generated during the operation of sewer systems such as methane (CH_4) and hydrogen sulphide (H_2S) were never accounted for in the reviewed studies. Methane, in addition to being explosive at low concentrations, is one of the main GHG contributors to global warming with a lifespan of approximately 12 years and a global warming potential of approximately 21–23 times higher than carbon dioxide (Doorn et al., 2006). The build-up of H_2S in the sewer atmosphere causes major detrimental effects such as adverse acute health effects (H_2S was reinstated in the Toxics Release Inventory program in 2012 (US EPA, 2013)) and corrosion which decreases the life-span of the sewer system components (Boon, 1995; Boon et al., 1998; Hvitved-Jacobsen, 2002). In summary, none of the studies conducted a comprehensive inventory including the construction and operational stages for the sewer systems.

Hence, the main goal of this paper is to propose a holistic environmental assessment (performed by a life cycle assessment) of UWS based on a comprehensive inventory including detailed construction and operation of sewer systems and wastewater treatment plants. A detailed inventory enables the appraisal of sewer system contributions to the overall environmental impacts of UWS.

(Insert Table 1)

2 Materials and methods

2.1 Comprehensive inventory approach

Figure 1 and **Figure 2** illustrate the proposed comprehensive inventory framework for sewer systems and WWTPs including the construction, operation and end-of-life, after adapting the graphical framework proposed for WWTPs in Foley et al. (2010) and extending with the sewer system.

(Insert Figure 1 here)

(Insert Figure 2 here)

2.2 Life Cycle Assessment of a real system

The general methodology described in the ISO 14040 and 14044 standards (ISO 14040, 2006; ISO 14044, 2006) was applied in this study through the 4 following steps: Goal & scope definition, inventory analysis, impact assessment and interpretation of results.

2.2.1 Goal & scope definition

The goal of this assessment is to compare the relative contributions on the environmental impacts generated from the construction and operation of the sewer system and the WWTP providing service to the town of Grabels (Montpellier conurbation, South of France). This system is designed to transport and treat sewage generated by 5200 population-equivalents (personal communication Veolia-Eau). With an average population density of approximately 1700 capita/km², the urban development of Grabels features a small dense city centre and a moderate urban sprawl in its periphery. The studied sewer system has 40 km of pipes, which make up a gravity-fed network with a main pipeline diameter of 200 mm, followed by a pumping station which raises the wastewater flow towards the Montpellier gravity sewer system. The existing Grabels sewer system features a 500 meter-long linking sewer section transporting wastewater by a pumping station over an elevation of 12 meters to the main sewer lines of the Montpellier sewer network via a main pipe with a diameter of 200 mm (**Figure 3**). The average hydraulic retention time (HRT) is 51 minutes (HRT variation = 0.5-2 h).

Wastewater treatment is performed at the Montpellier WWTP by a conventional activated sludge technology which biologically removes nitrogen and features a selective chemical precipitation of phosphates with iron (III) chloride as described in Boutin et al. (2011). The conventional sludge conditioning process starts with a thickening step on a belt thickener then is followed by a lime flocculation and, finally, the sludge is conveyed to a belt filter press for dewatering to obtain a stabilised, dry-cake sludge.

(Insert Figure 3 here)

The upstream system boundary is defined as the raw wastewater inflow to the sewer system. The downstream system boundary is set to release treated effluent from the WWTP to surface water and is the end-of-life for waste and by-products arising from the wastewater treatment. The modelled life cycle stages of the sewer system include construction (materials, pumps, transport, civil engineering works and related machinery), operation (electricity used by pumping stations and unwanted air emissions) and finally dismantling and end-of-life options of the sewer components (e.g., partial recycling of some materials such as cast iron manholes) (**Figure 1**). Similarly, we modelled the same life cycle stages for the WWTP system, from infrastructure building, operation and maintenance, to final dismantling and the end-of-life options for waste and by-products arising from the wastewater treatment (**Figure 2**).

Hence, pumps, electricity and ancillary chemicals required to operate the WWTP have been included. The end-of-life stages for both systems included dismantling of the infrastructures and a partial recycling for certain metals (40% for copper) and total recycling for others (aluminium, cast iron, stainless steel), while other building materials are sent to final disposal (e.g., concrete), landfill and/or municipal incineration (e.g., plastics). The sludge produced in the WWTP was assumed to have the following end-of-life which corresponds to usual French practice in sludge handling: 70% agricultural spreading, 20% incineration and 10% landfilling (Risch et al., 2012). The selected functional unit

(FU) is 1 day of operation for the urban wastewater system, i.e., the collection and treatment of wastewater generated by 5200 population-equivalents (PE) (corresponding to a BOD_5 load of 312 $kg \cdot d^{-1}$). The lifespan for both WWTPs and sewer system infrastructures is assumed to be 30 years.

2.2.2 Life cycle inventory of system components

As shown in **Figure 1** and **Figure 2**, the life cycle models of the sewer system and the WWTP are constructed from available processes using the SimaPro 7.3 LCA software package developed by Pré Consultants. The foreground life cycle inventory (LCI) data for the WWTP construction is compiled directly from detailed design documents and vendor-supplied information. Emissions to water (particulate phosphorus and dissolved phosphates, organic nitrogen, ammonium, nitrites, nitrates) and to air (nitrogen gas, nitrous oxide, carbon dioxide and methane) are estimated applying mass balances for phosphorus, nitrogen and carbon compounds in an activated sludge system (Boutin et al., 2011).

For the sewer system construction, a modular inventory was developed on two levels: (i) the level of basic components (CP) which includes linear sections of concrete pipes, concrete manholes or pumping stations, (ii) the level of combinations (or assemblies) of basic components. This second level includes sub-assemblies (SE) and sewer subsets (SR), which are network items combining two or more CP elements and require civil engineering works and equipment for their setup. SE elements refer to sewer mains linear sections, while SR elements describe the PVC pipes servicing a determined number of households in residential subdivisions. The detailed construction inventory data for the sewer system is attached in the Supporting Information (Appendix A, Section S2).

Estimates of dissolved inorganic nitrogen (DIN) emissions to ground and surface water from leaking sewer infrastructures for the serviced Grabels area were calculated by using the factor of 10.9 $kgDIN \cdot d^{-1}$ expressed as total N (geometric mean value from different scenarios investigated in Divers et al., 2013 as described in Supporting Information, Appendix A Section S2.3 in Table 2-4). Air emissions of CH_4 and H_2S were estimated using the SeweX model l (Guisasola et al., 2008; Sharma et al., 2008a, 2008b), obtaining values of 0.67 kg COD-$CH_4 \cdot d^{-1}$ and 1.33 kg S-$H_2S \cdot d^{-1}$, respectively. Electricity consumption from the pumping stations was obtained from Veolia Eau. It was assumed that no N_2O was emitted from the sewer system.

