Urban planning of sewer infrastructure: Impact of population density and land topography on environmental performances of wastewater treatment systems.

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Abstract Urban expansion is a multifaceted concept which has several direct or indirect environmental effects. This work intends to use Life Cycle Assessment (LCA), to assess the effect of urban expansion on sewer infrastructure for small and medium communities (1000-5000 inhabitants). This effect is discussed in relation to land topography and population density in terms of urban planning issues. The LCA results confirm the huge contribution of the sewer on the entire footprint of the sanitation system. They highlight the environmental effect of urban sprawl on the sewer itself for all impact categories except eutrophication which is mainly linked to the efficiency of the wastewater treatment plant (WWTP). It finally advocates for scientific research perspectives and associated assessment tools to compare centralized sewerage systems to clusters of wastewater treatment units especially on uneven land and/or existing sprawled suburbs.

1 Introduction

Urban expansion is a multifaceted concept which includes the spreading outwards of a city and its suburbs to its outskirts in low-density and auto-dependent development. It has several direct or indirect environmental effects such as land occupation, car dependency, high per-capita use of energy and water, loss of time and productivity for commuting, etc. This work intends to assess, using LCA, an additional environmental effect of urban sprawl on sewer infrastructure (as a first step for small and medium communities). This effect is discussed in relation to land topography and population density in terms of urban planning issues.

LCA has already been applied to classic Waste Water Treatment Plant (WWTP) [1] or to less conventional systems such as constructed wetlands [2] and [3]. The heavy contribution of sewer systems to resulting impacts of the whole sanitation system (sewer + WWTP) has also been highlighted in previous LCA [3] and [4]. The present paper proposes to give a finer level of detail of the sewer system to better identify the largest contributors to its environmental footprint. For this purpose, a modular and comprehensive Life Cycle Inventory (LCI) has been conducted to model several sewer infrastructure scenarios corresponding to different types of urban planning.

2 Materials and methods

2.1 LCA goal and scope, Functional Unit (FU), calculation methods and impact categories to be assessed

The main goal of the study is to compare different types of sewer network corresponding to different urban planning options. The study sets as a secondary goal the assessment of the shares of the main contributors to the whole sanitation system (including WWTP and sewer network). Commonly, the chosen functional unit for WWTP assessment is linked to the pollutant load (for instance wastewater volume or BOD mass). To assess the sewer system associated with urban development typology, it is indeed more meaningful to refer to population for the definition of functional unit in LCA using “per capita” units.

Regarding the impact categories to be assessed, the ReCiPe methodology [5] for Life Cycle Impact Assessment (LCIA) was chosen. ReCiPe calculates eighteen relatively robust midpoint indicators, but also three much more uncertain endpoint LCIA indicators.

The three ReCiPe indicators dealing with land occupation (Agricultural land occupation, Urban land occupation, Natural land transformation) are excluded from the present study because a sewer network is mainly an underground infrastructure and its relation with land occupation can't be easily established with this kind of indicators. Tab. 1 present the list of ReCiPe midpoint indicators used, their respective units and the corresponding abbreviations used in figures and graphics.

Tab. 1: Abbreviations of the midpoint impacts categories assessed

Abbrev.	Impact category	Unit of the indicator result
CC	Climate change	kg (CO_2 to air)
OD	Ozone depletion	kg (CFC-11 to air)
HT	Human toxicity	kg (14DCB to urban air)
POF	Photochemical oxidant formation	kg (NMVOC to air)
PMF	Particulate matter formation	kg (PM10 to air)
IR	Ionising radiation	kg (U235 to air)
TA	Terrestrial acidification	kg (SO_2 to air)
FE	Freshwater eutrophication	kg (P to freshwater)
ME	Marine eutrophication	kg (N to freshwater)
TET	Terrestrial ecotoxicity	kg (14DCB to industrial soil)
FET	Freshwater ecotoxicity	kg (14DCB to freshwater)
MET	Marine ecotoxicity	kg (14-DCB to marine water)
WD	Water depletion	m3 (water)
MD	Metal depletion	kg (Fe)
FD	Fossil depletion	kg (oil)

2.2 System overview and inventory

2.2.1 A complete sanitation system, including WWTP and sewer system

Fig. 1 presents a general overview of the entire sanitation system. The scope includes the entire life cycle of sewer and WWTP as well as sludge management (spreading or incineration). For some specific systems such as wetlands, the scope may also include the management of the harvested biomass (reeds and rhizomes) as shown in Fig. 1. It can be noted that the end of life options for solid wastes (plastics, papers …) are excluded from the present study because their management is independent of WWTP technology. As a first step, the depreciation of the useful life of the entire sanitation system is based over 30 years of usage.

