Elsevier Editorial System(tm) for Water Research
Manuscript Draft

Manuscript Number:

Title: Up-to-date and modular construction inventories for Life Cycle Assessment of small to medium wastewater treatment plants

Article Type: Research Paper

Keywords: civil works; inventory; LCA; WWTP

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Abstract: The construction stage impacts from wastewater treatment are commonly not considered in life cycle assessment. When they are, it is usually based on Ecoinvent construction inventories, which use wastewater treatment plant construction data that is 20 years old and based in Switzerland. Updated construction inventories have been obtained for four Spanish wastewater treatment plants of varying size. Results show that the Ecoinvent inventories have much higher consumption of materials than the inventories calculated in this study. This difference in consumption of materials translates into a 2 to 10 times overestimation of the environmental impacts when using the Ecoinvent construction inventories. This paper provides reliable equations to estimate material consumption for the construction of wastewater treatment plants as a function of plant capacity.

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Cover Letter, For Editor only

Universitat de Girona

ICRA Institut Català de Recerca de l'Aigua

UdG lequia ECO-INNOVATIVE WATER SOLUTIONS

26-04-2017, Girona

Dear Editor-in-chief,

Please find attached the manuscript entitled "Up-to-date and modular construction inventories for Life Cycle Assessment of small to medium wastewater treatment plants" to be considered for publishing at *Water Research*. We believe that the manuscript fits, as Research article, in the editorial line of *Water Research*. The submitted manuscript contains only original data and it is not under review in any other scientific journal. All the authors have read the submitted version of the manuscript and approved its submission.

Background - A former study entitled "*Using a detailed inventory of a wastewater treatment plant to estimate the relative importance of construction to the overall environmental impacts*", which is under review in Water Research, compared the contribution to environmental impacts of the construction phase against the operational phase for one ***large*** wastewater treatment plant (WWTP). In this present manuscript we focus on the construction phase, and provide construction inventories for four WWTPs varying in size from ***small to medium***. The results obtained are then compared to the inventories available in the widely used Ecoinvent LCA dadabase. Interestingly, we found large differences.

Rationale - We believe that our manuscript is worth publishing at *Water Research* for at least three main reasons:

1st) We go beyond a mere comparison between our results and Ecoinvent; In this paper, we provide reliable equations to estimate material consumption for the construction of small to medium wastewater treatment plants as a function of plant capacity. This means that LCA practitioners can easily build their own construction inventories just by providing plant capacity.

2nd) This is the first time in 30 years that wastewater treatment plant construction inventories provided by the widely used Ecoinvent LCA database (the reference in this field) are challenged. We obtained detailed construction inventories for four (small to medium) wastewater treatment plants. We found large differences between up-to-date construction inventories and the ones available in Ecoinvent.

3rd) This paper will help promote better use of LCA in the wastewater treatment field.

Sincerely yours,

Lluís Corominas

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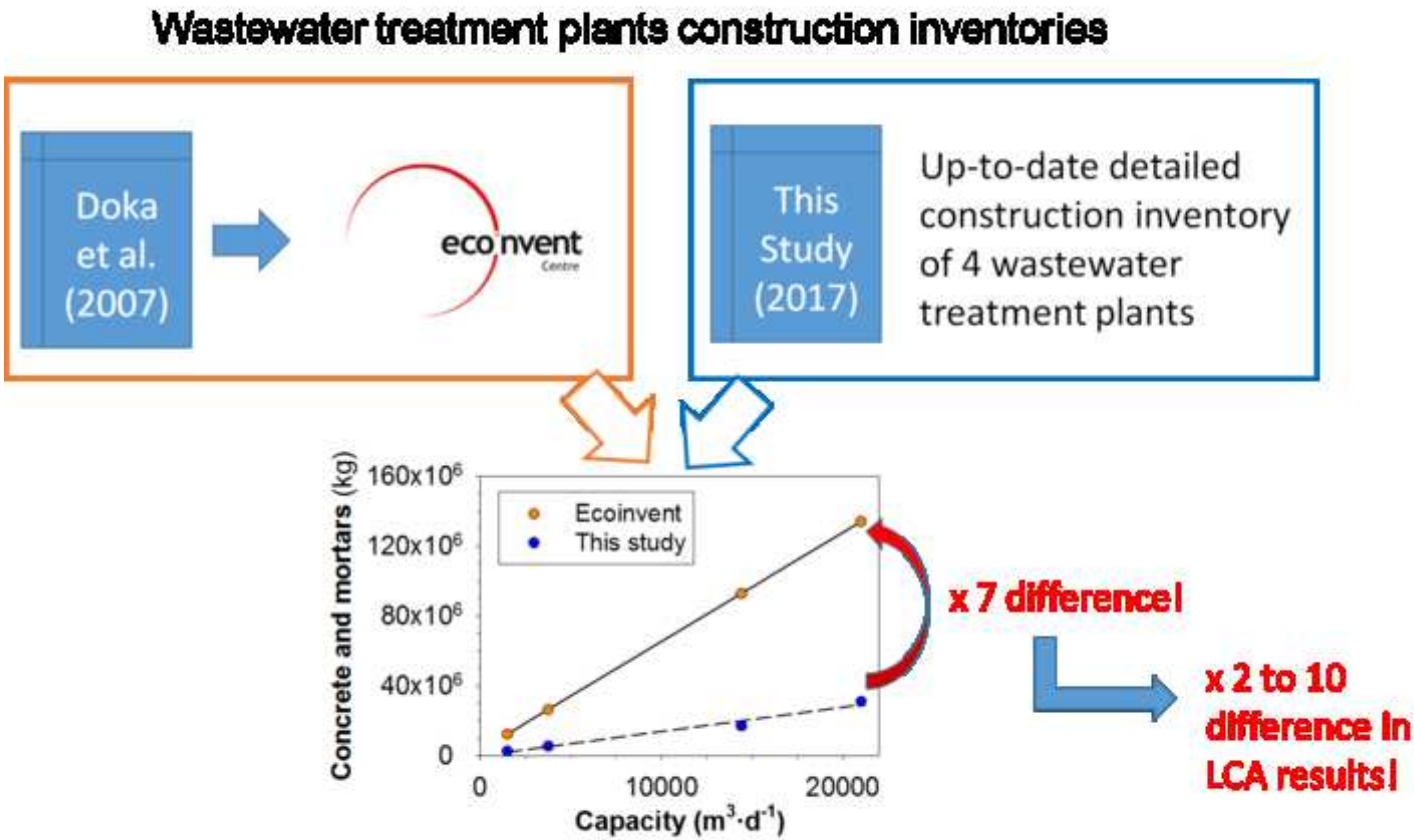
lequia TECNIO

***Highlights (for review)**

- Updated construction inventories have been obtained for four WWTPs
- Ecoinvent inventories have much higher consumption of materials
- Ecoinvent overestimates 2 to 10 times environmental impacts
- Equations to estimate material consumption as a function of capacity are provided

Graphical Abstract



Up-to-date and modular construction inventories for Life Cycle Assessment of small to medium wastewater treatment plants

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Abstract:

The construction stage impacts from wastewater treatment are commonly not considered in life cycle assessment. When they are, it is usually based on Ecoinvent construction inventories, which use wastewater treatment plant construction data that is 20 years old and based in Switzerland. Updated construction inventories have been obtained for four Spanish wastewater treatment plants of varying size. Results show that the Ecoinvent inventories have much higher consumption of materials than the inventories calculated in this study. This difference in consumption of materials translates into a 2 to 10 times overestimation of the environmental impacts when using the Ecoinvent construction inventories. This paper provides reliable equations to estimate material consumption for the construction of wastewater treatment plants as a function of plant capacity.

