Environmental and geometrical optimization of cylindrical drinking water storage tanks

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Abstract

Purpose

The construction of the urban water cycle is an important element to consider when assessing the sustainability of urban areas. The present study focuses on the structural and environmental analysis of cylindrical water tanks. The goal is to optimise cylindrical water tanks from an environmental (environmental impacts resulting from the life cycle assessment (LCA)) and geometrical perspective (quantity of building materials for the construction depending on the characteristics of the tanks).

Methods

A sample of 147 cases has been defined considering different positions (buried, superficial and partially-buried), dimensions (combinations of heights and radius) and storage capacities (between 100 and 10,000 m^3). A structural analysis has been done for the set of cases defined in order to determine the quantities of steel and concrete required for its construction. The environmental impacts of the whole life cycle were assessed using life cycle assessment (LCA). Additionally, the environmental standards (the less impacting option for each of the dimensions assessed: geometry, storage capacity and position) defined in the study have been applied to realistic cases in order to evaluate the potential environmental savings.

Results and discussion

The environmental assessment of the life cycle shows that materials are the main contributor to the environmental impacts, above transport, installation and end of life. For this reason, the results from the structural and the environmental assessments coincide. Higher water tanks have shown being less impacting (60 to 70% lower impacts for a 10.000 m^3 tank). Regarding the position, superficial water tanks have between 15 and 35% lower impacts compared with buried ones. The environmentally preferable water storage capacity is between 1,000 and 2,500 m^3, accounting for between 20 and 40% lower impacts. For instance, constructing a 8,000 m^3 tank, would emit 1,040 t of CO_2 eq. Applying the environmental standards the emissions would save 170.5 t of CO_2 eq (16% of the total).

Conclusions

The results of this study show that, among the cases analysed, the less impacting cylindrical water tanks are those superficially placed, with 8.5 m in height and between 1,000 and 2,500 m^3 of storage capacity.

The application of these standards to municipal water tanks construction projects could save significant environmental impacts (10 to 40%) in all impact categories.

1. Introduction

1.1 Urban water cycle and water supply

The supply of water is a worldwide basic need for the development of communities. The urban water cycle (UWC) consists of a series of stages connected each with the following, providing water to the population and evacuating the wastewater and the excess of rainwater (UNESCO, 2012). Water is treated after its abstraction from the environment in order to reach the required quality to be potable and is then transported to the consumption point. Then, it goes through the sewerage and it is treated again before being returned to the environment or reused.

Several previous articles applying life cycle assessment (LCA) to the UWC have shown that it holds significant environmental impacts. For instance, the construction and operation of the UWC can imply releasing 0.03 to 0.279 t CO_2 eq./year·inhabitant (Sharma et al., 2009; Friedrich et al., 2009) or 1.5 to 2.5 t of CO_2 eq./m^3 (Muñoz et al., 2010). One of the most impacting elements of the UWC is the wastewater treatment, as shown in some previous studies focused on this issue (Lassaux et al., 2007;). Thus, a further assessment of these environmental impacts is needed, in order to increase the completeness and accuracy of the available data.

Within the UWC, water transport networks represent a significant contributor to its environmental impacts (Sanjuan et al., 2013; Petit-Boix et al., 2014). The drinking water transport and distribution network (DWTDN) is the necessary infrastructure required to bring water from the drinking water tank to the consumption point and can account for between 20 and 40% of the UWC environmental impacts (Amores et al., 2013; Lemos et al., 2013).

The use phase of the DWTDN is especially relevant, due to the environmental impacts of the energy consumption for pumping the water (Piratla et al., 2012). However, its environmental impacts hold large variations depending on the case study. The amount of energy required to pump the water, whose consumption can imply emissions of 5.53 kg of CO_2 per inhabitant and year, depends on case-specific factors such as the topography of the area where the network is located and the position of the different elements (Sanjuan-Delmás et al., 2014). The environmental impacts of DWTDN maintenance phase are negligible in contrast with the construction phase (Venkatesh & Brattebø, 2011; Piratla et al., 2012; Del

Borghi et al., 2013). Provided the above, this article is focused in the phase of construction in order to obtain useful results that can be generalized for all the networks.

Focusing on the construction phase, most of the impacts occur during the expansion of the network (while the extended network is being built) (Venkatesh & Brattebø, 2012). A previous article from Sanjuan-Delmás et al. (2013) presents a method to calculate the environmental impacts of a small to medium city DWTDN. The output of the present study will contribute with new information about the drinking water supply, providing reliable data about the environmental impacts of the water tanks.

1.2 Drinking water tanks

This study analyses drinking water tanks, which are a basic element of the DWTDN. The configuration of water tanks within the DWTDN must be adequate to provide water with the required quantity, quality and pressure. However, few studies have analysed the water tank individually, which may have relevant impacts. The output of the study will fill the present gap in the environmental assessment of drinking water tanks using LCA, providing more completeness to the available data about the emissions of the DWTDN and UWC systems.

Typically, medium cities (from 10,000 to 50,000 inhabitants) have several water tanks, which hold one or more of the following functions: flow regulation, pressure regulation and supply security. Usually, municipal water tanks for the supply of medium and big cities are made of concrete, provided that it is the most common material for large tanks. According to their geometry, water tanks can present different shapes. The most common are the rectangular and the cylindrical geometry. Among all the possible configurations, the cylindrical one is the best structural solution and allows a greater optimization of the materials because it gets the minimum perimeter for a given height and volume (CEDEX, 2010). For this reason, the analysis performed in this paper is focused on cylindrical configurations, as a first step. However, cylindrical tanks cannot always be installed due to limitations of the urban form. Thus, the analysis of rectangular tanks would also be of interest for the audience.

Water tanks can require some maintenance operations given its long lifespan. Takeuchi et al. (2004) assessed the maintenance of a highly deteriorated 4,500 m^3 concrete water tank in Chiba (Japan). The repairs consisted of spraying anticorrosion painting in the inner surface, repairing concrete in the outer surface and replacing the dome.

Whereas several guidelines have been published focusing on the technical aspects of water tanks (EPA, 2002; AWWA, 1995; Walski, 2000; CEDEX, 2010), little research has been done regarding its environmental impact and sustainability. Small water tanks (up to 200 m^3) for water storage in rainwater harvesting systems were analysed from a LCA perspective (Angrill et al., 2011; Vargas-Parra et al., 2013). Also wastewater tanks have been environmentally assessed (Llopart-Mascaró et al., 2014), focusing on the influence and the quality of the wastewater.

The goal of the present article is to optimise cylindrical water tanks from a geometrical and environmental perspective. This is, to define environmental standards (the less impacting option for each of the dimensions assessed: geometry, position and storage capacity) to reduce the environmental impacts in the construction of a drinking water tank. The specific goals of the study are:

- To select a number of representative cases of cylindrical water tanks comprising realistic ranges of volumes, dimensions and positions (buried, superficial and partially buried).
- To assess the geometrical optimization and the environmental impacts of the water tank cases analysed following the LCA methodology.
- To determine which the most optimal water tank is (considering its dimension, position and volume) among the cases studied for each volume and define a curve for the calculation of the environmental impacts of the optimal cases.
- To apply the methodology of assessment to 3 case studies.

The results of the current study will provide new information about the environmental impacts of geometrically optimised municipal water storage tanks as well as information about which options are environmentally preferable.

2. Materials and methods

2.1 Case studies selection

The variables considered in order to assess the geometrical and environmental optimization of cylindrical water tanks were the following: (1) position in relation to the ground level, (2) storage capacity (volume of the tank) and (3) dimensions (in terms of height and radius). According to CEDEX (2010), for constructive reasons a 30cm wall thickness is generally used in the design of water tanks (due to the minimum distance between the walls needed to set the reinforcement and cast the formworks). Therefore a fixed logical value of 30 cm wall thickness is considered in the study carried out in this paper.

Three different positions with regards to the ground level were considered: superficial (S; 0% of the tank underground), partially-buried (P; 50% underground) and buried (B; 100% underground). For each, 7 different volumes were analysed (in m^3): 100; 500; 1,000; 2,500; 5,000; 7,500 and 10,000; covering the range of water tanks commonly used in small and medium municipalities (Agbar, 2013). Finally, for each tank position and volume, 7 different heights (and radius) were studied. The heights considered are (in m): 2.0, 3.0, 4.0, 5.0, 6.0, 7.0 and 8.0; all of them with an additional covering of 0.5 m for constructional reasons. All the different values considered in each of the cases studied are summarized in Table 1.