This paper will present impact assessment results in two parts, following the two system boundaries proposed in Fig. 1: (i) firstly, the entire sanitation system and (ii) secondly, the sewer network alone. The chosen WWTP LCA base model is an activated sludge (AS) system defined for a low-load AS technology with a selective chemical precipitation of phosphates using iron (III) chloride. A conventional sludge conditioning process with flocculation, coagulation and dewatering is then applied to obtain a stabilized, dry-cake sludge. The WWTP description and its life cycle inventory (LCI) are describe in detail in [6].

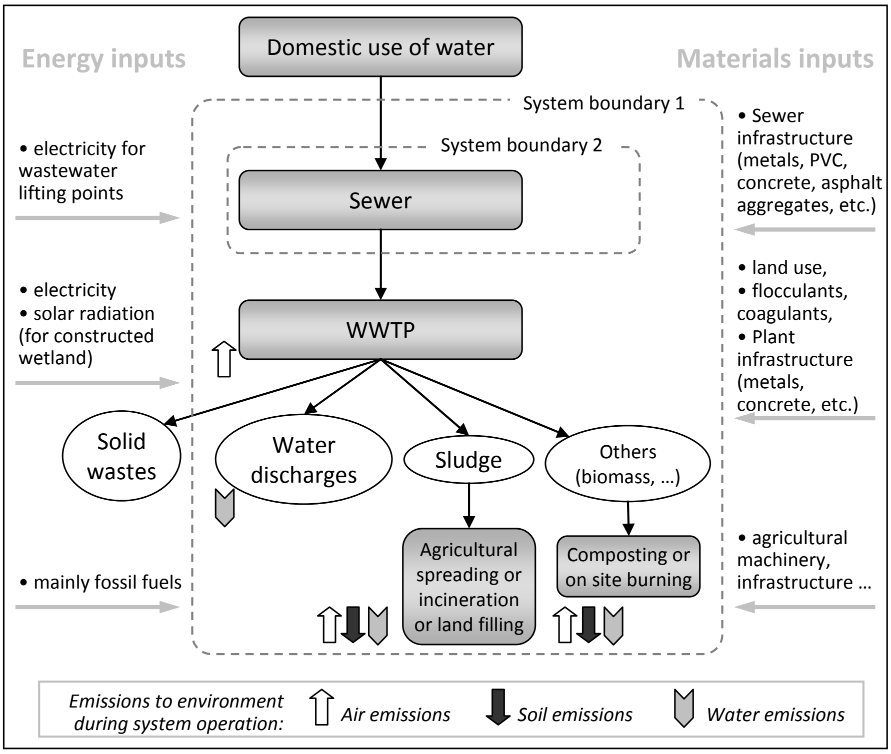

Fig. 1: Life cycle assessment scope for the complete sanitation system

2.2.2 Type of cities assessed

The present study focuses on sewer systems designed for communities of 1000-5000 Population-Equivalent. Tab. 2 presents the four modelled sewers, from dense population for Sw1 to scattered housing (urban sprawl) for Sw4. Two sewer inventories (Sw2 & Sw3) are based on actual French southern small towns using background data from sewer network maps (GIS drawings). In addition, and to better assess the effect of urban sprawl on the sewer footprint, two theoretical cities were also modelled, one (Sw1) with a high population density (26600 capita/km²) and the second with a scattered housing (Sw4). Tab. 2 also describes the city topography (flat or uneven) which has a direct effect on the number of lift pumps and therefore on electric energy consumption (note: the French energy mix from Ecoinvent [7] dominated by nuclear power is used in this study).