Keywords: civil works, inventory, LCA, WWTP

1. INTRODUCTION

As explained in Annex A of the ILCD Handbook (European Comission, 2010), studies with a very good level of quality have to account for at least 95% of the environmental impacts using adequate inventories with good technological, geographical and time-related representativeness; good data precision; and use of correct Life Cycle Inventories (LCI) methodologies. Construction inventories are not systematically included in Life Cycle Assessment (LCA) studies of wastewater treatment plants (WWTPs). According to Corominas *et al.* (2013), only 22 of the 45 LCA studies applied to WWTPs included the construction. This stage is usually not considered due to the difficulties in obtaining specific information about WWTP construction and, if any information is available, construction inventories are extremely time-consuming to develop.

Emmerson *et al.* (1995) was the first LCA study to include a construction inventory for activated sludge plants and concluded that 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. Subsequently, more studies conducted their own construction inventories (Machado *et al.* 2007; Ortiz *et al.* 2007) obtaining data from existing facilities. These two works, even though showed a contribution of the construction higher than 5%, they did not facilitate detailed inventories to be easily used or adapted to other WWTPs. Besides, the environmental impact was provided for the whole WWTP, no differentiation could be done among unit processes. In parallel, Doka (2007) compiled construction inventory data from studies carried out more than 20 years ago and incorporated into the Ecoinvent databases as 5 different WWTPs. That information has been widely used to create inventories for the construction of WWTPs without having to *manually* obtain all specific construction data. One example is Foley *et al.* (2010), which calculated the volume of reinforced concrete for each scenario analyzed. This volume of concrete was then used as a multiplier for the consumption of other materials, as defined by previously catalogued construction inventory data from Swiss WWTPs (Doka, 2007). The approach is reasonable but the data is starting to become old.

Besides, there are evidences that the contribution of construction to the overall impacts are larger than 5%. For example, Renou *et al.* (2008) estimated a contribution of 10% of the construction in global warming potential impact is described as well as a 11.5% in abiotic depletion. Risch et al. (2015) reports a contribution around 20% of the construction phase for global warming potential and human toxicity. In addition, the data obtained from Doka (2007) is based on studies carried out more than 20 years ago resulting in the use of possibly outdated information.

Besides the work from Doka, there has been no other study published that provides up-to-date detailed inventories from WWTPs that can systematically be used in LCA. Materials and practices applied to the construction of WWTPs have evolved during the years. Improved reporting is available now in the budgeting, and more information can be obtained thanks to the existence of complete databases (with information on materials and energy consumption, labor force, residues generated, and their expenses). Therefore, the motivation of this study is to perform detailed construction inventories from four WWTPs with capacities ranging from 1,500 to 21,000 $m^3 \cdot d^{-1}$ and compare them with respect to the Ecoinvent inventories. Finally, linear equations of the updated inventories will be explored to make estimates of construction materials as a function of plant capacity .

2. METHODOLOGY

2.1. Ecoinvent inventories

Ecoinvent distinguishes between five different WWTP capacities: 806; 5,321; 24,864; 71,133; and 233,225 population equivalents (PE). The inventories for the construction of these plants were based on the real construction inventories of three existing Swiss plants: Twann (1,600 PE), Ergolz (25,000 PE), and Werdhölzli (593,300 PE). These inventories contained information on the amount of materials and processes needed for each plant including: concrete, reinforcing steel, steel, drinking water, electricity, and excavation. By relating material usage to the corresponding plant capacity, a linear regression was developed that is able to estimate the inventories of the five Ecoinvent inventories.

It is worth noting that the inventory for the Ergolz plant included more materials than those of the other plants. Therefore equations for these materials were found using the x-intercepts of other materials. For instance, the x-intercept of steel was used to create a linear regression for metals and plastics. The x-intercept of concrete was used to estimate the linear regressions for bitumen and lime. For material transports, the following default distances in Ecoinvent were used: 600 km by train and 50 km by lorry for steel, bitumen, glass, copper, inorganic and organic chemicals; 200 km by train and 50 km by lorry, for aluminium, polyethylene, rubber, mineral wool and bitumen; 100 km by train and 20 km by lorry for lime; and finally, 20 km by lorry for concrete.

2.2 Up-to-date modular inventories

2.2.1. Unit processes classification

The functional unit of the study is the construction of a WWTP. Four WWTPs with capacities ranging from 1,500 to 21,000 $m^3 \cdot d^{-1}$ (

Table 4) were chosen for inventory development. The WWTPs have similar configurations, employing an oxidation ditch to remove carbon and nitrogen and simple sludge treatment via thickening and dewatering.

[Table 1]

The construction inventories for the four plants were created by first obtaining the constructive budget of each plant. Next, the constructive budget database, Banc BEDEC (Barcelona, Spain), was used to estimate the materials and energy use associated with each budget item. The budget items and associated materials and energy use were categorized based on WWTP treatment elements including: pre-treatment, secondary treatment, sludge line, buildings, urbanization, tube connections and power station (Table 5). More information on this inventory development methodology can be found in Morera et al. 2017.

[Table 2]

An assumption made is that reactors were all partially buried leaving a height of 1.5 meters above ground. The soil that was excavated was assumed to be compact soil in all cases. Gravity thickening was assumed for all WWTPs.

2.2.2. Materials classification and grouping

A grouping of materials was applied to compare the mass of materials between inventories of this study and of Ecoinvent, selecting one material representative and summing up all masses of materials belonging to the same group (Table 6, applies to Figure 1). No grouping was applied though when calculating the environmental impacts out of the inventories, and hence all materials with their own characterization factors were applied (this applies to Figure 2).

2.2.3. Differences between Ecoinvent and the up-to-date inventories

There are differences between Ecoinvent and the up-to-date inventories for the quantification of some processes. While for Ecoinvent a specific process for excavation exists, in the up-to-date inventories the excavation process was calculated from the consumption of diesel needed for the machines to excavate the needed volume of soil. We believe that this approach is more realistic for WWTPs than the Ecoinvent one. Furthermore, in the Ecoinvent inventories the electricity is assumed to be used directly from the network, while in this study the electricity is generated on site by an electrical generator (current practice on-site, after personal communication with the construction company Voltes S.L.U). Ecoinvent does not account for transport of the excess excavated soil to the landfill or the transport from the manufacturer to the workplace; this study includes these two transport processes with a distance of 40 km each, assuming also the internal transports considered in the Ecoinvent inventories. Finally, to ensure a fair comparison between inventories, the process considered for the concrete production used in WWTPs construction in Ecoinvent was changed from high-performance concrete (to resist very low temperatures and high salinity) to concrete with non-special requirements. This modification was made after personal communication with construction companies (e.g. Voltes S.L.U) that advised that the concrete used for the construction of WWTPs does not need any special requirements.

2.3. Simple equations to obtain modular WWTP construction inventories

The grouping of materials as explained in subsection 2.2.2 (Table 6) was the starting point. For each group of materials, the relationship between WWTP capacity and the quantity of material/energy used was evaluated via linear regression. To avoid negative values for capacities closest to the smallest WWTP, the trend line was fit to the data so as to exactly match the value for the smallest WWTP. Therefore, 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 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). Linear regressions with an r^2 value higher than 0.7 were considered significant. For the groups of materials where a lower coefficient of determination was obtained (r^2 lower than 0.7) a fixed range of values was provided in which the median value was chosen for each material. The calculation of environmental impacts from the simple equations (section 3.4.1.) is conducted by applying the characterization factor of the material representative of each group (Table 3).