Table 1. Case studies dimensions

Height (m)	**Radius (m) for a given volume**						
	100 m^3	**500 m^3**	**1,000 m^3**	**2,500 m^3**	**5,000 m^3**	**7,500 m^3**	**10,000 m^3**
2.5	4.0	9.0	13.0	20.0	28.5	35.0	40.0
3.5	3.3	7.5	10.5	16.5	23.5	28.5	33.0
4.5	3.0	6.5	9.0	14.5	20.0	24.5	28.5
5.5	2.6	5.7	8.0	13.0	18.0	22.0	25.5
6.5	2.4	5.2	7.5	12.0	16.5	20.0	23.5
7.5	2.2	4.8	7.0	11.0	15.5	18.5	21.5
8.5	2.0	4.5	6.5	10.0	14.5	17.5	20.0

In total, 147 different water tanks have been analysed.

In order to distinguish between the different case studies, the following nomenclature has been stated, all starting with C (cylindrical). First, the position of the tank (B=buried, PB=partially buried, S=superficial); then the volume of the tank (ex. 100 for a 100 m^3 tank) and finally the height (ex. 2 for 2.0 m plus 0.5 for constructional reasons). Therefore, a superficial cylindrical tank with 1,000 m^3 of capacity and 6.5 m in height would be expressed as ‘’CS10006’’.

2.2 Functional unit

The functional unit is the reference value to which all the cases compared must be referred to. This is a basic element of an LCA and must be properly defined. For this study, the functional unit considered is one cubic meter of water storage capacity including the production, transport, installation and end of life of the water storage tank for 50 years.

Since all the cases analysed are made of reinforced concrete, no differences have been considered regarding the lifespan of the cases for the comparison. Nevertheless, based on the expertise of the authors, the lifespan of a municipal water tank is estimated to be around 50 years. This lifespan was used, for instance, in Vargas-Parras et al. (2013).

Thus, the resulting total impact of the tank has been divided by its total capacity for each of the impact categories (impact/m^3 of water stored). The final volume required for storing water will depend on different service factors such as the number of inhabitants.

The life cycle stages of the system under assessment along with the system boundaries and the different elements considered for each of the stages are shown in Figure 1. Note that the operation phase has been excluded given that it involves a great variability depending on the specific case, especially because of the difference in the water pumping (section 1). As it can be observed, the energy and materials consumption, as well as the emissions derived from the system, have been considered when analysing the environmental impacts.

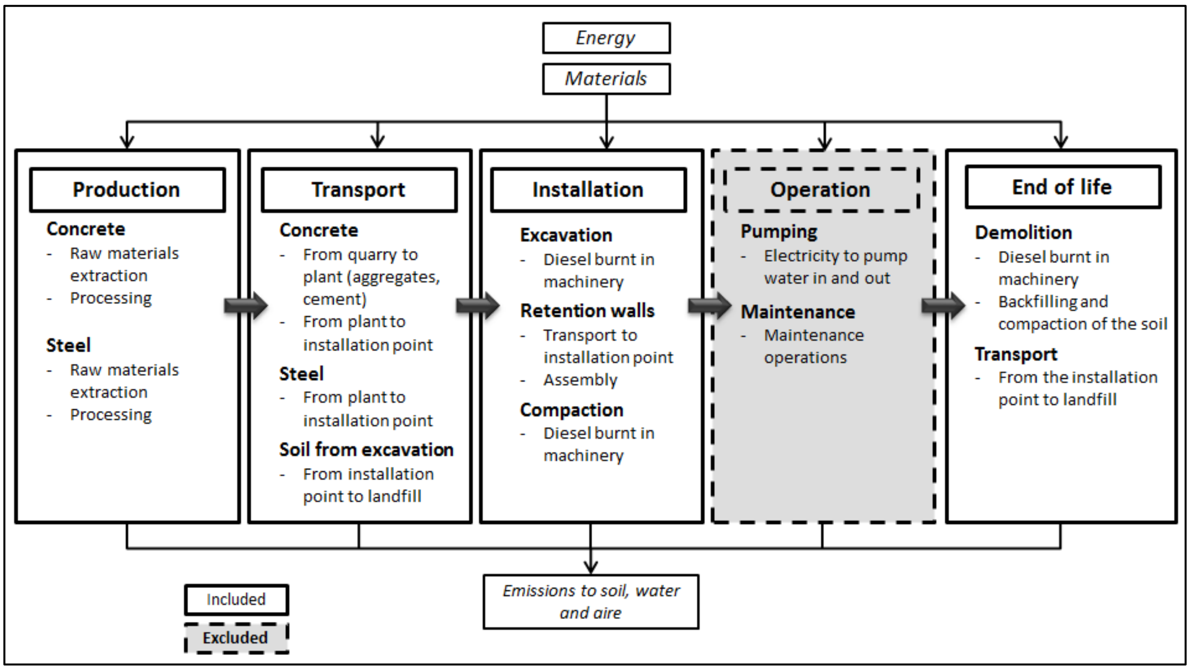

Figure 1 Diagram and system boundaries of the drinking water tank life cycle.

2.3 Structural design performance

The aim of the structural study is to analyse the influence of the variables set in the parametric study (volume, position with regards to the ground and dimensions) on the amounts of materials used for the construction of the water tank.

The volume of soil excavated and the concrete and reinforcement steel required for the construction of the tank were calculated considering its volume and geometry configuration. Such calculation is based on the design code EHE (Spanish Ministry of Public Works, 2008) which is the Spanish regulatory framework laying down the requirements which concrete structures must met to satisfy structural safety and security requirements. This code has already been used by other authors to design cylindrical water tanks (Riba et al., 2006; Orbe et al., 2013).

Figure 2 represents the flowchart of the structural sectional analysis design proposed by the EHE (Spanish Ministry of Public Works, 2008) code and performed in this study. The basis of the tank sizing used is the limit state design method. Limit States are defined as those situations in which, when exceeded, it may be considered that the structure does not fulfil one of the functions for which it has been designed. For the purposes of this paper, two Limit States were verified: Ultimate Limit State (ULS, covers all Limit States giving rise to the failure of the structure, due to a loss in equilibrium, collapse or breakage thereof or part thereof) and Serviceability Limit State (SLS, covers all Limit States for which the required functionality, comfort or aspect requirements are not fulfilled)

It must be checked that the structure does not exceed any of the Limit States in any of the design situations, taking into account the design values of the actions, the characteristics of materials and geometric data. For a certain Limit State the checking procedure consists in determining, on the one hand, the effect of the actions applied to the structure or part thereof and, on the other, the response of the structure for the limit situation being studied. The Limit State shall be guaranteed if it is verified, with a sufficient reliability index, that the structural response is no lower than the effect of the applied actions. To this end, the partial safety factors proposed within the EHE are considered to increase the effects of the actions as well as to reduce the strength of each of the constitutive materials.

According with the common practice in the sector, a concrete of 30 MPa and a B500S steel were used for the study. Moreover the tank was placed in a general exposure class IIB (exteriors in the absence of chlorides, subject to the action of rain water, in areas with an average annual rainfall under 600 mm) which according to the reference code used leads to a steel nominal covering of 30 mm.

Moreover, the most unfavourable effect of the actions applied to the tank was considered for the design (empty tank for the cases of buried and partially buried, and full tank in the case of superficial).