The LCI includes all materials, chemicals, energy inputs required to build/dismantle, operate and maintain the sewers system and the WWTP. The inventory of air and water emissions includes those occurring during wastewater transport and treatment (primary emissions) as well as secondary emissions (e.g., following land sludge application). **Table 2** summarises key inventory data obtained for this study with values relative to the functional unit of the urban wastewater system in Grabels.

It should be noted that the total nitrates (NO_3^-) emissions to surface water from the WWTP are estimated on the basis of secondary treated effluent quality and land spreading of the stabilised sludge. A conservative scenario was chosen for the land spreading of sludge (Risch et al., 2012) where there is significant leaching of nitrates not retained in the topsoil compared with the nitrates inputs from WWTP secondary treated effluents. With this scenario, almost 75% of nitrates originate from farmland runoff while 25% are from secondary WWTP effluents.

The background life cycle inventory data (e.g., LCI of 1 kWh electricity or 1 tonne of concrete) was provided by the Ecoinvent LCI database v2.2 (SCLCI, 2010), as implemented in Simapro 7.3. These process data were entirely European-based and were adopted without modification for this study.

(Insert Table 2 here)

2.2.3 Uncertainty assessment

The uncertainty associated to the inventory was estimated by using the Monte-Carlo routine in SimaPro (1500 runs). The uncertainty range for each parameter is provided in **Table 3**. Uncertainty ranges for unit processes taken from the Ecoinvent database were defined by the "data pedigree" algorithm available in SimaPro as proposed by Weidema and Wesnaes (1996). This algorithm relates the datum uncertainty to its source characteristics – i.e. reliability of the source, representativeness of the sample, currency of the period, geographical correlation, technological correlation and sample size. The uncertainty ranges associated to the amount of materials used, the transportation distances, the duration of civil works operations, the amount of energy and ancillary chemicals used during WWTP operation were defined according to expert judgement as described in **Table 3**. The uncertainties associated to the emissions from the sewer were estimated after running multiple simulations and varying key model inputs and parameters. Uncertainties related to emissions from

WWTP operation were obtained from literature. Depending on the emissions data sources (from literature or from the SeweX model for H_2S and CH_4), the uncertainty was modelled using normal or log-normal distribution to better fit with the available data and also to avoid negative random values of emissions during the Monte-Carlo runs. Based on this uncertainty data, the 95% confidence interval of cumulative LCI results is calculated and shown in the results plots.

(Insert Table 3 here)

2.2.4 Life cycle impact assessment methods (LCIA)

The impacts were calculated using the ReCiPe Midpoint (H) V1.07 method (Goedkoop et al., 2009). This method was chosen for the proposed harmonised impact assessment framework at two levels in the cause-effect chain, that is, an environmental mechanism, of an impact category. First, midpoint indicators quantify the relative importance of emissions or extractions that occur due to human operations in terms of reference substances (e.g., CO_2-eq for the global warming category, kg SO_2-eq for acidification). Next, endpoint indicators are calculated to reflect differences between stressors further in the cause-effect chain and are of direct societal concern (e.g., human health, ecosystem quality and resources).

In the characterisation step, the impact score is determined by multiplying the quantity of substance emitted to the environment by its specific characterisation factor. The score defines the potential impact per unit mass of the substance (e.g., 1 kgCH_4 = 25 kgCO_2-eq). Regarding H_2S emissions to the atmosphere, no characterisation factors are defined yet in ReCiPe V1.07, so we implemented factors from the CML 2001 V2.05 method to include categories on the impacts on human toxicity and terrestrial acidification. For the dissolved inorganic nitrogen (DIN), we selected ammonia (1.0 kg N-eq) for the nitrogen characterisation factor, which impacts the marine eutrophication category. Further information on the assumptions regarding these characterisation factors is given in the Supporting information (Appendix A, Section S3, Table 3-1).

3 Results

3.1 Impact assessment at the midpoint level

Figure 4 presents the LCA results obtained from the life cycle analysis of the Grabels UWS on the 18 midpoint impact categories. This graph shows the respective contributions of the WWTP and different elements included in the sewer system. The resulting graph shows that the sewer system generates larger impacts than the WWTP for 10 out of the 18 midpoint categories. Among these 10 impact categories, the construction phase of the sewer infrastructure appears to be the main contributor (90% of the total impact) in the natural land transformation category, approximately 86% in the categories of terrestrial ecotoxicity and marine ecotoxicity, 78% in the water depletion category, and around 65% in the categories of climate change, particulate matter formation, and freshwater ecotoxicity. A breakdown of the sewer infrastructure construction (**Figure 5**) reveals that onsite civil works required to build the sewers have the largest contributions on 6 impact categories (including climate change). Next, road rehabilitation works (bitumen paving) and the concrete aggregates (pipes bedding) are equally important as they both have contributions over 50% in 4 impact categories. Lastly, the impacts from the pipes materials are comparatively smaller.

The main contributor to the 8 other impact categories is the WWTP. The WWTP causes 95% of the impacts on freshwater eutrophication and fossil depletion, 81% on agricultural land occupation, and around 70% on marine eutrophication, ionising radiation and metal depletion. These large contributions on the categories dealing with aquatic ecosystems are linked to emissions to air, water and soil arising during wastewater treatment and sludge end-of-life processes, especially agricultural land spreading. The impacts on fossil depletion, and to a lesser extent on ionising radiation, are linked to electricity consumption during WWTP operation (mostly in the aerated tank). While the impacts on metal depletion and agricultural land occupation are dominated by the consumption of chemical reagents during WWTP operation. **Figure 6** presents the breakdown of WWTP contributions between infrastructure, operation and emissions/discharges. Three categories of impacts are particularly affected by the infrastructure, which represents 93% of the impact on terrestrial ecotoxicity, 61% on the marine ecotoxicity category and 82% of urban land occupation. Both terrestrial and marine ecotoxicities are mainly driven by diesel fuel consumption during the civil works for the construction phase.

(Insert Figure 4 here)

(Insert Figure 5 here)

(Insert Figure 6 here)

LCA results showed that the direct gas emissions generated during the sewer operation do not contribute significantly to overall environmental impacts. CH_4 emissions scored less than 1% in the climate change impact category. Impacts caused by H_2S emissions are relatively high at approximately 20% in the terrestrial acidification category. However, DIN losses from leaking sewers contribute to a significant impact of 30% in marine eutrophication.

3.2 Impact assessment at the endpoint level

At the endpoint level, as shown in **Figure 7**, results confirm the importance of impacts arising from the construction of the sewer system. Indeed, on the human health and ecosystems endpoint categories the sewer infrastructure (construction and dismantling) accounts for 64% of the impacts, while the WWTP generates approximately 35% of the impacts. Sewer-generated CH_4 and H_2S emissions, together with electricity consumption during sewer operation comprise the remaining 1%.

In the resources consumption endpoint category, the WWTP is responsible for most of the impact (92.3%), while the sewer infrastructure causes 3.7% and the electricity consumption of the pumping station induces the remaining 4% impact. This consequent impact is explained by the large amount of electricity required for operation of the aerated tanks in the WWTP.