3. RESULTS AND DISCUSSION

3.1. Inventory for the 4 studied WWTPs and comparison with Ecoinvent

Figure 1 compares the masses of materials used that were calculated with Ecoinvent inventories with respect to the four inventories obtained in this work for five construction materials. The Ecoinvent inventories consistently use larger masses of materials than the inventories from this study, with the exception of the category "Other Materials", which refers to materials such as sand, bitumen, paint, gravel, etc. However, for all materials, including "Other Materials", the difference between the Ecoinvent values and those estimated in this study increases with increasing plant capacity. This increase in differences with increasing plant capacity ranges between factors of 7 (Plastics) to 145 (Other Materials).

Figure 1 also shows the linear trends between the masses of materials and the capacity of the plant for the Ecoinvent plants, which is calculated based on the linear regressions from Doka (2007). Results from this study also seem to have a linear relationship, even though with a different slope, between the plant capacity and concrete and mortars as well as for reinforcing steel, which are the largest consumed materials for WWTP construction. For the rest of the materials (metals, plastics, and other materials), the linear relationship does not seem as evident (r2 < 0.7). Nevertheless, the mass of metals and plastics is very low compared with the most consumed materials, and thus, does not have a high influence on the material inventories.

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 types 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 6).

The total mass of materials for the inventory of the four WWTPs obtained in this study is lower than the corresponding plants in Ecoinvent. This is mainly explained by a larger consumption of concrete and reinforcing steel (Figure 1). In this study, the consumption of kg of concrete per volume of water treated per day ranges from 1,179 to 1,701 $kg/(m^3 \cdot d^{-1})$, while in the Ecoinvent plants the consumption of concrete ranges from 6,275 kg to 6,975 $kg/(m^3 \cdot d^{-1})$ of capacity (without taking into account the largest plant from Ecoinvent, which is out of the range of the plants studied in this paper). For reinforcing steel, in this study the consumption ranges between 21 and 55 $kg/(m^3 \cdot d^{-1})$ of capacity, while Ecoinvent plants use between 220 and 230 $kg/(m^3 \cdot d^{-1})$. With respect to the consumption of other metals and plastics, masses are also much higher in Ecoinvent than in the inventories from this study. In contrast, the consumption of “other materials” in this study is much higher, mainly due to the sand used during the urbanization process or to refill some excavated parts (which represents between 83 and 99% of the other materials masses).

The aforementioned differences between the Ecoinvent inventories and the inventories developed in this study can be explained via further analysis of the Ergolz WWTP. Comparison between the construction inventories of the Ergolz WWTP and the similarly-sized Balaguer WWTP (18,000 PE) show that the Ergolz plant consumes about 10 times the material used in the Balaguer WWTP. The higher materials use values associated with the Ergolz WWTP may be due to either overdesign to accommodate future population growth in the plant´s service area and/or to differences in construction practices.

3.2. Comparison of environmental impacts

The impact categories considered in this study are Climate change (CC), Ozone Depletion (OD), Metal depletion (MD) and Fossil depletion (FD). As shown in Figure 2, the environmental impacts generated by using the Ecoinvent inventories are higher than the impact results using the inventories from this study for all impact categories. In addition, for the CC, MD and FD categories the difference between the impacts generated by the plants in this study and Ecoinvent increases as the capacity of the plant increases. A 2 to 10-fold overestimation of the environmental impacts calculated with Ecoinvent construction inventories is observed, depending on the impact category and the WWTP capacity. Conversely, in the 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 largest plant uses extruded polystyrene with a higher impact factor in this category.

The higher environmental impacts for Ecoinvent plants are explained by the higher consumption of materials, especially the relatively larger consumption of concrete and reinforcing steel compared with that of the studied plants, but also for the higher consumption of metals and plastics. Finally, even though the mass of “other materials” is higher in this study than in Ecoinvent, the material grouping has a lower environmental impact potential than concrete and reinforcing steel.

3.3. Detailed analysis of the studied plants

Figure 3 shows the contribution of each one of the operational process units to the global impact of the studied plants for different impact categories (CC, FD, MD and OD). In every plant, the unit with the highest contribution to the impact is always by far the secondary treatment, followed by urbanization. In Balaguer and L’Escala, the sludge line has a slightly 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 buildings in the Manlleu WWTP as no information was provided in the budget). 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.

Figure 4 presents a cumulative graph for materials and unit processes for one of the four WWTPs studied (Navàs, 1,500 $m^3 \cdot d^{-1}$). The graph quantifies the contribution to the global impact of each unit process and the contribution of each material and (deposition and transport) processes used during the construction. In every plant, the secondary treatment has a large influence on the global impact for all categories.

With respect to the CC category, concrete has the highest influence, which is mainly due to the concrete consumed in the secondary treatment (bioreactor and secondary settler) and urbanization. In addition, the contribution of reinforcing steel is important in these two units. The contribution of mortars and precast pieces consumed in the buildings is also very relevant for the 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 largest influence. Also important is the contribution of the deposition of the excess excavated soil during urbanization.

For 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 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 infrastructure 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 high contributions

3.4. Simple equations to obtain up-to-date modular inventories

According to Table 4, process units directly related with the wastewater treatment (i.e. pre-treatment, secondary treatment and sludge line) were more likely to have linear regressions with high r^2 values (>0.7, white cells in Table 4) compared to the unit processes not directly related with wastewater treatment (i.e. tube connections, buildings, urbanization and power connections). R^2 values were higher than 0.85 for diesel consumed by machines, soil excavation and soil transport to landfill, concrete and reinforcing steel. Meanwhile, formworks for the concrete structures (steel, plastics and wood) reported r^2 values higher than 0.72. Plant capacity could also be used to estimate via regression the amount of mortars and precast pieces for the pre-treatment and sludge line (with a r^2 higher than 0.87). In the biological treatment, an r^2 of 0.728 was found for the "other plastics" group, which is likely due to the particularities or common practices of each construction company. Finally, transport had also a significant correlation because it only depends on the materials considered.

Regarding the components not directly related with wastewater treatment (i.e. connections, buildings, urbanization and power connections), linear regression was unable to accurately describe any trends as these units depend on how they are distributed inside the plant, specific location characteristics, and the constructive solutions adopted (e.g. type of the tubes or trenches). For the connections unit, linear regression was only possible for the diesel consumed by the machines. The size of the buildings shared valid linear regressions with concrete, reinforcing steel, plastics, wood and precast pieces. For urbanization, which is highly dependent on the distribution of the plant units and particularities of each plant, regression was only able to explain the amount of soil excavated and the group of other materials. There were no linear regressions corresponding to the power connection unit.

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

3.4.1. Validation of the usefulness of the equations

Figure 5 shows a comparison between the impacts calculated by using the developed equations (Table 4) for material consumption with respect to the impacts estimated with the complete (real) inventory. The overall calculated inventory of materials has been obtained by first estimating the materials consumed/used in each WWTP unit by using the corresponding equation and/or median of the 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. Table 3 summarizes the material or group of materials and the corresponding material from Ecoinvent used to calculate the impacts.

As seen in Figure 5, in general, the differences between the environmental impacts calculated with the real inventories and with the inventories estimated using the regressions and ranges are small. For CC and FD categories, there are mainly minor differences between the impacts using the real and calculated inventories. The results are indeed very similar for Navàs. The biggest difference is in the case of OD for L'Escala WWTP. The impact for OD category is higher for L'Escala when using the real inventory due to the inclusion, only in this plant for the real inventory, of extruded polystyrene, a building insulation material with a very high potential impact in this category. The calculated inventory never considers this material.