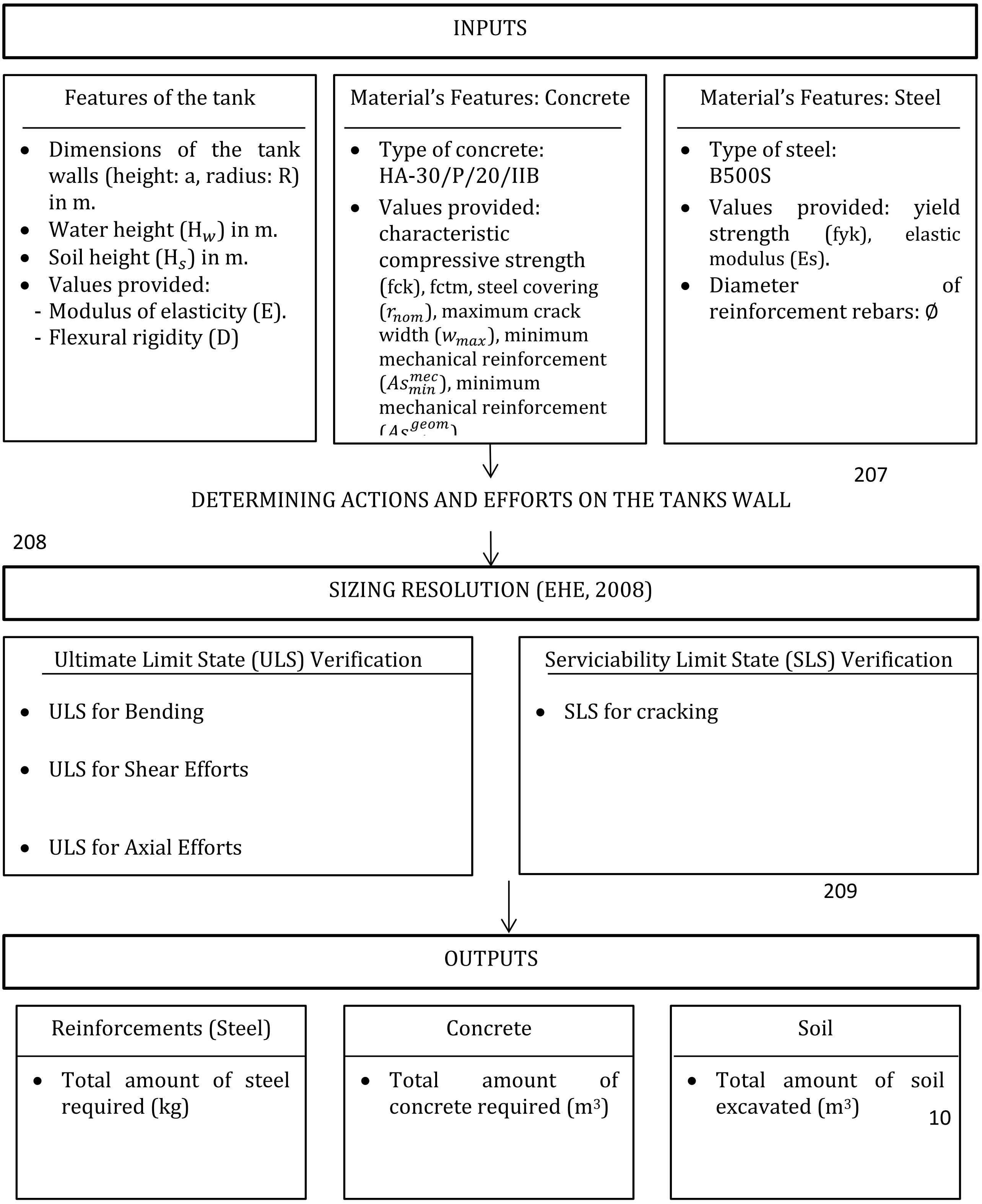

Figure 2. Flowchart of the general structural design performance.

2.4 Life cycle assessment

The methodology utilized for the calculation of the environmental impacts is the LCA stated in the ISO 14040 (ISO, 2006), which is a commonly accepted and used method within the scientific community (Guinée et al., 2011). The process-LCA methodology has been implemented in the study. Other methodologies types of LCA such as economic input-output LCA and hybrid LCA allow a wider consideration of the system and include second order environmental impacts (Stokes and Horvath, 2011;Noori et al., 2013, 2014). However, the process-LCA was considered more appropriate for this study, because it aims to include a large number of cases (147) and the optimization implemented is based on the engineering facet, not including economic valuation. Moreover, the study focuses on the construction of the tank (not the operation phase) reducing considerably the variations in the impacts of the different case studies.

There are currently different commonly used LCA methodologies, such as economic input-output LCA or hybrid LCA. The specific methodology selected in this paper is Process-LCA .

The software Simapro 7.3 has been used, along with the calculation method CML 2001 V2.05 (Guinée et al., 2002). All the environmental information has been taken from Ecoinvent 2.2 database (ecoinvent, 2009), allowing the comparability of all the cases under assessment.

The following 6 midpoint impact categories have been considered in the study: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion (ODP) and photochemical oxidation potential (POCP). Additionally, another midpoint impact category was considered, the cumulative energy demand (CED).

2.5 Data sources

The database from the Institute of Technology of Catalonia (Metabase Itec, 2010) has been used so as to obtain data regarding the amount of energy and materials consumed in the processes for the construction of the water tank.

For the transport of materials, the following standard distances have been considered, which have already been used in previous studies (Mendoza et al., 2012; Oliver-Solà et al., 2009; Kellenberger & Althaus, 2009). For the manufacture of the reinforced concrete 75 km were considered for cement from quarry to concrete plant; this distance was considered to be 40 km for aggregates. From the facility to the installation site, 30 km were defined, as well as from site to landfill at the end of life. From the plant to the installation site, 130 km were considered for the reinforcing steel bars.

In order to apply the results, 3 water storage tanks were considered as case studies. Table 2 includes the characteristics of these 3 case studies. These case studies were based on data about real water tanks.

Table 2. Technical characteristics of the water tanks analysed as case studies.

ID	Volume (m^3)	Diameter (m)	Height (m)	Wall thickness (cm)	Shape	Material
1	400	5.05	5	30	Cilindrical	Reinforced concrete
2	2,000	11	5.3			
3	8,000	18.5	7.4			

3. Results

3.1 Structural analysis of cylindrical water tanks

3.1.1 Geometrical assessment

The optimal geometrical configuration will be given for the solution using less materials for a given water volume. The amount of materials needed for each case will be given by the design phase. Considering that in accordance with standard designs, the concrete section for the all the different configurations studied remain relatively constant, the amount of concrete does not influence the result. Therefore, in this section the analysis will be focused on the amount of steel required for its construction.

Figures 3 present the required steel reinforcement for the construction of water tanks for all the volumes analysed depending on the different geometrical configurations. In order to improve the representation of the results, only superficial tanks have been represented (buried and semi-buried tanks present similar patterns) and the cases have been divided in two groups in relation to its volume. However, the rest of the data can be found in *Supplementary table A*.

As shown in Figure 3, tanks with higher heights (and shorter radius) are the ones which require lower amounts of material for its construction for all the volumes studied. This is because this relation between height and radius allows a better distribution of the stresses, reducing the requirements of reinforcement and therefore the quantity of materials required for its construction. Nevertheless, this curve has an inferior limit after which it becomes stagnant.

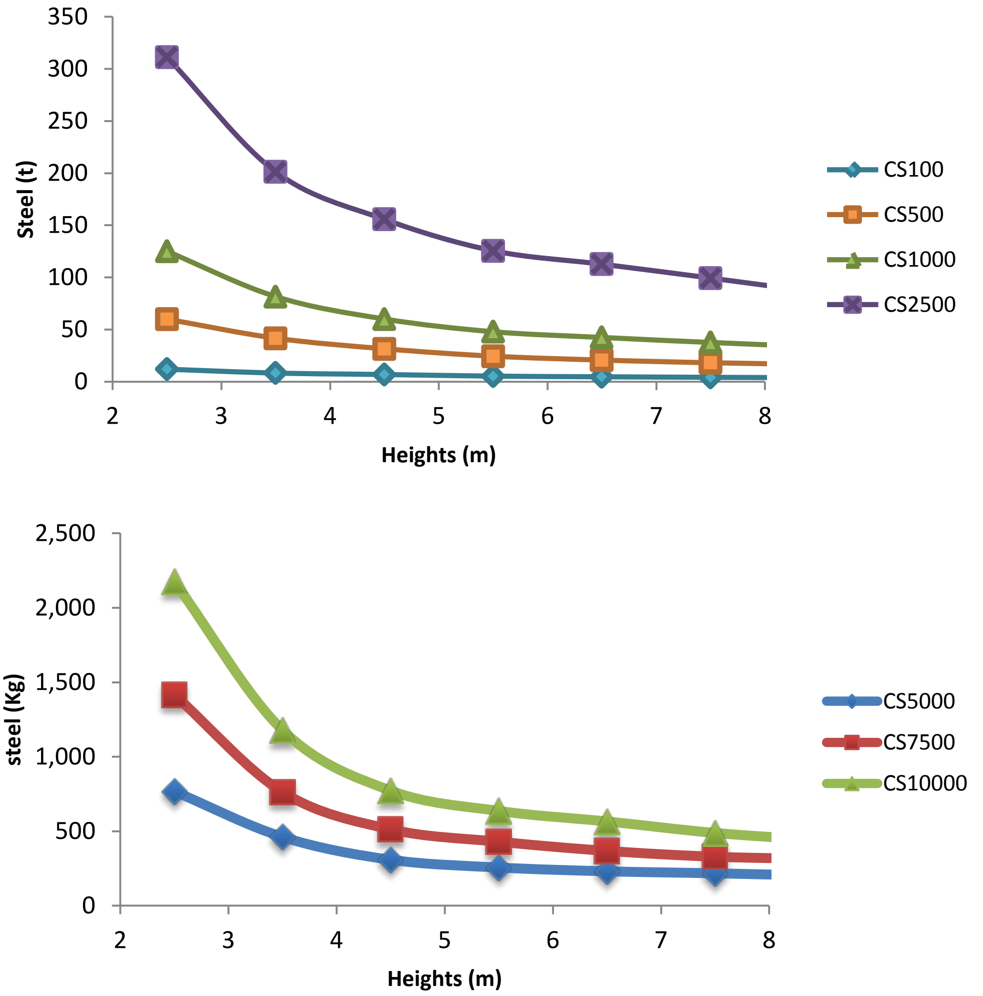

Figure 3. Total amount of reinforcing steel required for the construction of superficial water tanks with 100, 500, 1,000, 2,500, 5,000, 7,500 and 10,000 m^3 of storage capacity depending on its height.
CS= cylindrical water tanks superficially placed

3.1.2 Assessment of the position in relation to ground

The most optimal geometrical configuration (tanks with 8.5 meters of height) has been considered for the analysis of the different tank typology in relation to ground (partially buried, superficial or buried).