(Insert Figure 7 here)

3.3 Uncertainty assessment results

Figure 8 shows the associated 95% confidence intervals from the Monte Carlo analyses on the endpoint scores (human health, ecosystems and resources) for the entire UWS, but also for the sewer system (orange) and the WWTP (blue), including their respective emissions. Sewer emissions are not significantly contributing to the endpoint scores, whereas concerning the WWTP, its emissions are contributing to approximately half of its endpoint damage score. There is a significant uncertainty range on direct WWTP emissions linked with the large uncertainty on the N_2O emission factor, for which substantial discrepancies are found in the literature.

(Insert Figure 8 here)

4 Discussion

After presenting a comprehensive inventory for sewer systems and WWTPs and applying it to a real case study to assess the relative contribution of sewer systems to the overall impacts of UWS, we can state that the sewer network infrastructure cannot be neglected. Studies which omitted civil works and/or road refection (bitumen) and/or concrete aggregates (pipes bedding) in their inventories underestimated the impacts of sewer infrastructure. This is the case for most of the studies presented in **Table 1**, except for Doka (2009) and Herz and Lipkow (2002). In any case, it is not acceptable to assume that construction can be omitted based on previous results from literature. Whether to include or not the construction stage depends of the case and of the goal of the study and system boundaries. Nowadays, new inventory data is available (in Supporting Information of this paper) which facilitates the inclusion of construction-related processes. Further, some detailed aspects on the novelties included in the study are discussed.

4.1 Sewer system construction

The results obtained in this study show that the sewer system construction significantly contributes to the overall impacts of the UWS (superior or equal to 40%) in 12 out of 18 impact categories. These results are relying on the initial assumption on the lifespan of the infrastructure (which is set at 30 years without any maintenance, for both the sewer system and the WWTP). Indeed, the "potential" environmental impacts considered in the scope of a LCA study are related to the fulfilment of a functional unit, which is defined in this study as the normal operation of the UWS for one day. This means that the total environmental burdens arising from the construction are to be divided by the lifespan of the system. UWS infrastructure deterioration has multiple causes and depends of operating and maintenance conditions, of materials and technology used and of the quality of their implementation, of soil conditions, etc. Insofar as no direct relationship between the usable life of the assets and the operating and maintenance conditions is available in scientific literature, we have assumed 30 years lifespan duration (the duration commonly used for economic depreciation).

In addition, a basic sensitivity analysis on the sewer infrastructure lifespan is presented in supplementary information (Appendix A) with the reference lifespan of 30 years used in this study (without any maintenance modeled), a reduced lifespan of 15 years and an extended lifespan of 100 years. A reduction of half of the usable life of the sewer networks (e.g. from 30 to 15 years) translates into an increase in the range of 40 to 50% in the categories most concerned with the civil works and the associated diesel consumption, which are climate change, terrestrial, freshwater and marine ecotoxicity. Other categories also strongly impacted include photochemical oxidant formation, particulate matter formation, and natural land transformation with the disposal processes of concrete and bitumen. An increase of the lifespan from the reference 30 years to 100 years shows a reduction in the range of 45 to 60% in the same midpoint categories. Hence, the relative contribution of sewer systems to the overall environmental impacts would be larger for shorter lifespans and smaller for longer lifespans as this is more driven by construction rather than operation aspects.

Finally, the uncertainty associated to sewer construction is quite low as shown on **Figure 8**. For the interpretation on this result, it should be noted that this uncertainty is estimated (i) from expert judgement for foreground system (quantity of materials and hours of civil work as described in **Table 3**) and (ii) from data quality indicators for all background processes used from Ecoinvent database.

4.2 UWS emissions to air

Detrimental compounds generated during the operation of sewer systems have been accounted for the first time in a LCA study of a UWS. H_2S and CH_4 are two of the most harmful substances emitted from sewers worldwide (Foley et al., 2009; Hvitved-Jacobsen, 2002). However, the dissolved CH_4 concentration range predicted by the SeweX model for the studied sewer system in Grabels (3-23 mg COD-CH_4/L, just downstream of the pumping station) was significantly lower than those reported in other sites in Australia (20-120 mgCOD-CH_4/L) (Foley et al., 2009; Guisasola et al., 2008). These low emissions are linked to the specific configuration of the Grabels sewer system. Indeed, this sewer network has a short length and features almost exclusively gravity pipes (98%), hence only 2% of the network is pressurised (rising mains pipes). As reported in the literature, in-sewer H_2S and CH_4 production occurs primarily in anaerobic rising mains with long hydraulic retention times (Hvitved-Jacobsen, 2002; Sutherland-Stacey et al., 2008). In general, longer pressurised rising mains networks with longer retention times and more pumping stations are expected to generate more GHG emissions (Gutierrez et al., 2009). Although H_2S emissions were around 50% lower than those reported in Sharma et al (2008a), (1.33 kg S-$H_2S \cdot d^{-1}$ vs 2.1-2.5 kg S-$H_2S \cdot d^{-1}$), the impacts caused by H_2S emissions were still relatively consequent with approximately 20% in the terrestrial acidification category.

In this LCA study, we have only considered the direct environmental impacts of H_2S and CH_4 emissions to air. However, indirect effects (e.g., corrosion of pipes and infrastructures induced by H_2S) will have to be included in future assessments. When H_2S is present in the sewer atmosphere, it can be biologically converted to sulphuric acid (H_2SO_4) and lead to corrosion processes, leading to losses of concrete mass, cracking of the sewer pipes and ultimately, structural collapse (Joseph et al., 2012). The rehabilitation and replacement of corrosion-damaged sewers entails very high costs. It is estimated that the annual cost of concrete corrosion within the water and wastewater infrastructure is about $36 billion in USA (Koch et al., 2002). Moreover, this cost is expected to increase as the ageing infrastructure continues to fail (Sydney et al., 1985; US EPA, 1991). Therefore, the lifespan of the sewers could be significantly reduced with consequences on maintenance and rehabilitation expenditures, as well as road rehabilitation. The lifespan choice for the sewer infrastructure (30 years of useful lifetime) is one of the main hypotheses that might influence the overall contribution of the sewer infrastructure to environmental impacts. Based on these first results, further work is needed to investigate longer sewer lifespans and should include maintenance expenditures.

Recent research on municipal gravity sewers shows contrary to current international (IPCC) guidance (Doorn et al., 2006) that these sewers are a likely source of N_2O and develops a presumptive emission factor for gravity sewers which is comparable to the IPCC-adopted value of Czepiel et al.,

(1995) for joint primary and secondary wastewater treatment (Short et al., 2013). This warrants that N_2O emission potential should be further investigated (by combining models and experimental results) from a broader system perspective in order to identify clearly the respective contributions of the sewer system and WWTP. It should be noticed that there is still no consensus on the extent of N_2O emissions thus making difficult to discriminate between its uncertainty and variability. As a consequence the results of Monte Carlo simulations, showing a significant uncertainty range as defined in Table 3 and illustrated in Figure 8, need to be considered in the light of this limitation.