In the case of Balaguer and Manlleu, the environmental impacts using the calculated inventory are higher than those using the real inventory (negative values in the difference bar of Figure 5). Conversely for L'Escala, we found the opposite trend as the impacts for calculated inventories from equations and ranges are lower than the impact from complete inventories (positive values in the difference bar of Figure 5), except for MD. The difference between the real and the calculated values in the case of the MD category is due to the increase with plant capacity in the proportion of the reinforcing steel per cubic meter of concrete except for Balaguer. As a result, there may be an overestimation of the reinforced steel used, but as big as in Ecoinvent inventories.

4. CONCLUSIONS

In relation to the objective to perform detailed construction inventories and provide linear equations to estimate up-to-date and modular inventories as a function of plant capacity, the following conclusions can be withdrawn:

- It is necessary to carry out and publish new construction inventories for subsequent application to other WWTPs. Currently, the information available in Ecoinvent databases is limited only to WWTPs constructed at the end of 1980s or in the early 1990s in Switzerland, which may be different to current plant construction processes and also to practices in other countries.

- Comparing inventories available in Ecoinvent databases and the inventories carried out in this case highlights that there are big differences in relation with the diversity of materials used and the mass consumed. This study contains a more diverse array of materials. However, Ecoinvent inventories have higher masses associated.

- When the construction of WWTPs is considered, the analysis has to consider the entire plant, not only pre-treatment, secondary treatment and sludge line, but also the units not directly correlated with the operation, as connections, buildings and urbanization, which might suppose around 50% of the overall contribution.

- The equations provided in this work aid in accurately adjusting inventories, especially when estimating construction inventories of activated sludge WWTPs, with the capacity of the plant (in $m^3 \cdot d^{-1}$) as the only input parameter.

5. ACKNOWLEDGEMENTS

The authors would like to thank Aigües de Catalunya, Aigües de Manresa, Depuradores d'Osona, Consorci Costa Brava for providing the data from the four WWTPs, Voltes S.L.U. for the technical support, Banc BEDEC, the Ministry of Economy and competitiveness for the Ramon and Cajal grant from Lluís Corominas (RYC-2013-14595) and the REaCH project (CTM2015-66892-R MINECO/FEDER, UE). Serni Morera's FI scholarship (2015FI_B2 00071), STSMscholarship from EU-Cost Action Water2020 (ECOST-STSM-ES1202-110614-044095). LEQUIA and ICRA were recognized as consolidated research groups by the Catalan Government with codes 2014-SGR-1168 and 2014-SGR-291, respectively.

6. REFERENCES

Banc BEDEC. ITEC- Institut Tecnològic de la construcció de Catalunya. https://itec.cat/

Corominas, L., 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 Res., 47 (15), 5480–5492.

Doka, G. (2007). Life Cycle Inventories of Waste Treatment Services. Ecoinvent report No. 13, Swiss Centre for Life Cycle Inventories, Dübendorf, December 2007.

Emmerson, R. H. C., Morse, G. K., Lester, J. N., Edge, D. R. (1995). The Life-Cycle

Analysis of Small-Scale Sewage-Treatment Processes. J.CIWEM, 9, 317–325.

European Commission - Joint Research Centre - Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. (2010). EUR 24708 EN. Luxembourg. Publications Office of the European Union. First edition March 2010.

Foley, J., de Haas, D., Hartley, K., Lant, P. (2010). Comprehensive life cycle inventories of alternative wastewater treatment systems. Water Res., 44 (5), 1654–66.

Machado, A. P., Urbano, L., Brito, A. G., Janknecht, P., Salas, J. J., Nogueira, R. (2007). Life cycle assessment of wastewater treatment options for small and decentralized communities. Water Sci. Technol., 56 (3), 15.

Morera, S., Corminas, Ll., Rigola, M., Comas, J. (2017). Using a detailed inventory of a WWTP to estimate the relative importance of construction to the overal environmental impacts. (submitted)

Ortiz, M., Raluy, R. G., Serra, L. (2007). Life cycle assessment of water treatment technologies: wastewater and water-reuse in a small town. Desalination, 204 (1-3), 121–131.

Renou, S., Thomas, J. S., Aoustin, E., Pons, M. N. (2008). Influence of impact assessment methods in wastewater treatment LCA. J. Clean. Prod., 16 (10), 1098–1105.

Risch, E., Gutiérrez, O., Roux, P., Botuin, C., Corominas, Ll. (2015). Life cycle assessment of urban wastewater systems: Quantifying the relative importance contribution of sewer systems. Wat. Res. 77, (2015) 35-48.

Voltes S.L.U. http://www.voltes.com/

TABLES

Table 1: Location, capacity and operation scheme of the studied WWTPs. Dark grey represents the pretreatment, black the biological reactor, light grey secondary settler and light grey with lines in diagonal represents the sludge treatment.

Table 2: Elements considered in the budget that were included in the construction inventory.

Table 3: Construction materials and processes considered (representative of groups, materials in each group and correspondence to Ecoinvent 3).

Table 4: 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 factors of the materials consumed divided by the plant capacity is provided, to calculate the inventory in these cases is necessary to multiply the plant capacity but of the factors. Eq.: Equation. Parameter “x” in the obtained equations is the plant capacity of the studied plant in $m^3 \cdot d^{-1}$.

Table 4: Location, capacity and operation scheme of the studied WWTPs. Dark grey represents the pretreatment, black the biological reactor, light grey secondary settler and light grey with lines in diagonal represents the sludge treatment.

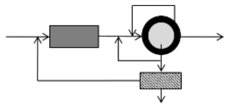
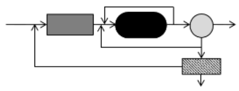
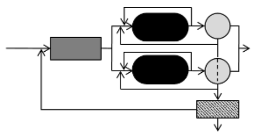
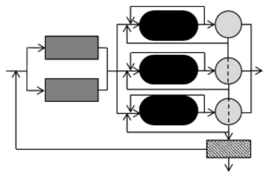
Location (Region)	**Capacity ($m^3 \cdot d^{-1}$)**	**Configuration**
Navàs (Bagès)	1,500 $m^3 \cdot d^{-1}$	
Balaguer (La Noguera)	3,750 $m^3 \cdot d^{-1}$	
Manlleu (Osona)	14,400 $m^3 \cdot d^{-1}$	
L'Escala (Alt Empordà)	21,000 $m^3 \cdot d^{-1}$	

Table 5: Elements considered in the budget that were included in the construction inventory.

Elements	**Sub-elements**
Pre-Treatment	- Receiving waters well - Pumping station - Screening - Grit removal - Degreasing operations
Secondary Treatment	- Biological reactor - Secondary settler
Sludge Line	- Thickener - Dewatering
Buildings	- Control and Services Buildings - Buildings that hold key elements
Urbanization	- Process of asphalting inside the WWTP - Sidewalks construction - Construction of green zones - Placement of metallic fences around the WWTP
Tube connections	- Tube connections
Power connections	- Buildings that hold the electricity transformer

Table 6: Construction materials and processes considered (representative of groups, materials in each group and correspondence to Ecoinvent 3).