For each cylindrical tank typology, Figure 4 presents the amount of materials required for the construction of each volume. The chosen variables have been expressed by the following ratios. (1) The materials consumption is expressed in terms of $\frac{kg\ Steel}{kg\ Concrete}$. As the amount of concrete remains constant for each different typology, this ratio expresses the evolution of the materials consumption for all volumes depending on its geometrical configuration. And (2) the geometrical configuration for each volume evaluated as $\frac{2R}{H_w}$ over height of the water in the tank), which allows considering the geometry established in every volume, allowing to express the results of all volumes evaluated together.

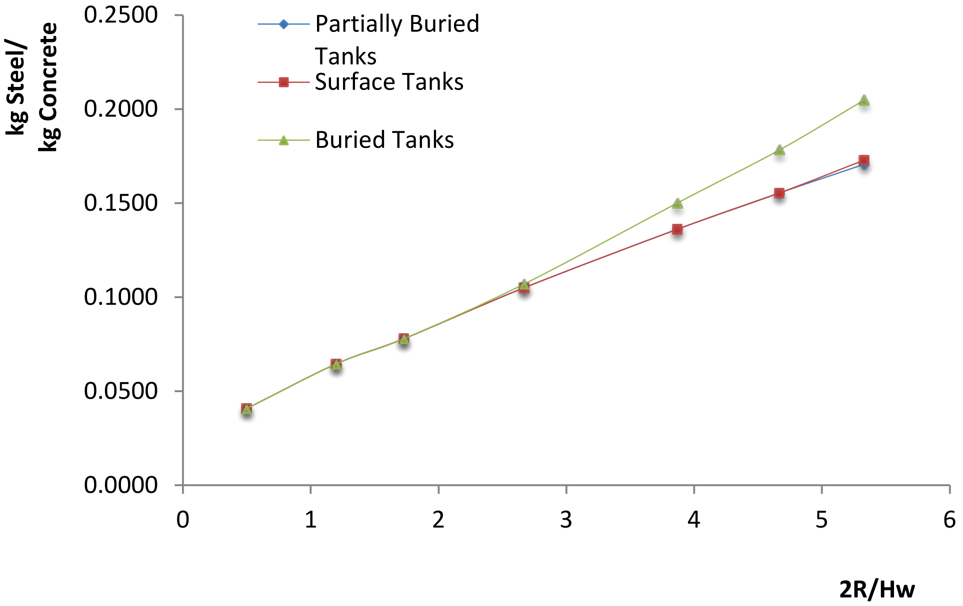

Figure 4. Materials consumption evolution for all volumes. D=diameter, Hw=Water level in the tank

As shown in Figure 4, for low 2R/Hw ratios the SLS cracking criteria in the design prevails leading to unnoticeable differences in the three different typologies studies. However, as the volume evaluated increases, the buried tank typology requires a higher amount of materials than the other two typologies. This is due to the fact that as the configuration of the tank gets higher the efforts enhance increase as well, producing a remarkable increasing of the required reinforcements in the buried typology to fulfil the ULS. Based on the comparison of the evolving materials consumption shown in Figure 4, it is concluded that the tank configuration that requires the higher materials consumption is the buried one.

3.1.3 Analysis of the storage capacity

Finally, the quantity of steel and concrete per m^3 of storage capacity has been calculated considering the optimal cases defined above (tanks with 8.5 m in height and superficially placed) for each of the volumes assessed. Similar results have been observed for other positions (buried, partially-buried) but not for cases with different dimensions.

Figure 5 shows the quantity of concrete and steel per cubic meter of water storage capacity. It can be observed that whereas the relative amount of concrete is lower for larger volumes, the opposite happens with steel, whose relative amount is higher for larger volumes

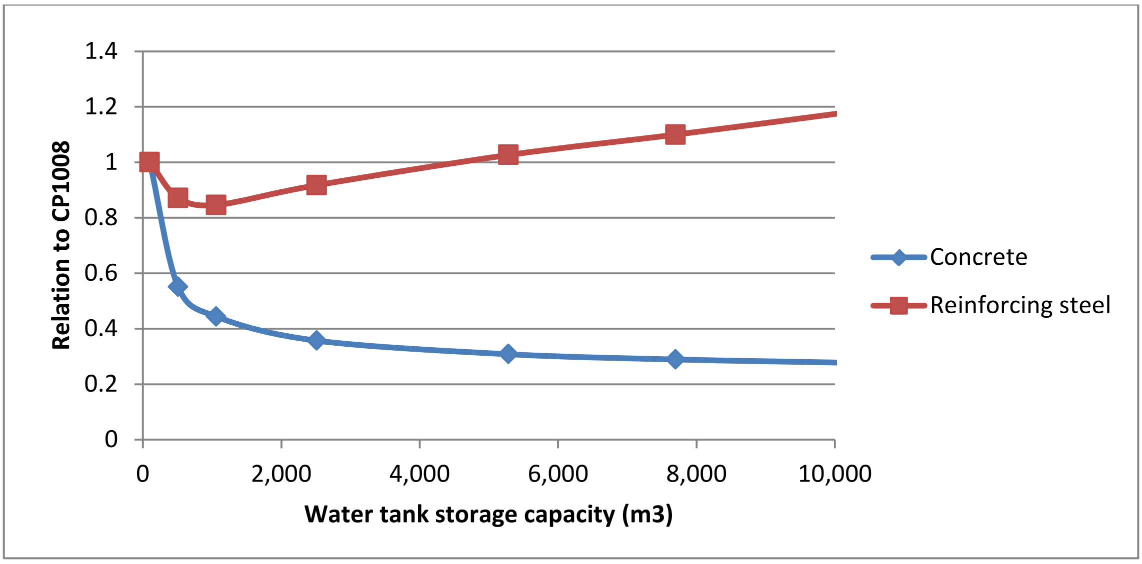

Figure 5. Comparison of the quantities of concrete and steel per cubic meter of water storage capacity and the ratio between these materials considering superficially placed water tanks with 8.5 m in height

Case nomenclature: CP=cylindrical water tank partially buried, 100=capacity (m^3), 8= 8.5 m in height

The quantity of concrete per cubic meter decreases sharply from 100 to 2,500 m^3 (-65%) and lightly from 2,500 to 10,000 m^3 (-20%). In contrast, the amount of steel decreases by 15% from 100 to 1,000 m^3 and increases in nearly 30% from 1,000 to 10,000 m^3. This is because smaller volumes only require the minimum (constant) reinforcement whereas larger ones need larger reinforcement.

Thus, the proportion of steel and concrete is different for different storage capacities. The environmental performance of each case will then depend on the environmental impacts per unit of concrete and reinforcing steel as well as on the ratio of these two materials.

3.2 Environmental assessment

3.2.1 Geometrical configuration

Firstly, the impacts of the different geometrical configurations (different height and radius combinations; section 2.1) considered for each of the volumes have been assessed. In order to represent these results, the environmental impacts of the smallest (100 m^3) and the largest (10,000 m^3) partially buried water tanks were included in Table 3. The rest of the cases (with intermediate volumes and other positions) present values within the range observed in Table 3. The results for the rest of the cases can be found in *Supplementary table B.*

The results show that the tank with the highest height (CP1008) has around half the impact of the lowest (CP1002) for 100 m^3 water tanks and around one third of the impact for 10,000 m^3 tanks in all the impact categories analysed. As explained in section 3.1, these lower requirements of steel and concrete in higher tanks can be explained by a better distribution of the stresses. Thus, the results of the environmental assessment match with those of the structural analysis.

However, increasing the height and reducing the radius of the tank is only valid until a certain point.