4.3 Sewer system leakages

The effect of DIN emissions to ground and surface water has a significant impact (30%) on marine eutrophication. It should be noticed that there is a lack of consolidated data regarding this emission factor which is based on a study out of Pittsburgh, USA (Divers et al., 2013). These flows are proportional to several parameters associated to leaks in sewers such as pipes technology, age, soil conditions, topography, etc. Therefore, the associated impacts should be interpreted carefully insofar as representativeness of those flows for other cities is definitely not consolidated and not quantifiable.

4.4 Usefulness of the approach

The outcomes of this study add also a relevant contribution to the debate between centralized versus decentralized options for UWS. As stated in Libralato et al. (2012) traditional centralized approaches are changing in favor of new decentralized treatment levels. Keeping in mind that decentralized options do not require the construction of large sewer systems, the outcomes of this paper suggest that decentralized systems would lead to more environmentally friendly UWS when combined with emerging technologies for wastewater recovery and reuse.

An interesting perspective on the further extension of this work would be to investigate how the results may be different for a larger or more densely populated city. This may include the scale effect as well as the urban form effect (dense versus sprawled development) for both components of the system: sewer & WWTP. A recent peer-reviewed literature paper (Loubet et al., 2014) shows that a large part of impacts associated to the entire urban water system are generated after the tap (if water heating is not considered). By demonstrating that sewers have a greater contribution than expected (compared to previous LCAs), the results of the present study hope to promote further research in this direction.

5 Conclusions

For the first time this study proposed a comprehensive life cycle analysis of an urban wastewater system comprised of a sewer network and a WWTP. This work highlights the importance of sewer-related impacts, which have to be understood to inform decision making in the field of urban wastewater treatment. Overall, the study shows that sewer systems have to be included in the environmental analysis of wastewater treatment infrastructures because their contributions to a wide range of impacts are very relevant, especially those arising from the construction phase. The main findings of the study are:

– Contributions to environmental impacts of the sewer system were often assumed as negligible in previous studies based on incomplete sewer system inventories.
– The sewer system inventory should not only include construction materials (pipes, cement, miscellaneous components) as included in previous studies. It should also take into account civil works (excavation, backfill), pipes bedding (concrete aggregates) and connections as well as road rehabilitation operations (bitumen paving).
– It has been shown that with a comprehensive inventory of its infrastructure, the sewer system has greater contributions than the WWTP on half of the studied range of impact categories.
– Sewer-generated CH_4 and H_2S emissions have overall limited contributions to the range of impacts covered in the life cycle methodology.
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Supporting information

Appendix A.

A description of the modular inventory used to build the sewer system model is given in this supporting information file, as well as a description of the assumptions leading to the assessment of the energy consumption in the sewer system, and details concerning the impact assessment phase (chosen method) to ensure the reproducibility of this Life Cycle Assessment (LCA).

Appendix B.

Further supplementary data regarding the Life Cycle Inventory (background datasets) of the sewer system is available in this pdf file.

Appendix C.

A description of the LCI datasets and calculated LCIA results for the sewer and WWTP systems are provided in this Excel file.

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List of Tables and Figures

		Construction						Operation		Maintenance
		Building materials and equipments				Works		Direct	Indirect	
Stages included in the LCA inventory of sewer systems → **Authors ↓**	Com-ments	**Pipes** (cement, PVC, metals)	**Various** manholes & connection systems	**Pumping stations** (infrastruc-ture)	**Concrete & aggregates** for pipes bedding and other uses	**Civil works** to build the sewer on site (excavation, backfill, compaction)	**Road rehabilitation on** due to excavation (including bitumen)	**Sewer-generated emissions** of gas (CH_4, H_2S) and nitrogen leaks	**Pumping stations** (Electricity)	**Sewer maintenance expenditures** (renewal, replacement & repair interventions on pipelines, etc.)
Carbon or energy footprint approaches (i.e. inventory limited to greenhouse gas emissions and/or cumulative or gross energy demand)										
(Borghi and Gaggero, 2008)		X	1		X					
(De Sousa et al., 2012)		X	X	X						
(Herz and Lipkow, 2002)		X	1		X	X				
(Mouri and Oki, 2010)		X		X		1			X	
(Venkatesh et al., 2009)		X	X			2				
Multicriteria LCAs (i.e. inventory of all resource consumption and pollutant emissions)										
(Barjoveanu et al., 2013)		X	X						X	X (Diesel consumption, piping materials and waste produced)
(Benetto et al., 2009)	(a)									
(Doka, 2009) – Ecoinvent database v2.0	(b)	X	X		X	X				
(El Sayed et al, 2010)	(c)									
(Friedrich, Pillay, 2009)		X	X	X					X	
(Gagnon et al., 2008)		X		X	X				X	
(Godskesen et al., 2013)		3	1	X	1	1			X	

(Lassaux et al., 2007)		X			1	1				
(Lemos et al., 2013)		6								
(Lundie et al, 2004)	(d)	X	X	X	1				X	X additional materials estimated to cope with system upgrades and maintenance included
(Remy et al., 2006)		X	X		4	5				
(Tarantini et al, 2001)	(e)									
(Uche et al, 2013)		X		X	X	X	1		X	
(Slagstad et al, 2014)		X	X	X	X	2			X	
Current study		X	X	X	X	X	X	X	X	*Not yet included (30-yr lifespan, no maintenance included)*

<u>Legend:</u>

X: included; **1:** not explicitly specified in the paper, considered not-taken into account; **2:** only fuel consumption; **3:** Ecoinvent database v2.0 was used (Doka, 2009); 4**:** partially taken into account; 5: only energy demand; **6:** f or simplification, all pipes were considered to be PVC pipes

<u>Comments:</u>

(a) The authors excluded the infrastructures (mainly sanitation equipments and sewer network) from the scope of their study on the basis that their contributions to environmental impacts were considered negligible according to (Remy et al., 2006).

(b) This Life Cycle Inventory (LCI) report of Waste Treatment Services was conducted for the Ecoinvent database. It includes a readily useable inventory for multicriteria LCAs. No pumping energy required as the wastewater is carried through the sewers with gravity and gentle slopes.

(c) « The research included assessment of the water treatment plants, water distribution system, wastewater treatment plants (WWTP) and the sewerage system. Only the operational phase of the infrastructure is taken into consideration in the LCA because it has the highest contribution to the total environmental impact of the life cycle (Friedrich and Buckley, 2001; Lundie, 2004). »

(d) « Impacts of the production of the construction materials are included, but energy used during the construction process is excluded. This is a simplification based on other wastewater case studies (Tillman et al, 1998 and Lundin and Morrisson, 2002) which have concluded that operational impacts are more important than asset creation impacts and that material production is the most important part of the asset creation impacts. »

(e) This study does not include in its LCI the equipments, waterworks and buildings for processing and distributing clean drinking water and wastewater : it was assumed to remain unchanged both in "existing" and in the "innovative" scenario. The focus of the LCA study was to analyse the chemicals, energy, materials consumption and their transport to the final use location.