Material/Process	Materials considered in each group	Correspondence to Ecoinvent 3 database
Diesel machines	Diesel used for excavation	Diesel, burned in building machine {GLO}| market for | Alloc Def, U
Soil deposition	Excavated soil	Inert waste {RoW}| treatment of, sanitary landfill | Alloc Def, U
Transport	Transport from material distributors to the plant and transport of excavated from works to a landfill	Transport, freight, lorry >32 metric ton, EURO4 {GLO}| market for | Alloc Def, U
Concrete	Concrete	Concrete, normal {GLO}| market for | Alloc Def, U
Reinforcing steel	Reinforcing steel and wire used in reinforced concrete	Reinforcing steel {GLO}| market for | Alloc Def, U
Metals for shoring	Steel used in formworks	Steel, low-alloyed {GLO}| market for | Alloc Def, U
Other metals	Steel, galvanized/stainless steel, brass, aluminium, cast iron	Steel, chromium steel 18/8 {GLO}| market for | Alloc Def, U
Plastics for shoring	PVC used in formworks	Polyvinylchloride[1]
Other plastics	PVC, synthetic rubber, polyurethane, polyethylene, polypropylene, nylon, polyester, polyethylene terephthalate, extruded polystyrene, silicone, glass fibre reinforced plastic	Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U
Woods for shoring	Wood used during formworks and wooden planks	Glued laminated timber, for outdoor use {GLO}| market for | Alloc Def, U
Mortars	Lime mortar, cement mortar, adhesive mortar, cover plaster, concrete for specials uses	Lime mortar {GLO}| market for | Alloc Def, U
Precast pieces	Concrete blocks, bricks, lightweight concrete blocks	Clay brick {GLO}| market for | Alloc Def, U
Other materials	Sand, gravel, epoxy resin, glass, water, paint, varnish, mastic asphalt, bitumen, solvents	Sand {GLO}| market for | Alloc Def, U
Diesel electricity	Diesel used in electricity generation	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.

Table 4: 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 factors of the materials consumed divided by the plant capacity is provided, to calculate the inventory in these cases is necessary to multiply the plant capacity but of the factors. Eq.: Equation. Parameter "x" in the obtained equations is the capacity of the studied plant in $m^3 \cdot d^{-1}$.

Material/Unit		Pretreatment	Secondary treatment	Sludge line	Tube connections
Diesel burned in machines (MJ)	Eq.	$1.74 \cdot 10^1 x$	$1.59 \cdot 10^2 x + 1.39 \cdot 10^5$	$8.76x + 1.57 \cdot 10^3$	$2.22 \cdot 10^1 x + 1.20 \cdot 10^5$
	R^2	1	0.999	0.991	0.953
Soil excavation (kg)	Eq.	$1.16 \cdot 10^2 x$	$1.06 \cdot 10^3 x + 9.30 \cdot 10^5$	$5.76 \cdot 10^1 x$	0 t $1.51 \cdot 10^3$
	R^2	1	0.999	0.967	
Soil transport to landfill (tkm)	Eq.	$4.65x$	$4.24 \cdot 10^1 x + 3.72 \cdot 10^4$	$2.31x$	0 to $6.04 \cdot 10^1$
	R^2	1	0.999	0.967	
Concrete (kg)	Eq.	$6.52 \cdot 10^1 x + 4.39 \cdot 10^4$	$1.11 \cdot 10^3 x - 2.98 \cdot 10^5$	$9.27 \cdot 10^1 x - 6.56 \cdot 10^3$	$3.61 \cdot 10^{-5}$ to $3.64 \cdot 10^1$
	R^2	0.901	0.997	0.960	
Reinforcing steel (kg)	Eq.	$2.54x - 5.74 \cdot 10^2$	$4.27 \cdot 10^1 x - 2.41 \cdot 10^4$	$2.93x - 2.29 \cdot 10^3$	0 to 1.40
	R^2	0.886	0.971	0.873	
Metals for formworks (kg)	Eq.	$9.14 \cdot 10^{-3} x + 4.25 \cdot 10^1$	$1.65 \cdot 10^{-1} x + 1.05 \cdot 10^2$	$1.01 \cdot 10^{-2} x - 7.01$	0 to $2.48 \cdot 10^{-3}$
	R^2	0.766	0.944	0.733	
Other metals (kg)	Eq.	$4.26 \cdot 10^{-2}$ to $3.12 \cdot 10^{-1}$	$3.13 \cdot 10^{-2}$ to $2.31 \cdot 10^{-1}$	$5.20 \cdot 10^{-2}$ to 3.02	$1.62 \cdot 10^{-1}$ to 3.60
Plastics for	Eq.	$3.94 \cdot 10^{-4} x + 1.83$	$7.11 \cdot 10^{-3} x + 4.54$	$4.29 \cdot 10^{-4} x - 3.11 \cdot 10^{-1}$	0 to $1.07 \cdot 10^{-4}$

formworks (kg)	R^2	0.766	0.943	0.723	
Other plastics (kg)	Eq.	$4.00 \cdot 10^{-3}$ to $9.30 \cdot 10^{-2}$	$7.95 \cdot 10^{-1}x - 1.19 \cdot 10^{3}$	$1.47 \cdot 10^{-2}$ to $1.18 \cdot 10^{-1}$	$5.30 \cdot 10^{-2}$ to 2.11
	R^2		0.729		
Wood for formworks (kg)	Eq.	$7.30 \cdot 10^{-3}x + 3.40 \cdot 10^{1}$	$1.56 \cdot 10^{-1}x - 1.41 \cdot 10^{2}$	$3.87 \cdot 10^{-2} x + 5.26 \cdot 10^{1}$	0 to $2.49 \cdot 10^{-3}$
	R^2	0.766	0.999	0.975	
Other Wood (kg)	Eq.	No	0 to 1.84	0 to $3.55 \cdot 10^{-2}$	0 to $3.29 \cdot 10^{-2}$
	R^2				
Mortars (kg)	Eq.	$5.58x - 8.2 \cdot 10^{3}$	$4.27 \cdot 10^{-1}$ to 2.61	$5.05x + 2.62 \cdot 10^{3}$	0 to 4.81
	R^2	0.911		0.876	
Precast pieces (kg)	Eq.	$1.01 \cdot 10^{1}x - 1.51 \cdot 10^{4}$	$5.32 \cdot 10^{-1}$ to $1.80 \cdot 10^{1}$	$8.71x + 1.31 \cdot 10^{4}$	0 t $2.94 \cdot 10^{1}$
	R^2	0.955		0.902	
Other materials (kg)	Eq.	$2.44 \cdot 10^{-2}$ to $2.69 \cdot 10^{1}$	$5.31 \cdot 10^{1}$ to $3.31 \cdot 10^{2}$	$4.63 \cdot 10^{1}$ to $9.17 \cdot 10^{1}$	$4.58 \cdot 10^{1}$ to $2.87 \cdot 10^{2}$
	R^2				
Diesel for electricity (MJ)	Eq.	$2.32 \cdot 10^{-2}$ to 2.58	$5.02 \cdot 10^{-3}$ to $1.23 \cdot 10^{-1}$	$2.35 \cdot 10^{-2}$ to 2.80	0 to $6.26 \cdot 10^{-1}$
	R^2				
Material transport (tkm)	Eq.	$2.93x + 1.41 \cdot 10^{3}$	$4.62 \cdot 10^{1}x - 1.29 \cdot 10^{4}$	4.38x	1.84 to $131 \cdot 10^{1}$
	R^2	0.909	0.996	0.953	

Table 4 (cont.)