Table 3. Comparison of the environmental impacts of 100 and 10,000 m^3 water tanks considering 7 different geometrical configurations (height and radius), percentages are related to the lowest height (2.5 m)

	Percentage of environmental impact						
	CP1002	**CP1003**	**CP1004**	**CP1005**	**CP1006**	**CP1007**	**CP1008**
ADP	100%	74%	66%	55%	51%	50%	45%
AP	100%	79%	74%	63%	61%	62%	55%
EP	100%	74%	66%	54%	51%	49%	44%
GWP	100%	78%	73%	63%	61%	63%	56%
ODP	100%	80%	76%	66%	64%	66%	59%
POCP	100%	72%	62%	50%	45%	43%	38%
CED	100%	75%	68%	57%	54%	53%	48%

	CP100002	**CP100003**	**CP100004**	**CP100005**	**CP100006**	**CP100007**	**CP100008**
ADP	100%	55%	42%	38%	36%	33%	31%
AP	100%	59%	48%	44%	42%	38%	36%
EP	100%	54%	42%	38%	36%	33%	31%
GWP	100%	58%	45%	41%	38%	34%	32%
ODP	100%	61%	49%	45%	43%	40%	37%
POCP	100%	52%	40%	36%	34%	31%	29%
CED	100%	56%	43%	39%	37%	34%	31%

ADP=Abiotic depletion potential, AP=Acidification potential, EP= Eutrophication potential, GWP=Global warming potential, ODP=Ozone layer depletion potential, POCP=Photochemical oxidation potential, CED=Cumulative energy demand

Case nomenclature: CP=cylindrical water tank partially buried, 100-10000=capacity (m^3), 2-8=2.5 to 8.5 m in height

3.2.2 Position in relation to ground

Similarly to the prior section, only the smallest and the largest of the volumes analysed were included in Figure 6. The optimal dimensions (8.5 m in height and 40 m in diameter) found in section 3.1 and 3.2.1 were considered for all the cases. The environmental impacts for the rest of the case studies analysed can be found in *Supplementary table B*.

As shown in Figure 6, superficial water tanks hold the lowest environmental impacts in all impact categories (between 15 and 35% lower for 100 m^3 water tanks and between 20 and 35% for 10,000 m^3 water tanks). Superficially placed water tanks do not require the excavation of soil and its transport to landfill. For this reason, superficial water tanks are the environmentally preferable option. These results are also consistent with section 3.1, since superficial water tanks require less quantity of reinforcing steel. Nevertheless, an extra possibility not considered in this study might be using the excess of soil as reinforcement for the tank walls, avoiding at least partially the impact of the transport and landfilling of this material.

Although there are economic incentives to place the tanks on the surface (since the installation requires less energy, materials and working hours) it must be highlighted that the position of the tank cannot always be selected. In urban areas, tanks are usually placed buried when there are limitations regarding the space or the price of the land or for aesthetical reasons. Providing this, the selection of the optimal position (superficial) is not always possible.

Figure 6. Comparison of the environmental impacts of 100 and 10,000 m^3 cylindrical water tanks with 8.5 m in height placed buried, partially-buried or superficial

ADP=Abiotic depletion potential, AP=Acidification potential, EP= Eutrophication potential, GWP=Global warming potential, ODP=Ozone layer depletion potential, POCP=Photochemical oxidation potential, CED=Cumulative energy demand

Case nomenclature: CP=cylindrical water tank partially buried, 100/10000=capacity (m^3), 2/8=2.5 and 8.5 m in height

3.2.3 Optimization of the capacity

Finally, the environmental impacts per cubic meter of storage capacity have been calculated for each volume considering the most optimal cases stated in section 3.2.1 and 3.2.2 (the highest tanks superficially-placed). Figure 7 shows the results, including one curve per impact category evaluated. The absolute environmental impacts per cubic meter of stored water can be found in *Supplementary table C*.

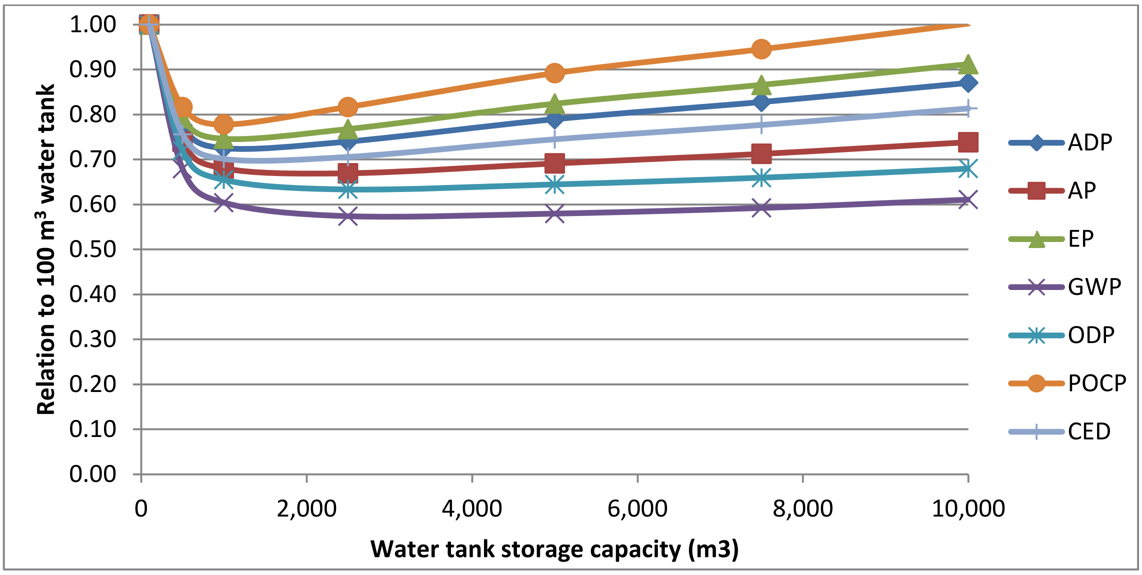

Figure 7. Environmental impacts per m^3 of storage capacity for superficially-placed water tanks with 8.5 m in height

ADP=Abiotic depletion potential, AP=Acidification potential, EP= Eutrophication potential, GWP=Global warming potential, ODP=Ozone layer depletion potential, POCP=Photochemical oxidation potential, CED=Cumulative energy demand

The variation of the environmental impacts is not equal for all the categories. For AP, ODP and GWP the 2,500 m^3 water tank holds the lowest environmental impact, being between 15 and 40% higher for tanks smaller than 500 m^3. Nevertheless, the environmental impacts increase slightly from 1,000 m^3 to 10,000 m^3. This means that, regarding greenhouse gas emissions, there would be few differences in building a 10,000 m^3 water tank or 10 tanks with 1,000 m^3 of capacity. Considering these categories, the decision of selecting one or another should be based then in other factors such as cost, the available space or periodic maintenance and cleaning.

For the rest of the impact categories (CED, ADP, EP and POCP) the lowest environmental impacts correspond to the 1,000 m^3 water tank, being significantly higher for volumes lower than 500 m^3 (between 5 to 30% higher) and larger than 5,000 m^3 (between 5 and 20% higher). In this case, water tanks between 500 and 2,500 m^3 present small variations. For this reason, volumes comprised within this range are environmentally preferable, being 1,000 m^3 the optimal one.

As explained in section 3.1.3, the reason for these differences between impact categories is the variation on the relation between the inputs required for the different volumes. It must be highlighted that the relative environmental impacts of steel are higher than those of concrete. This explains why the optimal volumes are in 1,000 and 2,500 m^3 and why it varies depending on the impact category (due to the different proportion of these materials, which hold different environmental impacts).

3.2.4 Impact of the water tank elements

In order to allow its representation, 2 representative impact categories have been included in Figure 8 to assess the contribution of each life cycle element to the environmental impacts of the water tank (ADP and GWP). EP, ADP and CED hold a similar pattern of environmental impacts, as well as GWP, AP, EP and POCP (section 3.2.3). The water tanks represented in this section are partially buried, since the optimal (superficial) does not include the excavation, with 8.5 m in height. Also the lowest and highest volumes have been represented. The results of the rest of the cases in the study are within the range presented.

As it can be observed in Figure 8, steel and concrete account for most of the impacts of the water tanks for all the options (between 70 and 80% for all the cases). This means that the amounts of concrete and steel used for the construction of the water tank are the major factor determining its environmental impacts, which explains why similar results have been obtained in the structural and the environmental assessments. Thus, the structural optimization of the tanks is crucial for the reduction of its environmental impacts.

Nonetheless, the contribution of each specific material is different depending on the volume and the impact category. The contribution of steel to the environmental impacts of ADP is higher than for GWP (around 50% to 75% for ADP as opposed to 30 to 60% for GWP). Also, because water tanks with larger storage capacities require more reinforcing steel, the contribution of steel is higher for higher volumes (nearly 60% for 10,000 m^3 as opposed to 30% for 100 m^3 for GWP). For POCP, the percentage of impact provided by steel is higher than for the rest of the impact categories (between 70 and 85% for all the volumes), which explains the differentiation of its curve in Figure 6.

Another significant contributor to the environmental impacts in all the cases is the transport of materials, which represents around 10% of the total. It must be highlighted that this element is highly related to the quantity of materials required for the construction, which reinforces the importance of concrete and steel.