Table 1 - Literature review of sewer inventory models used in LCA of urban wastewater systems

Functional Unit: Collection and Treatment of a wastewater load from **5200 PE/d** (≡312kgBOD5/d)	Activated sludge, enhanced P precipitation, sludge conditioning with lime	Sewer model representing the current Grabels gravity-fed network
Urban wastewater system (UWS)	WWTP	Sewer system
Electricity consumption, kWh (use stage)	670	31.6
Sludge production, kg DM (dry matter)	769	N/D
Ancillary chemicals consumption, kg		
Conditioning agent (lime, hydrated)	199	0.00
Precipitating agent (iron chloride (III))	95.7	0.00
Flocculant (polymer)	0.26	0.00
Principal air emissions, kg	WWTP	Sewer system
CO_2	427	N/D
CH_4	0.75	0.89
N_2O	1.65	N/D
H_2S	0.00	1.41
Water Emissions, kg	WWTP	Sewer system
P (particulate)	0.89	N/D
PO_4^{3-}	2.72	N/D
N (organic)	1.55	10.90
NO_2^-	1.05	*
NO_3^-	100	*
NH_4^+	2.07	*
Total N (inorganic) : NO3- + NO2- + NH4+	*103*	*10.90*

Table 2. Summary of key inventory data assumptions for the urban wastewater system servicing Grabels (5200 PE). Functional Unit: Collection and treatment of a wastewater load from 5200 PE/d (equivalent to 312kgBOD5/d). N/D means not defined, *means that only total inorganic nitrogen is quantified.

Type of component	Inventory (LCI) component	LCI Data source	Distribution type	Uncertainty characterisation (1)	Uncertainty source
Infrastructure construction	Materials manufacturing (kg)	Ecoinvent database	Ecoinvent (2)		
	Materials transportation distance from manufacturing to local building site (t.km)	Current study	normal	CV=30%	see (3)
	Amount of material used (kg)	Current study	normal	CV=5%	see (3)
	Civil work teams (h)	Current study	normal	CV=15%	see (3)
Operation	Electricity production (kWh)	Ecoinvent database	Ecoinvent (2)		
	Amount of electricity consumption (kWh)	Current study	normal	CV=10%	see (3)
	Ancillary chemicals production (kg)	Ecoinvent database	Ecoinvent (2)		
	Amount of ancillary chemicals used (kg)	Current study	normal	CV=10%	see (3)
Emissions	Sewer-generated CH_4 emitted to air	Current study	normal	M= 0.89 kgCH_4/d, SD=0.53	see (4)
	Sewer-generated H_2S to air	Current study	normal	M= 1.41 kgH_2S/d, SD=0.0106	see (4)
	Dissolved inorganic nitrogen leaks from sewers to ground/surface water	Current study	lognormal	GM=10.9 kgDIN/d, GSD^2= 1.712	see (4)
	WWTP emission of CH_4	Current study	lognormal	GM=0.128 gCH_4/PE/d, GSD^2=1.21	see (4)
	WWTP emission of N_2O	Current study	lognormal	GM=0.1462 gN_2O/PE/d, GSD^2=26.99	see (4)

(1) CV= coefficient of variation, M=mean, SD=standard deviation, GM= geometric mean, GSD=geometric standard deviation
(2) Uncertainty from the Ecoinvent database when defined, assessment of data quality based on a pedigree matrix (Weidema and Wesnaes, 1996). For our system, up to 70% of the Ecoinvent processes have available uncertainty information.
(3) Estimated uncertainty (SD) based on expert judgement
(4) See supplementary information (Appendix A) for details of uncertainty assessment and associated references