Tab. 2: Description of the modelled sewer system

Sewer network characteristics	Sw1	Sw2	Sw3	Sw4
Sewer model	“Theoretical” dense housing	City of Saussan, 1400 hab. (FR-34570)	City of Grabels, 5200 hab. (FR-34790)	“Theoretical” scattered housing
Population density (capita/km²)	26 600	2 813	1 700	758
Type of urban planning	Three floors housing using 56% of available land	A village centre quite dense combined with scattered building lots	Small city centre with a lot of scattered building lots	Urban sprawl with plots of 2500 m² for 2.5 habitants
Topography	Slightly uneven topography	Flat terrain	Uneven topography	Relatively flat terrain

2.2.3 Modular sewer inventory

The required level of detail on the sewer components in order to better identify the largest sewers contributions is obtained through a modular inventory built with a similar approach used in [8]. This modular inventory combines three levels of system description: (i) elementary components, (ii) sewer subsets and (iii) sewer subset assemblies. At level (i) an inventory of all needed materials for one meter of pipe installed at a certain depth is done as shown in Fig. 2 (same for elements such as pumping stations or manholes). Level (ii) provide inventory of sewer subsets combining elementary components and implementation (civil work) as well as operation (mainly for lift pumps). At level (iii) the sewer subsets are assembled with respect to sewer length estimated from GIS drawings. Calculation checks on water flows consistency with pipes diameters were also made at that level. The first two levels of inventory use elementary data (metal, materials, energy, emissions to air, soil and water …) from the LCI database Ecoinvent [7].

This modular sewer inventory includes combinations of 15 construction equipment and 7 civil engineering teams, 68 different elementary components for pipes, manholes and pumping stations, 15 different sewer subsets and 34 sewer sub-assemblies. As it is not conceivable to summarize such a large life cycle inventory (LCI) in a conference paper, supplementary data (including end of life hypotheses) will be available on request to the corresponding author.

The four sewers assessed in this paper are mainly composed of Asbestos-cement (AC) pipes which were used extensively in sewage systems all over the world during the last decades. In addition, parts of the sewer networks are made of PVC pipes. Other miscellaneous pipes, connections, equipments and manholes are made mostly from concrete, stainless steel and cast iron.

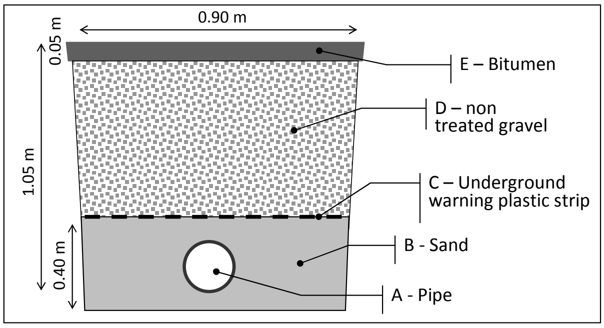

Fig. 2: Cross cut of sewer pipes (example for PVC SN8 pipe D200, depth 1.05 m)

3 Results and discussion

3.1 Sewer network contribution to the impacts of the entire sanitation system

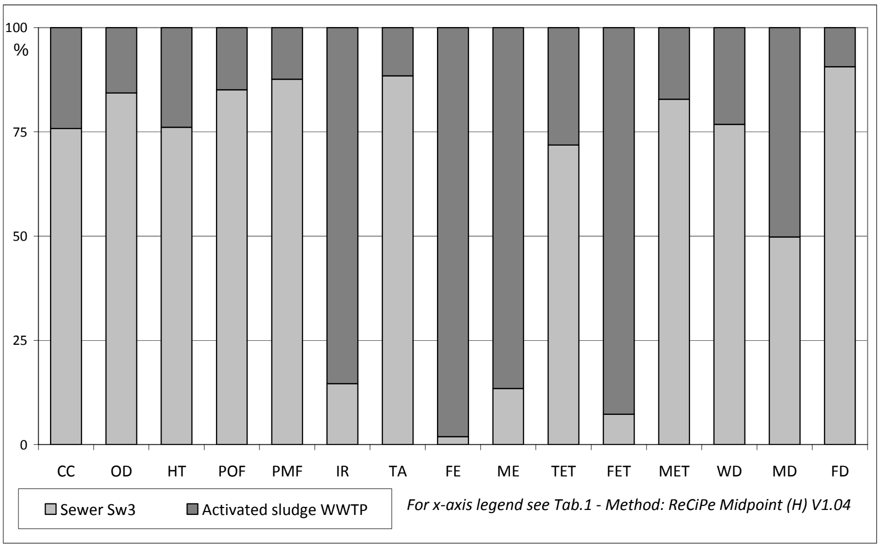

Fig. 3: ReCiPe impacts of the entire sanitation system

As shown in Fig. 3, for most of the indicators, sewers represent more than 75% of the impact scores for mid points indicators. This confirms their huge contribution to the sanitation system footprint. Obviously, for freshwater and marine eutrophication (FE, ME) the WWTP is the greatest contributor because of nitrogen and phosphorous loads discharged in surface waters. Same for freshwater ecotoxicity (FET) where the WWTP impacts are mainly due to the contents of water discharges (see [6] for more information).