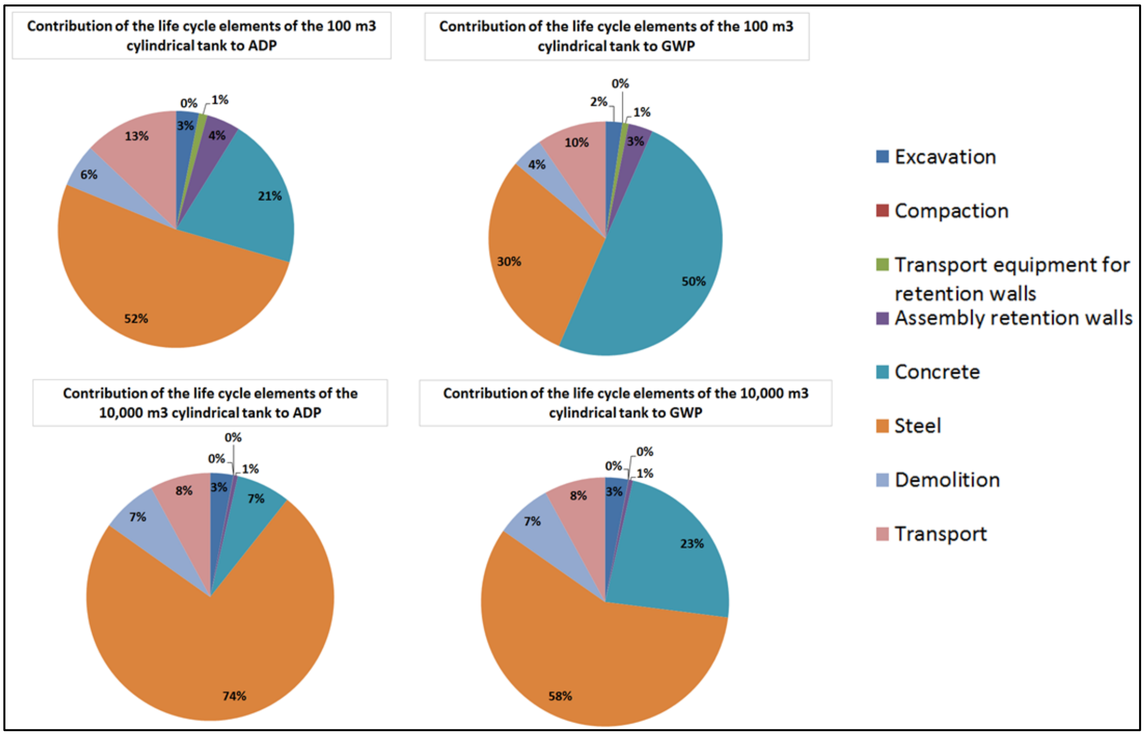

Figure 8. Contribution of each life cycle element to the environmental impacts of ADP and GWP of 100 and 10,000 m^3 cylindrical partially-buried water tanks with 8.5 m in height

ADP=Abiotic depletion potential, GWP=Global warming potential

Similar results have been found in the cases of superficial and buried water tanks. For superficial water tanks, there is no impact regarding the excavation and the transport of the extracted soil whereas for buried tanks its environmental impacts are higher. Apart from that, the contributions of the different elements to the environmental impact show a similar pattern in these other cases (*Supplementary table D*).

3.2.5 Environmental assessment of real case studies

The results of three real case studies assessment are presented in Figure 9. As shown, the environmental impacts of the most optimal water tank are significantly lower (between 10 and 40%) for all cases. Also, the reduction of the environmental impacts is similar in all impact categories. Optimized water tanks 1 and 2, which are smaller in capacity (400 and 2,000 m^3), present a relatively lower environmental improvement in comparison with water tank 3 (4,000 m^3). The absolute environmental impacts obtained are presented in *Supplementary table E*.

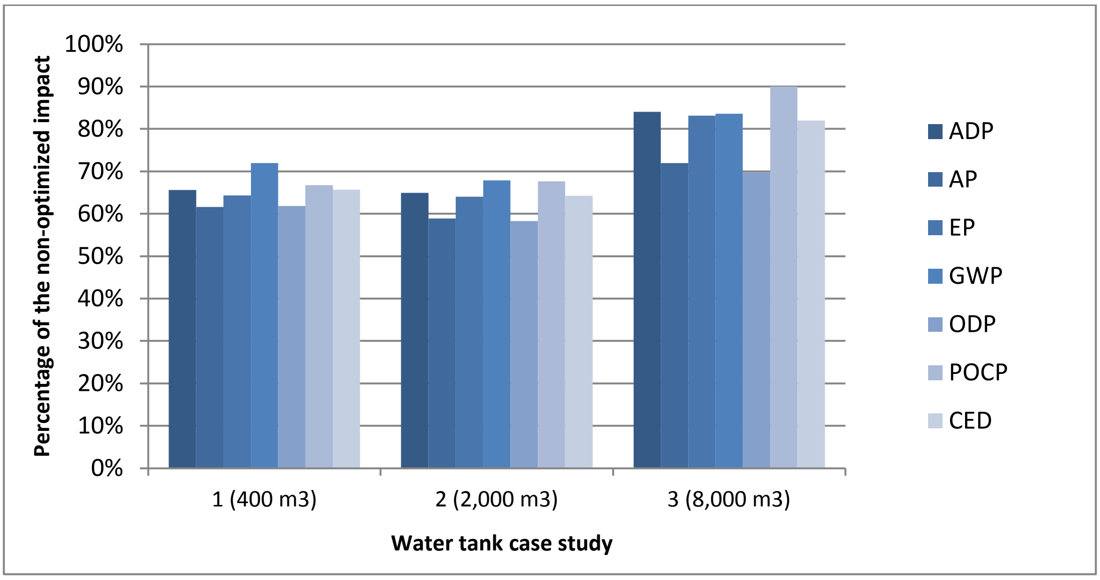

Figure 9. Estimation of the environmental impacts of 3 real drinking water tanks considering the current situation and a hypothetical optimal water tank for the same volume.

ADP=Abiotic depletion potential, AP=Acidification potential, EP= Eutrophication potential, GWP=Global warming potential, ODP=Ozone layer depletion potential, POCP=Photochemical oxidation potential, CED=Cumulative energy demand

For water tanks 1 and 2, the main savings in the environmental impacts come from the reduction in the quantity of reinforcing steel required for its construction, which is around 30% less impacting. In contrast, for concrete, only a reduction of around 5% of the environmental impact takes place. Regarding water tank 3, these environmental savings are smaller, all below a 5% reduction. For the 3 cases, the process of excavation was removed (along with its environmental impacts), given that the most optimal water tank found in the sample assessed is placed superficially.

In absolute values, the optimization of these water tanks would imply avoiding the emission of between 19.2 (for the 400 m^3 water tank) and 170.5 t of CO_2 equivalents (for the 8,000 m^3 water tank).

Although these environmental savings cannot be applied to existing water tanks, applying the environmental standards discussed along the article would allow significant reductions in the environmental impacts of new municipal water tanks.

4. Conclusions

After analysing the sample of 147 cases, it is concluded that the cylindrical water tank which environmentally performs better is the superficially placed with 8.5 meters in height (and its corresponding radius according with the volume) and a storage capacity of between 1,000 and 2,500 m^3.

It is environmentally preferable to place water tanks superficially rather than buried because less reinforcing steel is needed, reducing the environmental burdens of manufacturing steel. Moreover, no excavation or transport of soil is required, allowing significant energy savings. However, installing the tank superficially is not always possible since it depends on specific conditions of the installation point such as the urban form.

Considering the set of water tanks studied in this paper (all of them with a constant wall thickness of 30cm) the ones with the highest heights (cases with 8.5 meters in height) and lowest diameters are the best option both from the geometrical and environmental perspective. These dimensions imply a more optimal geometry and a reduction of the quantity of steel.

The structural optimization of water tank is essential provided that the reinforcing steel and concrete required for the construction are the elements that contribute the most to its environmental impacts (between 30 and 75% of the global impact for steel and between 7 and 50% for concrete).

Regarding the water storage capacity, water tanks with a volume of between 1,000 and 2,500 m^3 are environmentally preferable. This is because of the relative quantity of steel and concrete required for the construction of the tank, which varies with its volume. Steel and concrete have different environmental impacts and the ratio between one and the other also varies with the volume. Water tanks with 1,000 m^3 are the best option in GWP, ODP and AP (up to 40% lower environmental impacts) whereas 2,500 m^3 water tanks are better in ADP, EP, POCP and CED (up to 30% lower impacts). These results are a consequence of the relation between steel and concrete and its impacts derived, as shown in the structural analysis.

The application, when possible, of the environmental standards (the less impacting option for each of the dimensions assessed in the study: geometry, position and storage capacity) stated along the article is of interest in order to reduce the impacts of new water tanks during its construction. These can imply savings of between 10 and 40% in the environmental impacts, as observed in the application to the three real case studies.