Table 3. Randomisation parameters for the different components of the system

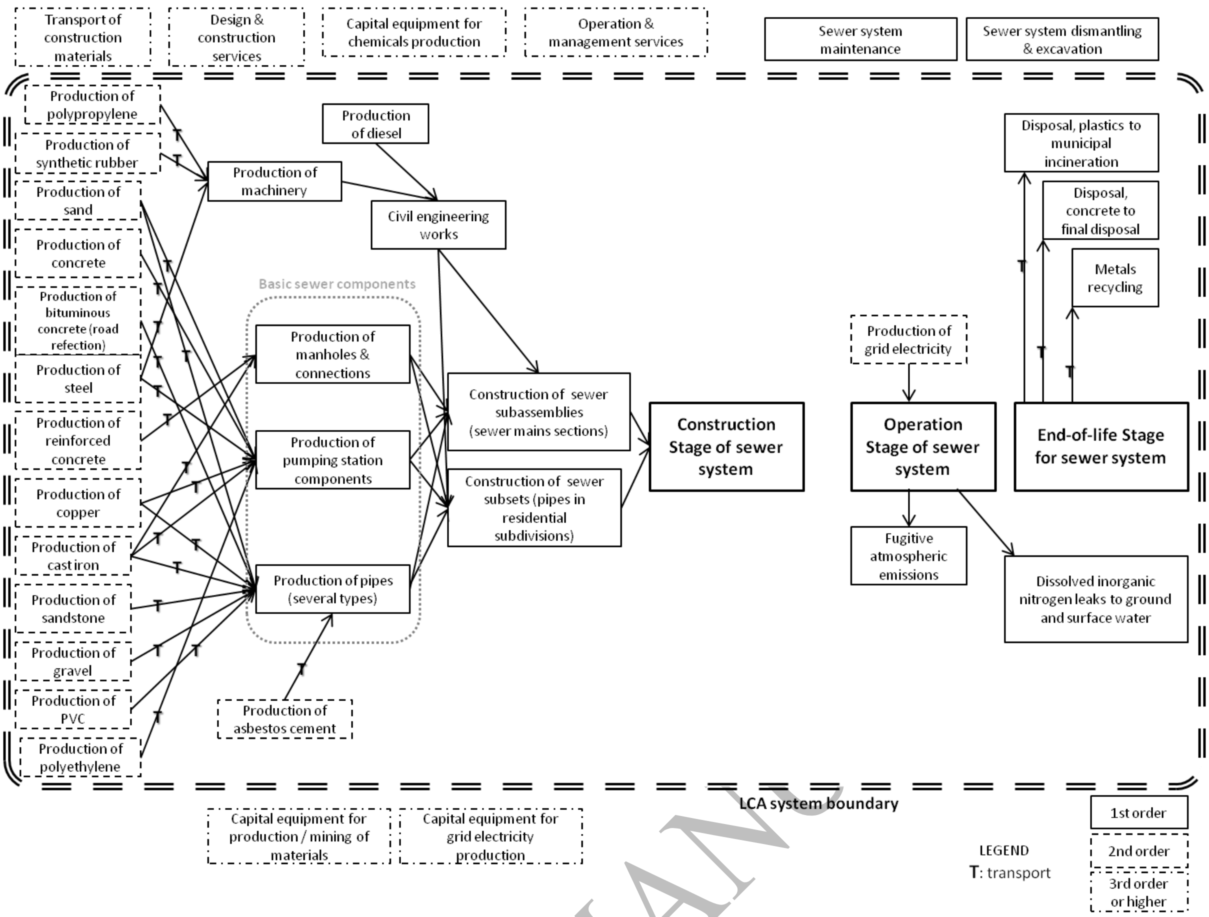

Figure 6. System boundary for life cycle inventory of sewer systems

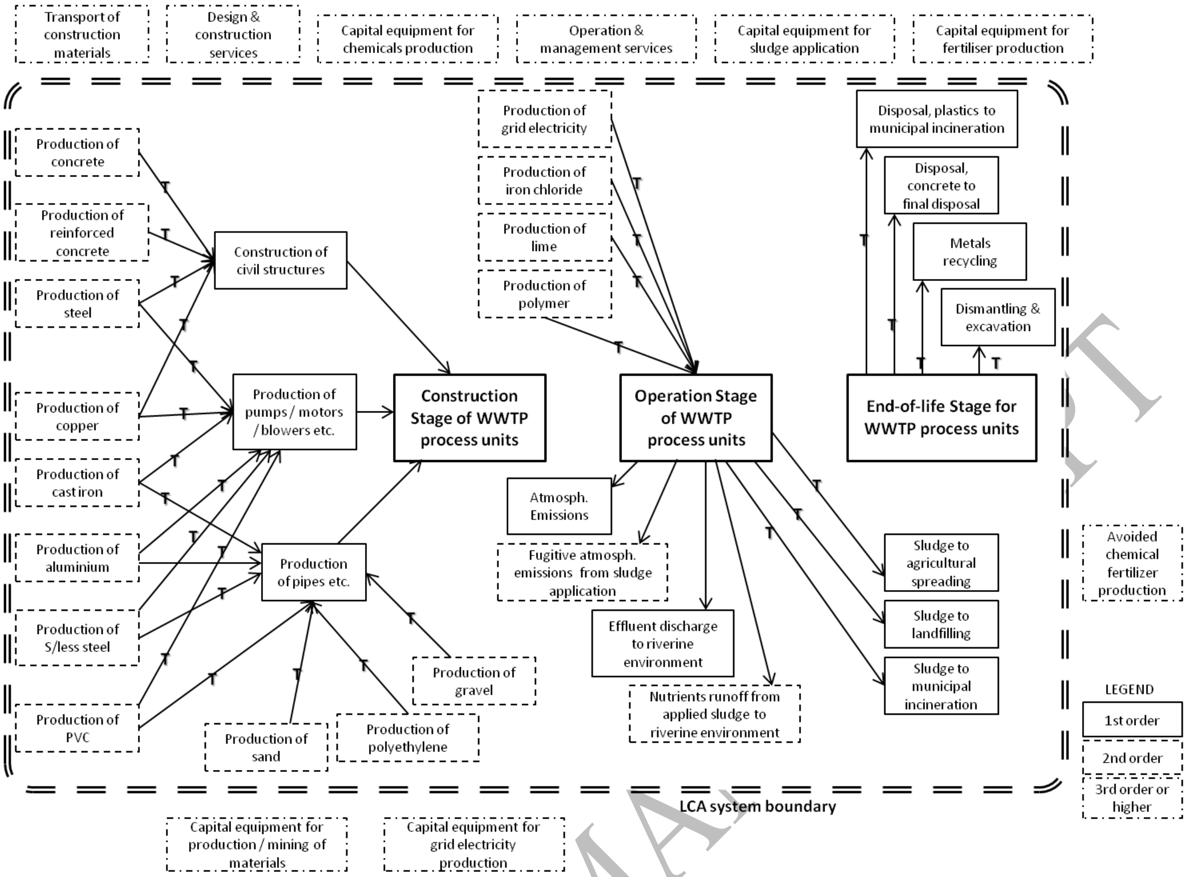

Figure 7. System boundary for life cycle inventory of WWTPs

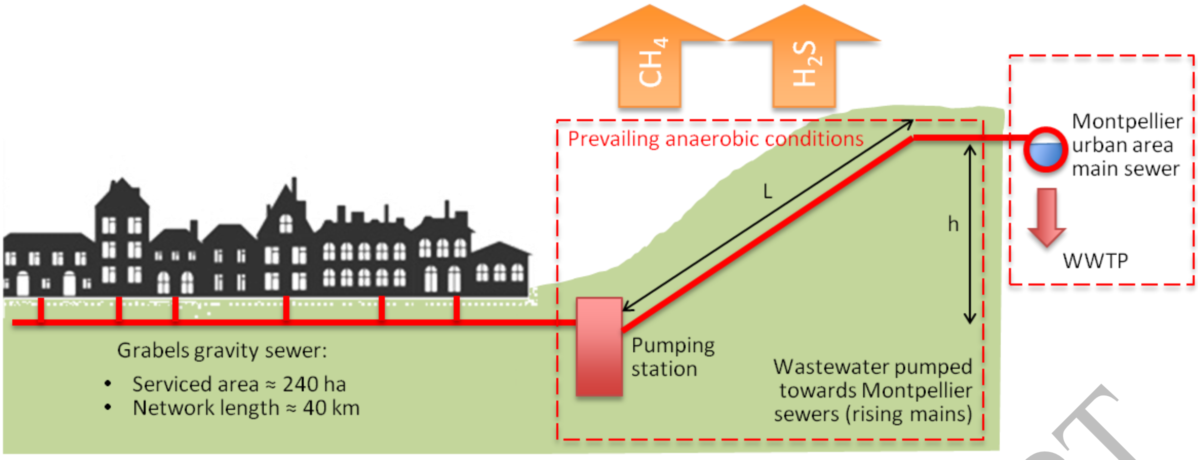