Material/Unit		Buildings	Urbanization	Power connection	Full plant
Diesel burned in machines (MJ)	Eq.	2.97 to $1.97\cdot10^{1}$	$1.67\cdot10^{2}$ to $2.92\cdot10^{2}$	0 to $4.92\cdot10^{1}$	$4.30\cdot10^{2}x+4.15\cdot10^{5}$
	R^2				0.997
Soil excavation (kg)	Eq.	$1.08\cdot10^{1}$ to $7.15\cdot10^{1}$	$2.19\cdot10^{3}x+3.20\cdot10^{5}$	0 to $1.22\cdot10^{1}$	$3.94\cdot10^{3}x+5.81\cdot10^{5}$
	R^2		0.990		0.939
Soil transport to landfill (tkm)	Eq.	$5.39\cdot10^{-2}$ to$7.22\cdot10^{-1}$	7.60 to $4.07\cdot10^{1}$	0 to $2.46\cdot10^{-2}$	$6.16\cdot10^{1}$ to $1.53\cdot10^{2}$
	R^2				
Concrete (kg)	Eq.	$3.75\cdot10^{1}x+3.16\cdot10^{5}$	5.53 to $2.93\cdot10^{2}$	0 to $2.90\cdot10^{1}$	$1.33\cdot10^{3}x+5.50\cdot10^{5}$
	R^2	0.995			0.977
Reinforcing steel (kg)	Eq.	$1.73x+3.42\cdot10^{3}$	0 to 1.16	0 to $6.60\cdot10^{-2}$	$5.09\cdot10^{1}x-2.50\cdot10^{4}$
	R^2	0.999			0.953
Metals for formworks (kg)	Eq.	$1.38\cdot10^{-2}$ to $3.76\cdot10^{-2}$	0 to $6.14\cdot10^{-3}$	0 to $9.55\cdot10^{-5}$	$2.02\cdot10^{-1}x+1.71\cdot10^{2}$
	R^2				0.894
Other metals (kg)	Eq.	$2.43\cdot10^{-1}$ to 2.65	$1.51\cdot10^{-2}$ to $8.66\cdot10^{-1}$	0 to $1.96\cdot10^{-1}$	1.15 to 8.12
Plastics for formworks (kg)	Eq.	$8.09\cdot10^{-4}$ to $5.65\cdot10^{-3}$	0 to $2.62\cdot10^{-4}$	0 to $4.11\cdot10^{-6}$	$8.74\cdot10^{-3}x+7.27$
	R^2				0.873
Other plastics (kg)	Eq.	$6.23\cdot10^{-2}x+7.01\cdot10^{1}$	0 to $7.34\cdot10^{-2}$	0 to $2.41\cdot10^{-1}$	$2.97\cdot10^{-1}$ to 3.38
	R^2	0.988			
Wood for formworks (kg)	Eq.	$1.11\cdot10^{-2}$ to $3.00\cdot10^{-2}$	0 to $5.03\cdot10^{-3}$	0 to $7.63\cdot10^{-5}$	$2.16\cdot10^{-1}x-3.03\cdot10^{1}$
	R^2				0.986

Other Wood (kg)	Eq.	$1.48\cdot10^{-1}x+2.97\cdot10^{2}$	0 to $1.16\cdot10^{-1}$	No	$2.17\cdot10^{-1}$ to 2.00
	R^2	0.982			
Mortars (kg)	Eq.	9.04 to $4.21\cdot10^{1}$	$5.38\cdot10^{-1}$ to 4.20	0 to $1.30\cdot10^{-1}$	8.08 to $5.55\cdot10^{1}$
	R^2				
Precast pieces (kg)	Eq.	$1.36\cdot10^{1}x+8.29\cdot10^{4}$	1.88 to $2.29\cdot10^{1}$	0 to 2.27	$1.91\cdot10^{1}$ to $1.46\cdot10^{2}$
	R^2	0.999			
Other materials (kg)	Eq.	5.47 to $7.21\cdot10^{1}$	$2.96\cdot10^{3}x-4.01\cdot10^{6}$	0 to $2.34\cdot10^{3}$	$4.94\cdot10^{3}x-5.34\cdot10^{6}$
	R^2		0.958		0.953
Diesel for electricity (MJ)	Eq.	$3.53\cdot10^{-1}$ to $8.85\cdot10^{1}$	0 to 2.49	0 to $1.00\cdot10^{-1}$	$3.49\cdot10^{-1}$ to $1.43\cdot10^{1}$
	R^2				
Material transport (tkm)	Eq.	$2.12x+1.61\cdot10^{4}$	$1.20\cdot10^{2}x-1.44\cdot10^{5}$	$1.33\cdot10^{-4}$ to $9.36\cdot10^{1}$	$2.58\cdot10^{2}x-2.18\cdot10^{5}$
	R^2	0.998	0.956		0.959

FIGURES

Figure 1: Comparison of the masses of the most important materials considered.

Figure 2: Comparison of the potential environmental impacts of the complete plants. Raw inventories from Ecoinvent (with a change in the concrete type as explained in materials and methods) were run through SimaPro using RECIPE.

Figure 3: Percentage of contribution of each unit in the environmental impacts of the different studied plants.

Figure 4: Analysis of the contribution of each material and unit for Navàs WWTP.

Figure 5: Comparison between the real impact of the WWTPs construction and impact calculated by means of the equations and ranges provided. For real inventories all materials and processes were considered (no grouping was applied). For the calculated inventories, only the characterization factors of the representative group material were applied.