Further studies might focus in other water tank shapes, such as for rectangular tanks, which are very common. Although cylindrical water tanks have lower requirements in terms of materials and thus have lower environmental impacts (section 1), the construction of rectangular water tanks can be required for limitations of the urban form. Thus, its environmental assessment would be of interest.

5. Acknowledgements

The authors are also grateful to the Government of Catalonia for awarding with a research scholarship (FI-DGR 2014) to David Sanjuan Delmás.

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List of abbreviations

Abiotic depletion potential (ADP)
Acidification potential (AP)
Buried (B)
Centro de Estudios y Experimentación de Obras Públicas (CEDEX)
Compressive strength (fck)
Cumulative energy demand (CED)
Cylindrical (C)
Drinking water transport and distribution network (DWTDN)
Elastic modulus (Es)
Eutrophication potential (EP)
Flexural rigidity (D)
Global warming potential (GWP)
Height (a)
International Standard Association (ISO)
Life cycle assessment (LCA)
Maximum crack width (w_{max})
Minimum geometrical reinforcement (As_{min}^{geom})
Minimum mechanical reinforcement (As_{min}^{mec})
Modulus of elasticity (E)
Ozone layer depletion (ODP)
Partially buried (PB)
Photochemical oxidation potential (POCPPOCP)
Radius (R)
Serviceability Limit State (SLS)
Soil height (Hs)
Steel covering (r_{nom})
Superficial (S)
Ultimate Limit State (ULS)
United Nations Educational, Scientific and Cultural Organization (UNESCO)
Urban water cycle (UWC)
US Environmental Protection Agency's (EPA)
Water height (Hw)
Yield strength (fyk)

Supplementary data

- *Supplementary table A* - Quantity of concrete and reinforcing steel required for the construction of each case in the study
- *Supplementary table B* - Absolute environmental impacts for the construction of the storage water tanks assessed
- *Supplementary table C* - Absolute environmental impacts per cubic meter of water stored for superficial cylindrical tanks of 8.5 m in height
- *Supplementary table D* - Environmental impacts of the life cycle elements of cylindrical water tanks with 8.5 m in height and 100 and 10,000 m3 of capacity for superficial, buried and partially buried positions
- *Supplementary table E* - Environmental impacts of the case study assessed considering realistic conditions and applying the environmental standards defined

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Tables

Table 1. Case studies dimensions

Height (m)	Radius (m) for a given volume						
	100 m^3	500 m^3	1,000 m^3	2,500 m^3	5,000 m^3	7,500 m^3	10,000 m^3
2.5	4.0	9.0	13.0	20.0	28.5	35.0	40.0
3.5	3.3	7.5	10.5	16.5	23.5	28.5	33.0
4.5	3.0	6.5	9.0	14.5	20.0	24.5	28.5
5.5	2.6	5.7	8.0	13.0	18.0	22.0	25.5
6.5	2.4	5.2	7.5	12.0	16.5	20.0	23.5
7.5	2.2	4.8	7.0	11.0	15.5	18.5	21.5
8.5	2.0	4.5	6.5	10.0	14.5	17.5	20.0

Table 2. Technical characteristics of the water tanks analysed as case studies.

ID	Volume (m^3)	Diameter (m)	Height (m)	Wall thickness (cm)	Shape	Material
1	400	5.05	5	30	Cilindrical	Reinforced concrete
2	2,000	11	5.3			
3	8,000	18.5	7.4			

Table 3. Comparison of the environmental impacts of 100 and 10,000 m^3 water tanks considering 7 different geometrical configurations (height and radius), percentages are related to the lowest height (2.5 m)

	Percentage of environmental impact						
	CP1002	CP1003	CP1004	CP1005	CP1006	CP1007	CP1008
ADP	100%	74%	66%	55%	51%	50%	45%
AP	100%	79%	74%	63%	61%	62%	55%
EP	100%	74%	66%	54%	51%	49%	44%
GWP	100%	78%	73%	63%	61%	63%	56%
ODP	100%	80%	76%	66%	64%	66%	59%
POCP	100%	72%	62%	50%	45%	43%	38%
CED	100%	75%	68%	57%	54%	53%	48%

	CP100002	CP100003	CP100004	CP100005	CP100006	CP100007	CP100008
ADP	100%	55%	42%	38%	36%	33%	31%
AP	100%	59%	48%	44%	42%	38%	36%
EP	100%	54%	42%	38%	36%	33%	31%
GWP	100%	58%	45%	41%	38%	34%	32%
ODP	100%	61%	49%	45%	43%	40%	37%
POCP	100%	52%	40%	36%	34%	31%	29%
CED	100%	56%	43%	39%	37%	34%	31%

ADP=Abiotic depletion potential, AP=Acidification potential, EP= Eutrophication potential, GWP=Global warming potential, ODP=Ozone layer depletion potential, POCP=Photochemical oxidation potential, CED=Cumulative energy demand

Case nomenclature: CP=cylindrical water tank partially buried, 100-10000=capacity (m^3), 2-8=2.5 to 8.5 m in height

Figure captions

Figure 1. Diagram and system boundaries of the drinking water tank life cycle.

Figure 2. Flowchart of the general structural design performance.

Figure 3. Total amount of reinforcing steel required for the construction of superficial water tanks with 100, 500, 1,000, 2,500, 5,000, 7,500 and 10,000 m3 of storage capacity depending on its height.

Figure 4. Materials consumption evolution for all volumes. D=diameter, Hw=Water level in the tank

Figure 5. Comparison of the quantities of concrete and steel per cubic meter of water storage capacity and the ratio between these materials considering superficially placed water tanks with 8.5 m in height

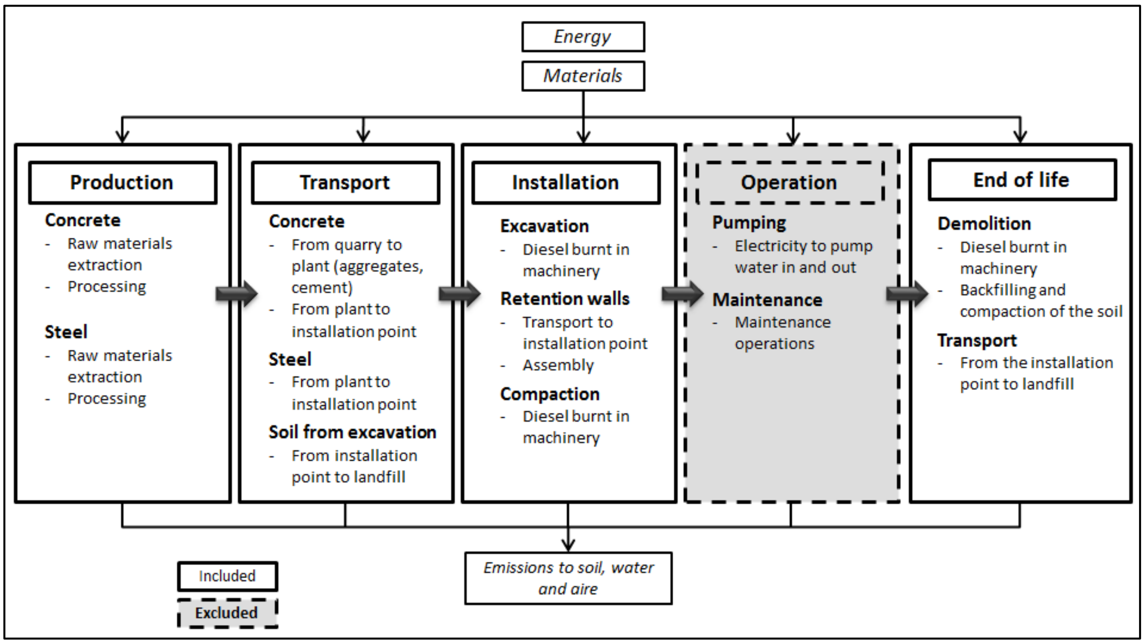
Figure 6. Comparison of the environmental impacts of 100 and 10,000 m3 cylindrical water tanks with 8.5 m in height placed buried, partially-buried or superficial