Figure 8. Sewer model of the serviced area of Grabels, France

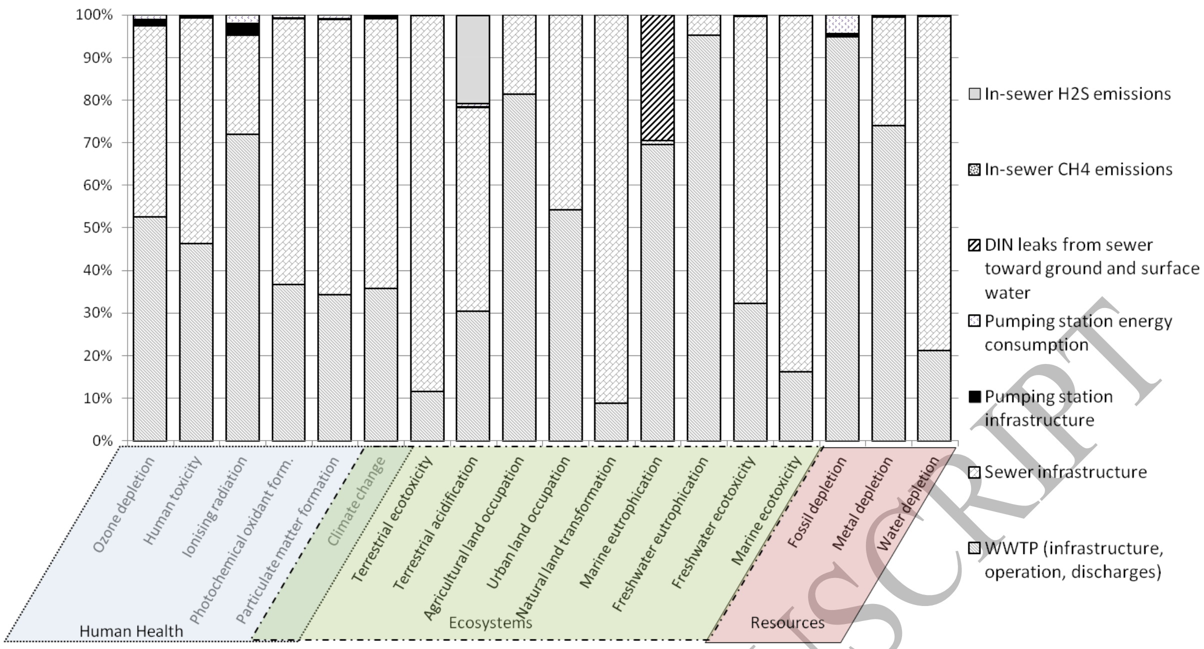

Figure 9. Life Cycle Impact Assessment (LCIA) using ReCiPe V1.07 midpoint indicators for the Grabels urban WWT system (sewer + WWTP)

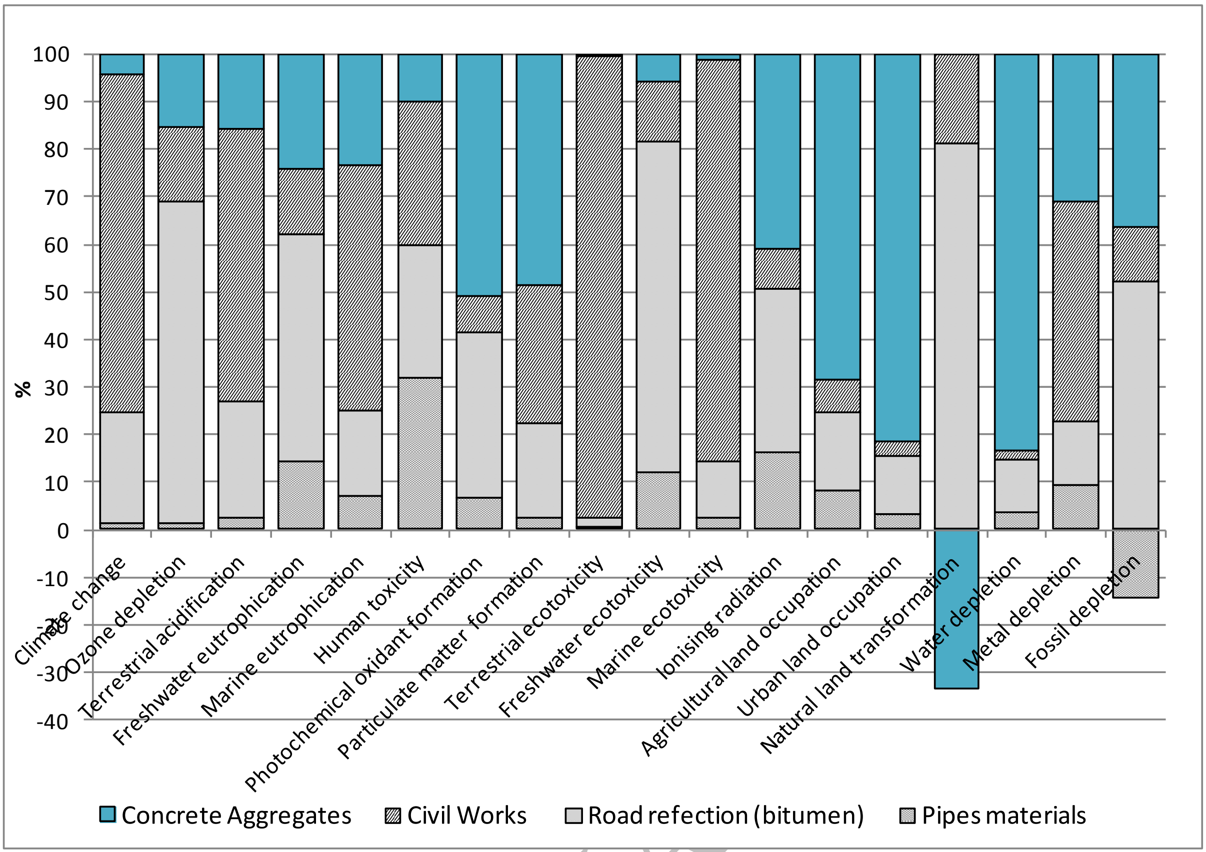

Figure 10. Breakdown of sewer infrastructure construction using ReCiPe V1.07 midpoint indicators