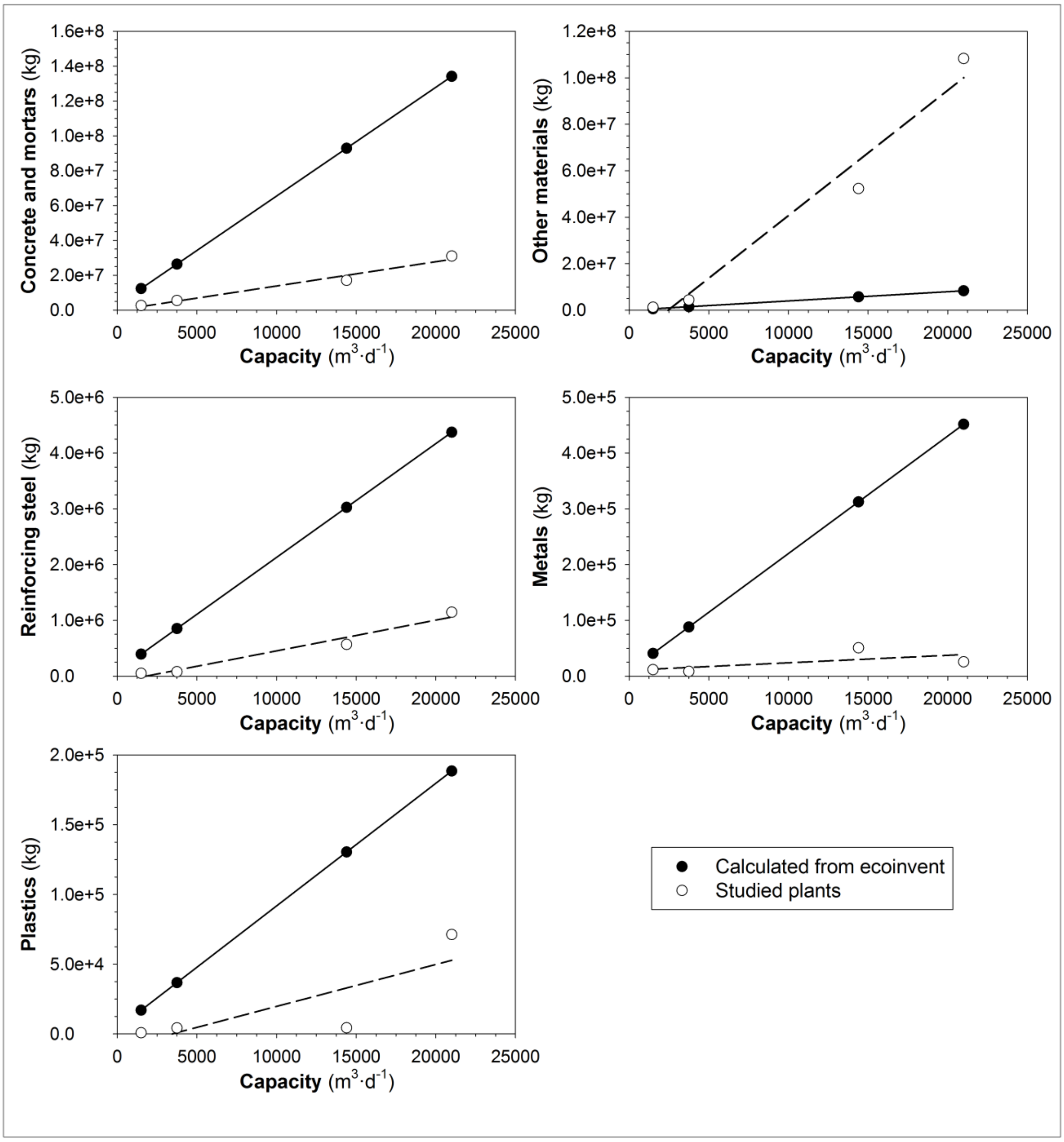


Figure 6: Comparison of the masses of the most important materials considered

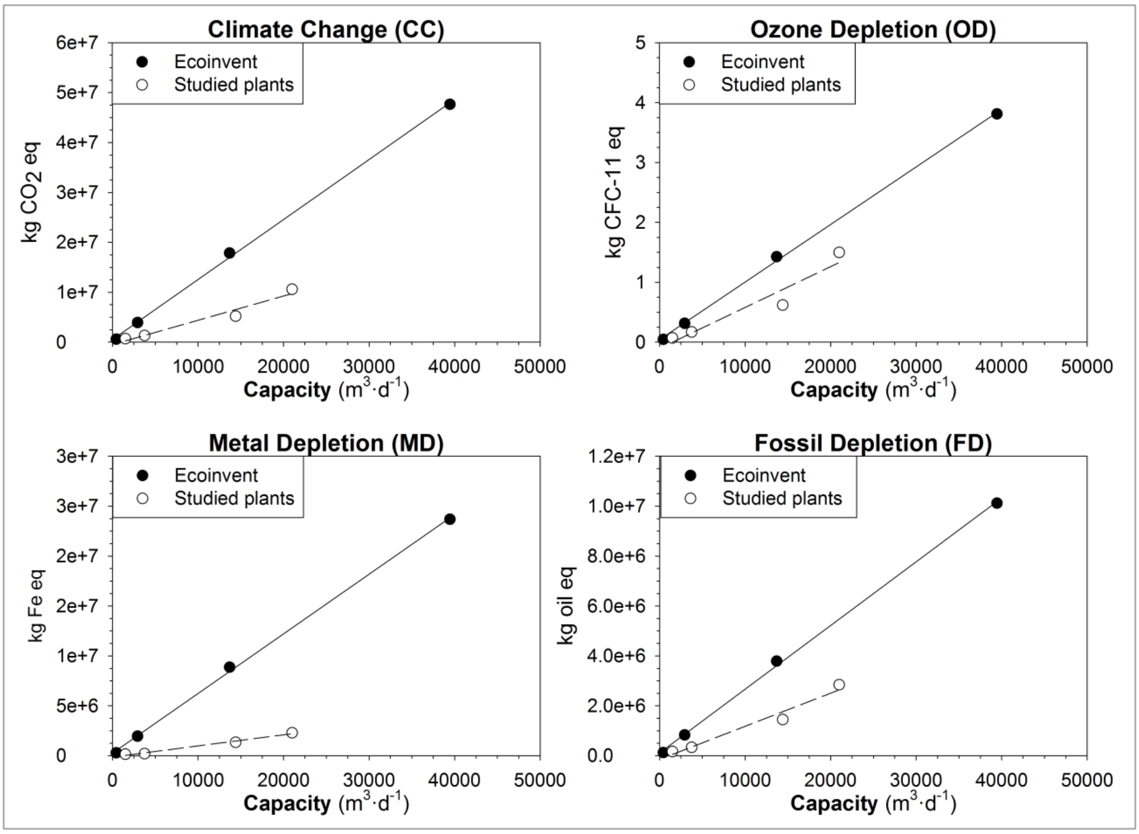


Figure 7: Comparison of the potential environmental impacts of the complete plants. Raw inventories from Ecoinvent (with a change in the concrete type as explained in materials and methods) were run through SimaPro using RECIPE

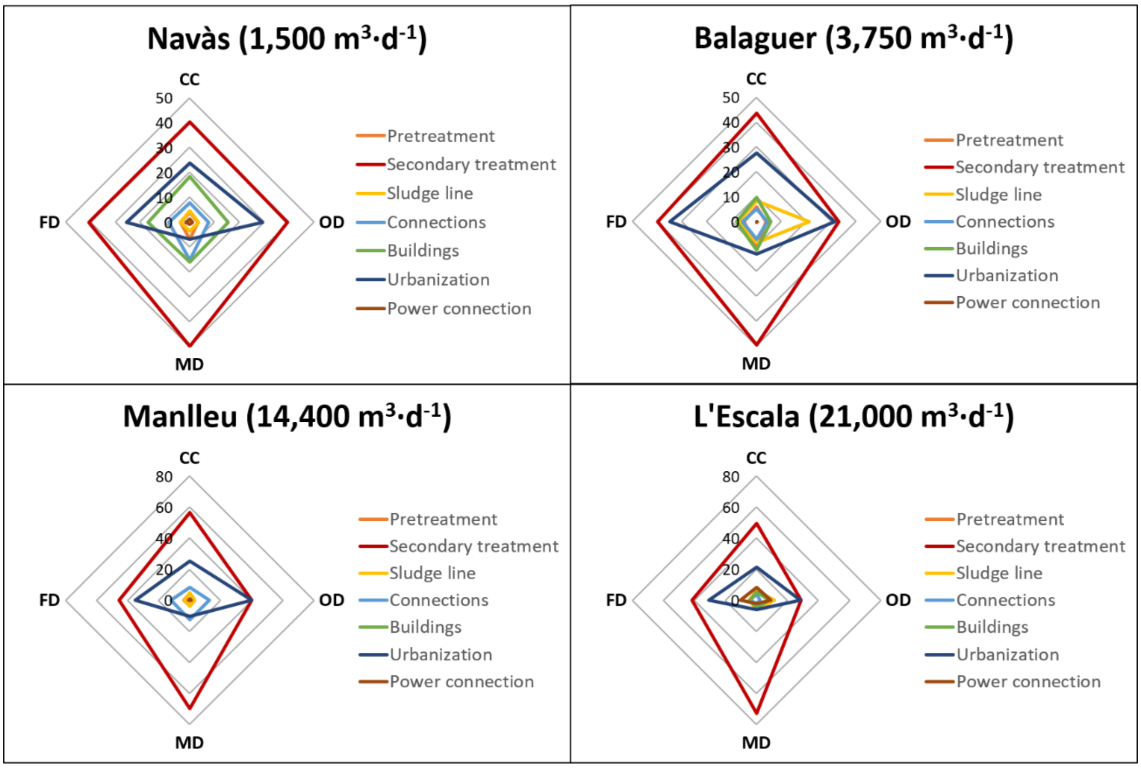


Figure 8: Percentage of contribution of each unit in the environmental impacts of the different studied plants