3.2 Main contributors to impacts in a sewer system

Fig. 4 gives an overview of the main contributions for a typical Asbestos-cement (AC) and PVC pipes sewer (Sw2). The negative impacts for metal depletion (MD) are due to the partial recycling of sewer components. Civil works are the greatest contributors to climate change (CC), terrestrial ecotoxicity (TET) and acidification (TA) while construction materials (concrete, aggregates + AC-asbestos-cement) contribute significantly to all other impact categories. More surprisingly, the impacts associated with the rehabilitation of asphalt pavements (bitumen) when digging trenches are quite important. The ionising radiation impacts are mainly due to the electric consumption of lift pumps using the French electricity mix (major nuclear power share).

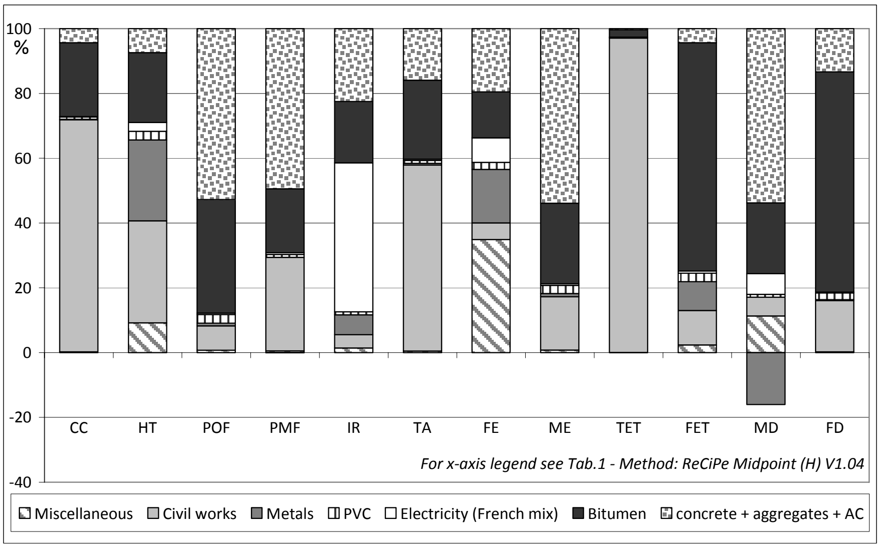

Fig. 4: Contribution graph for sewer Sw2

3.3 Sewer comparison in terms of urban sprawl and topography effects

Fig. 5 presents a comparison of Sw2 sewer for a flat or uneven terrain (modelled by adding more lift pumps in the system). Except for the impacts directly linked to the lift pumps (IR due to electricity use), the topography effect is not so marked. The Sw2 sewer with an uneven topography has also an higher contribution to eutrophication impact (FE) due to electricity and copper use in pumps, but we must recall that the contribution of the sewer to the global eutrophication of the entire sanitation system is very low (cf. Fig. 3). It should be noted here that the indirect effects of topography on the civil engineering work (for instance due to the presence of rocks on uneven terrains) was not modelled. This could be the subject of future work.