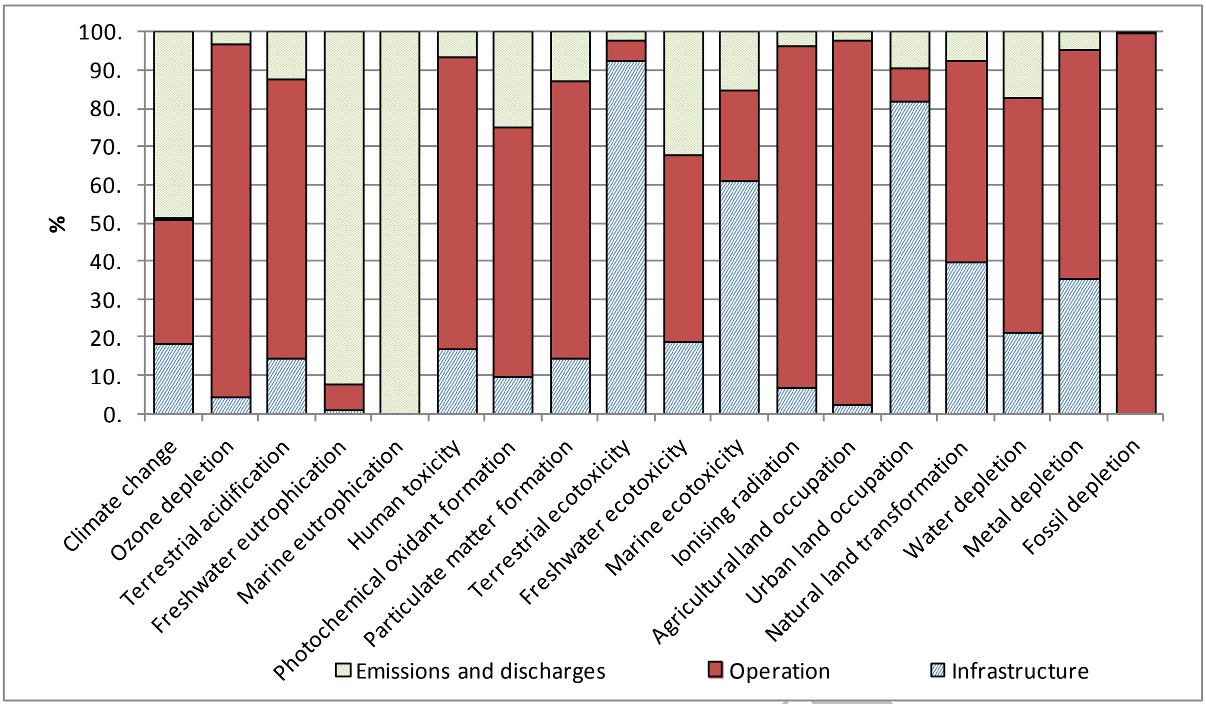

Figure 6. Breakdown of the WWTP model using ReCiPe V1.07 midpoint indicators

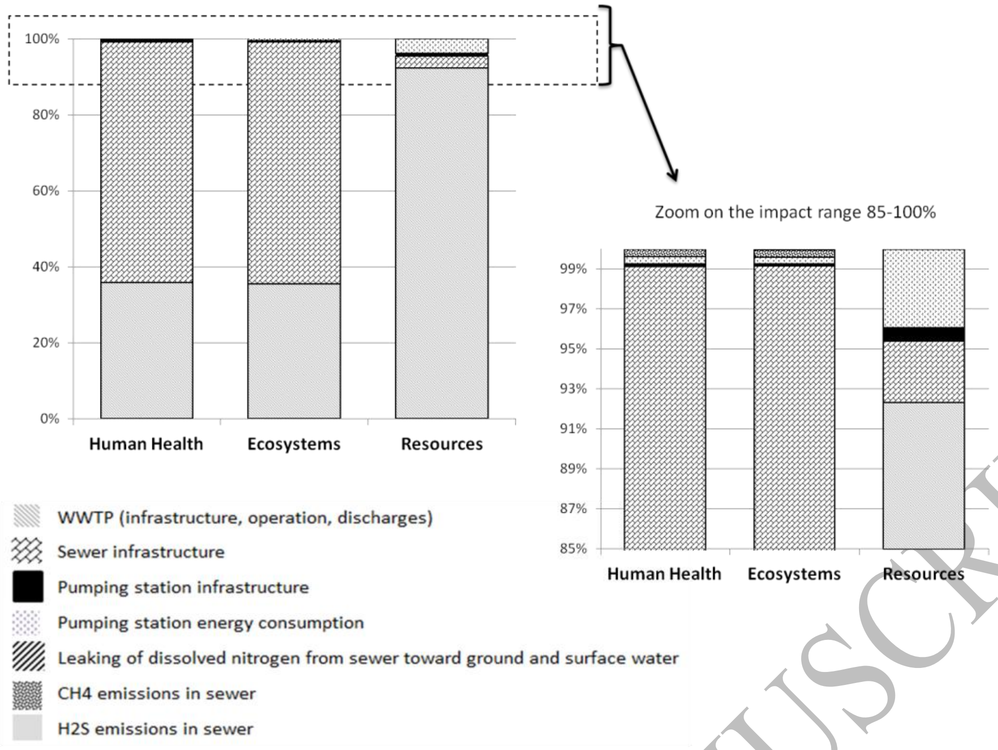

Figure 7. Life Cycle Impact Assessment (LCIA) using ReCiPe Endpoint (H) V1.07 / World ReCiPe H/H for the city of Grabels urban WWT system (sewer + WWTP)

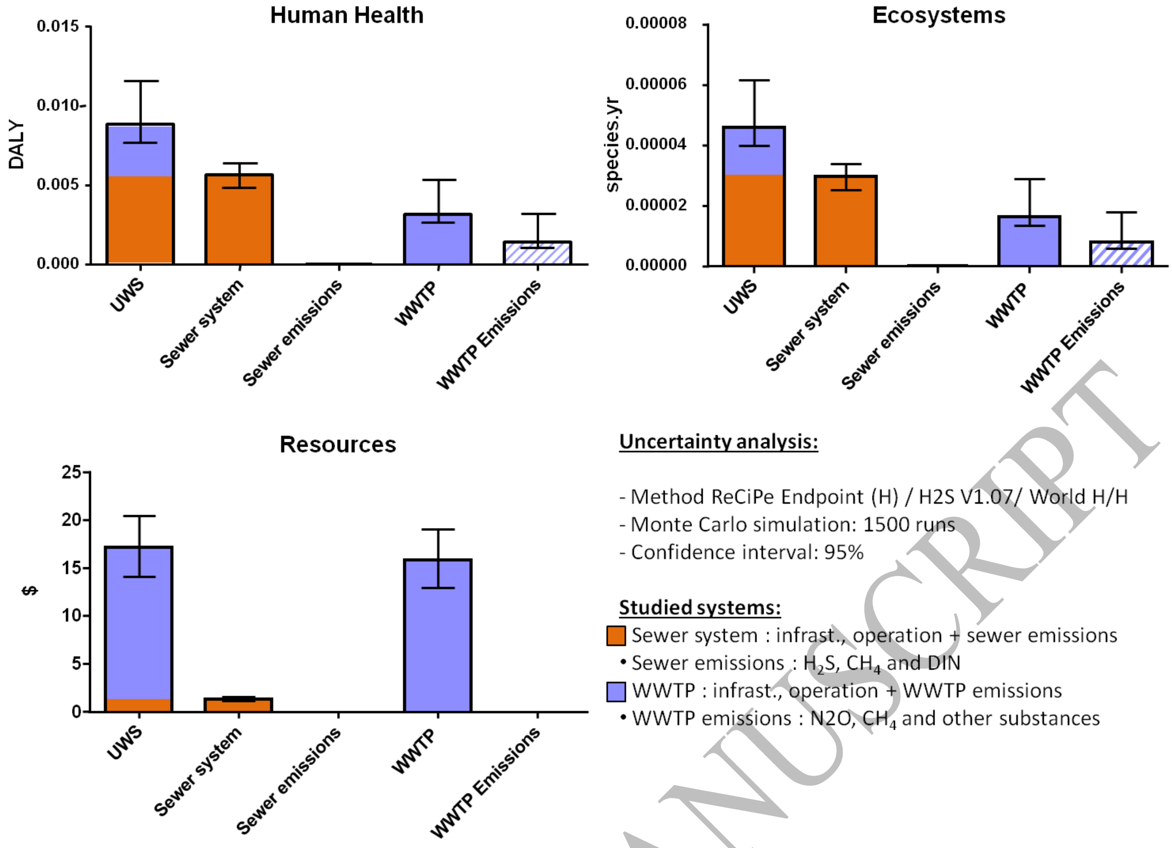

Figure 8: Uncertainty analysis results at the endpoint level (confidence interval of 95%) for the main components of the urban water system