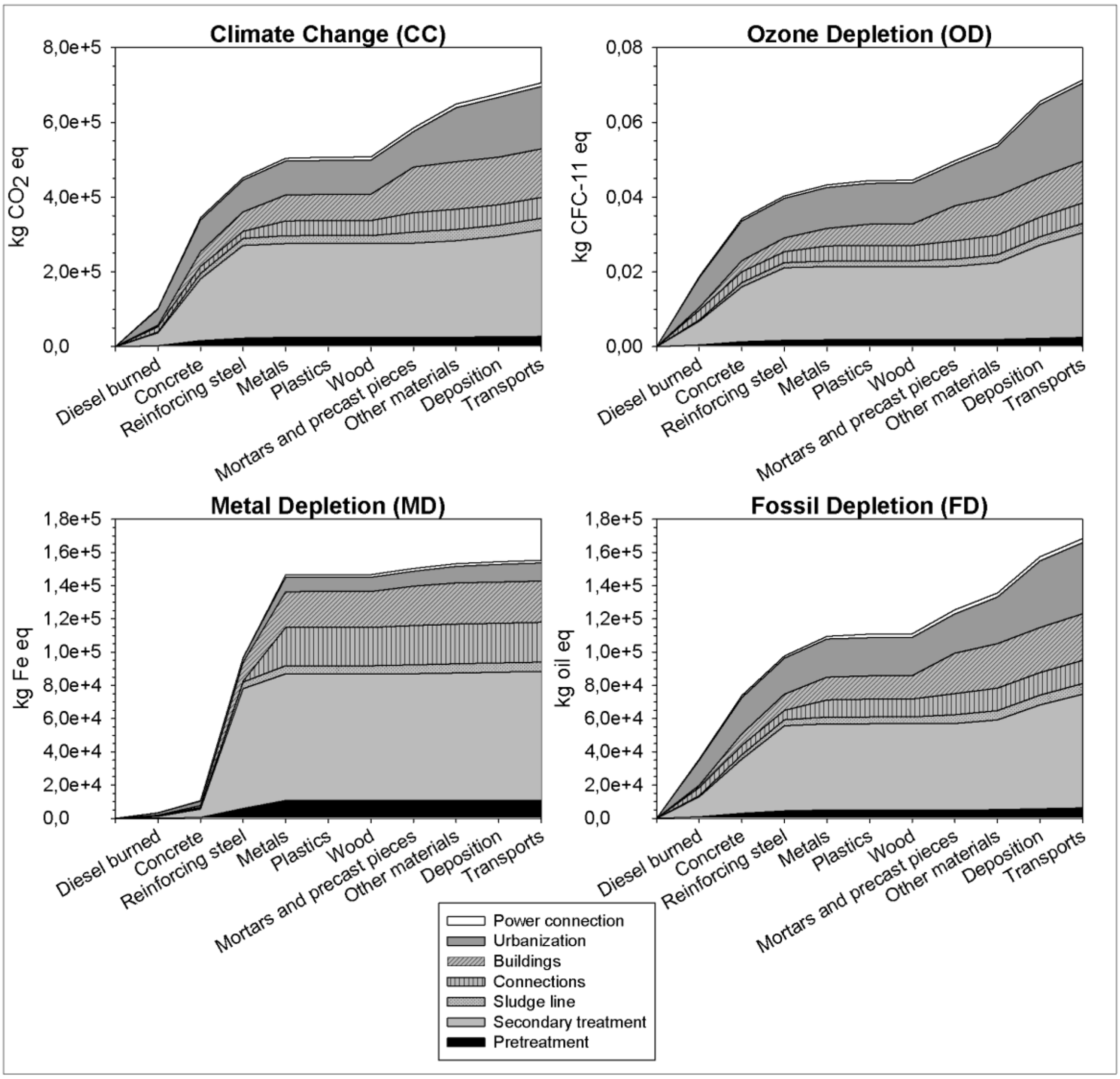


Figure 9: Analysis of the contribution of each material and unit for Navàs WWTP

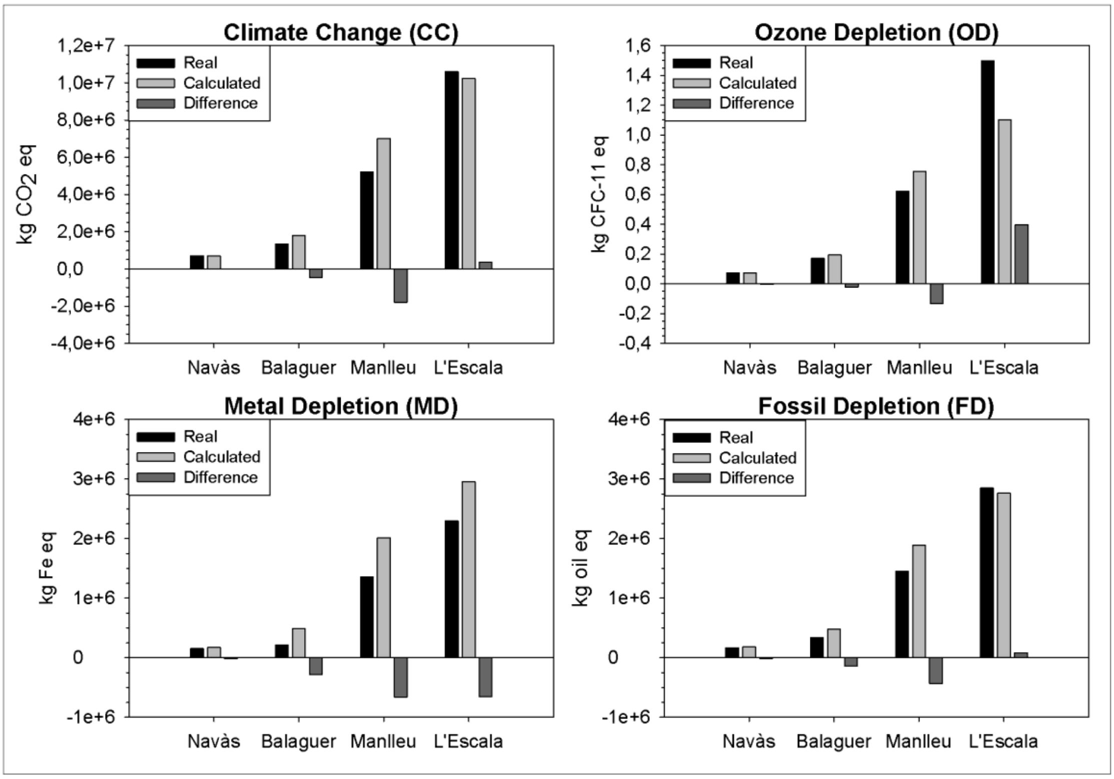


Figure 10: Comparison between the real impact of the WWTPs construction and impact calculated by means of the equations and ranges provided. For real inventories all materials and processes were considered (no grouping was applied). For the calculated inventories, only the characterization factors of the representative group material were applied