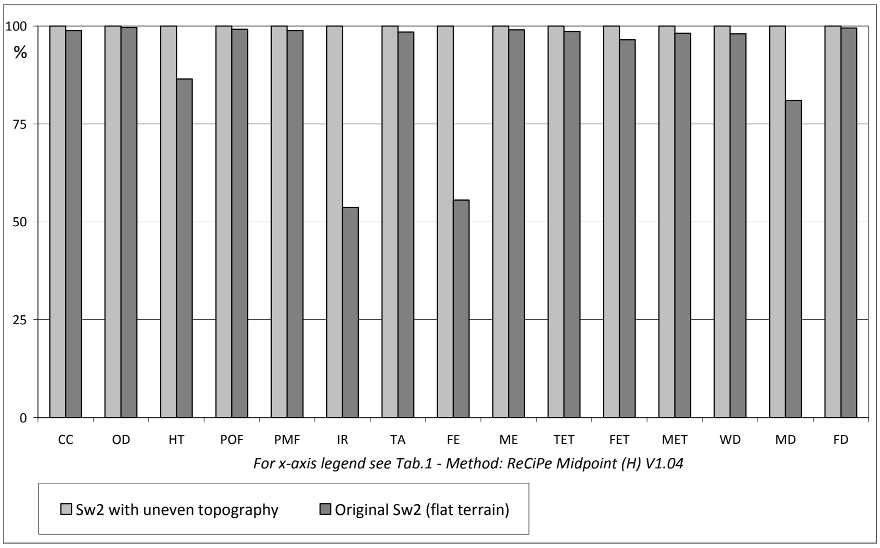

Fig. 5: Uneven topography vs. flat terrain: impacts comparison

In Fig. 6, the four sewers are compared between the highest population density (Sw1: 26600 capita/km²) to the lowest one (Sw4: 758 capita/km²). This comparison highlights a huge effect of population density with almost a factor ten between the dense populated zones and the sprawled zones. It is shown in all impacts categories except ionising radiations (IR) which is the direct consequence of terrain topography (lift pumps) and relatively independent of population density.

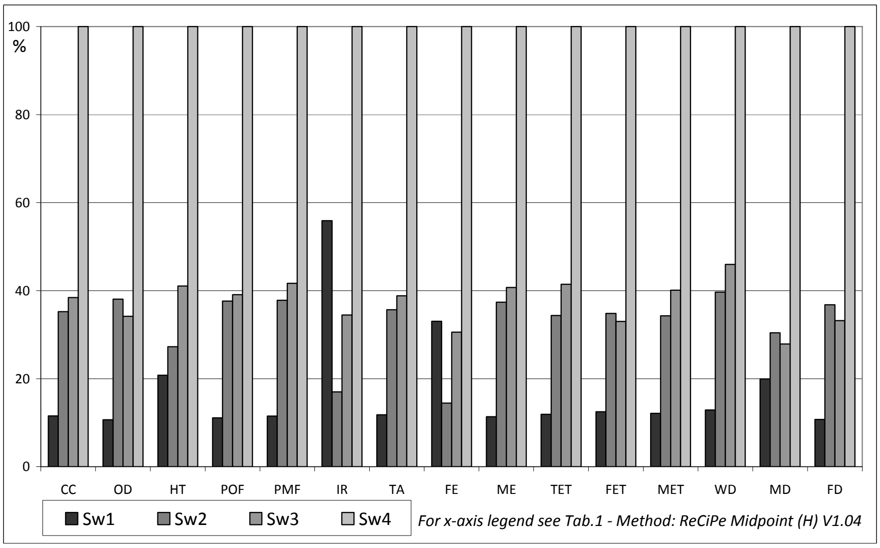

Fig. 6: Comparison of the impacts generated by the four modelled sewers

4 Conclusion, perspectives

With the exception of water quality impacts (eutrophication and ecotoxicity), the LCA results confirm the huge contribution of the sewer on the total footprint of the sanitation system (more than 75% of the contribution share). Among the various parameters that affect the environmental performances of the sewer network, the housing density is indeed the main one, up to a factor of about 10 between a dense city and a scattered one (resulting from urban sprawl).

Based on the modular sewer inventory, investigation should be conducted with different depreciations of the useful lifetime (30 to 70 years or more) for the studied infrastructure taking or not into account a partial reconstruction of the network. A comparison between combined sewers (including storm water drainage) with separative sewers would also be an interesting issue to be assessed.

These first conclusions advocate for the need of urban policy guidelines and associated LCA tools related to these questions in order to be able to compare for instance centralized sewerage systems to clusters of smaller wastewater treatment units such as those described in [9]. Finally, it may be advisable to link the sewer system footprints to other relationships linking urban forms and their environmental effects (land occupation, car dependency, high per-capita use of energy [10] and water, loss of time and productivity for commuting, etc.).

5 Acknowledgement

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