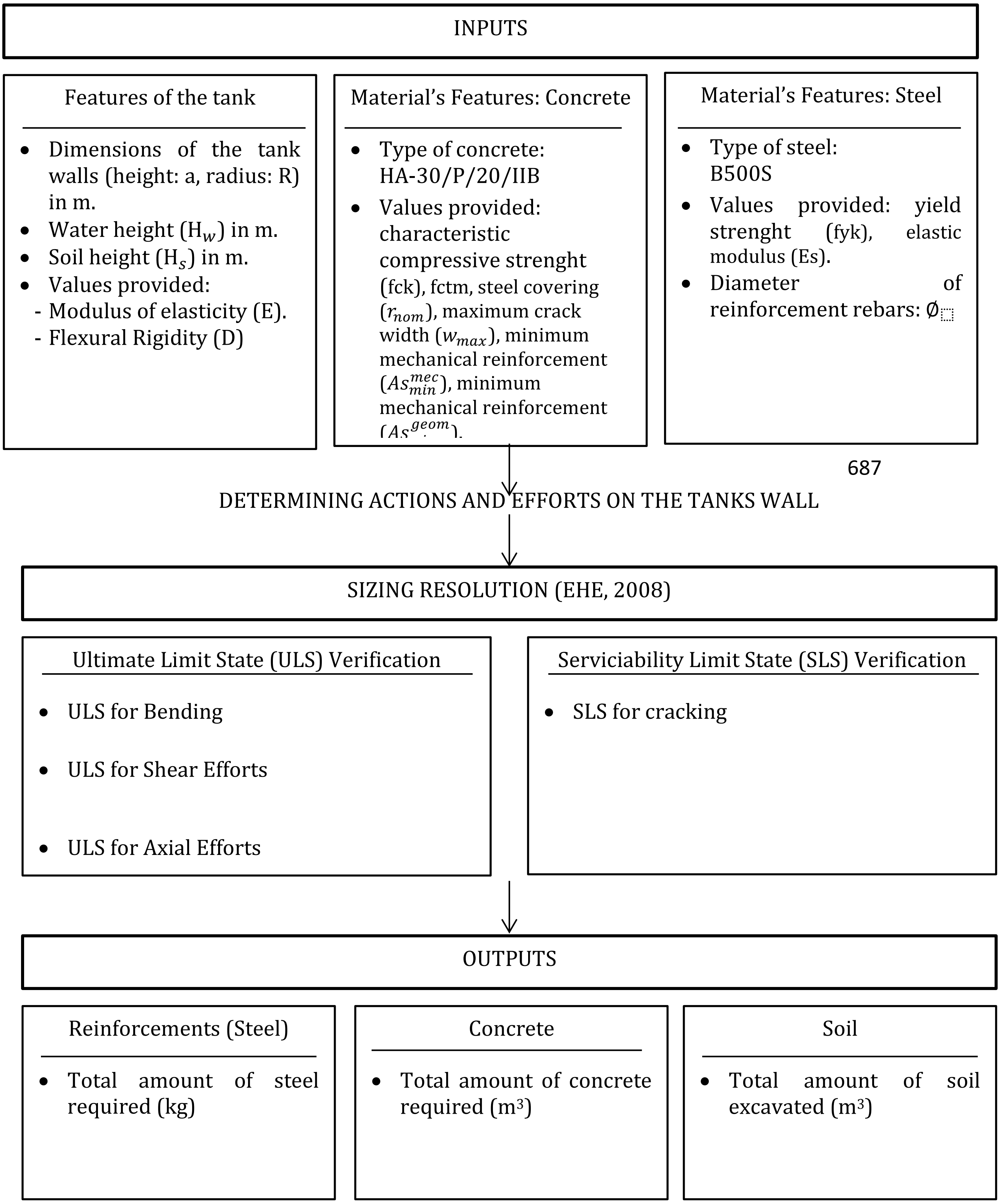
Figure 7. Environmental impacts per m3 of storage capacity for superficially-placed water tanks with 8.5 m in height

Figure 8. Contribution of each life cycle element to the environmental impacts of ADP and GWP of 100 and 10,000 m3 cylindrical partially-buried water tanks with 8.5 m in height

Figure 9. Estimation of the environmental impacts of 3 real drinking water tanks considering the current situation and a hypothetical optimal water tank for the same volume.

Figures


Energy
Materials
Production
Concrete
- Raw materials extraction
- Processing
Steel
- Raw materials extraction
- Processing
Transport
Concrete
- From quarry to plant (aggregates, cement)
- From plant to installation point
Steel
- From plant to installation point
Soil from excavation
- From installation point to landfill
Installation
Excavation
- Diesel burnt in machinery
Retention walls
- Transport to installation point
- Assembly
Compaction
- Diesel burnt in machinery
Operation
Pumping
- Electricity to pump water in and out
Maintenance
- Maintenance operations
End of life
Demolition
- Diesel burnt in machinery
- Backfilling and compaction of the soil
Transport
- From the installation point to landfill
Emissions to soil, water and aire
Included
Excluded



INPUTS

Features of the tank

- Dimensions of the tank walls (height: a, radius: R) in m.
- Water height (H_w) in m.
- Soil height (H_s) in m.
- Values provided:
  - Modulus of elasticity (E).
  - Flexural Rigidity (D)

Material's Features: Concrete

- Type of concrete: HA-30/P/20/IIB
- Values provided: characteristic compressive strenght (fck), fctm, steel covering (r_{nom}), maximum crack width (w_{max}), minimum mechanical reinforcement (As_{min}^{mec}), minimum mechanical reinforcement (As^{geom}).

Material's Features: Steel

- Type of steel: B500S
- Values provided: yield strenght (fyk), elastic modulus (Es).
- Diameter of reinforcement rebars: Ø

DETERMINING ACTIONS AND EFFORTS ON THE TANKS WALL

SIZING RESOLUTION (EHE, 2008)

Ultimate Limit State (ULS) Verification

- ULS for Bending
- ULS for Shear Efforts
- ULS for Axial Efforts

Serviciability Limit State (SLS) Verification

- SLS for cracking

OUTPUTS

Reinforcements (Steel)

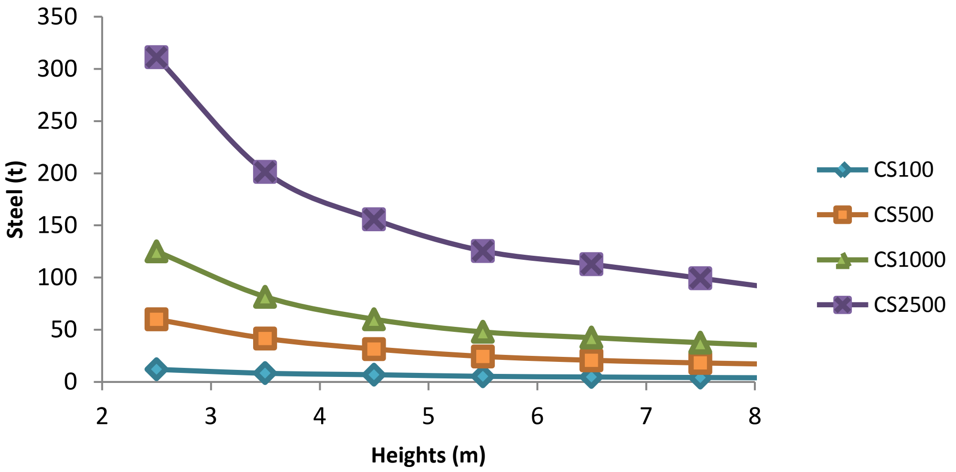
- Total amount of steel required (kg)

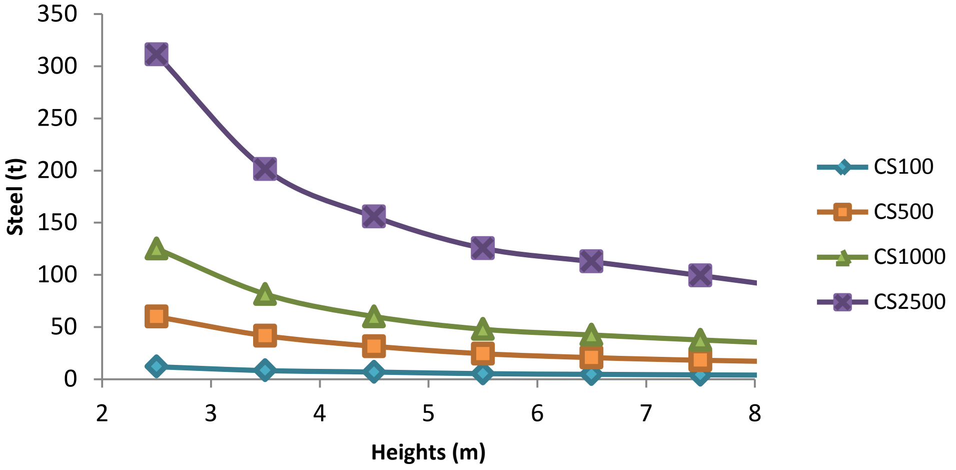
Concrete

- Total amount of concrete required (m^3)

Soil

- Total amount of soil excavated (m^3)


Steel (t)
350
300
250
200
150
100
50
0
2
3
4
5
6
7
8
Heights (m)
CS100
CS500
CS1000
CS2500


Steel (t)
350
300
250
200
150
100
50
0
2
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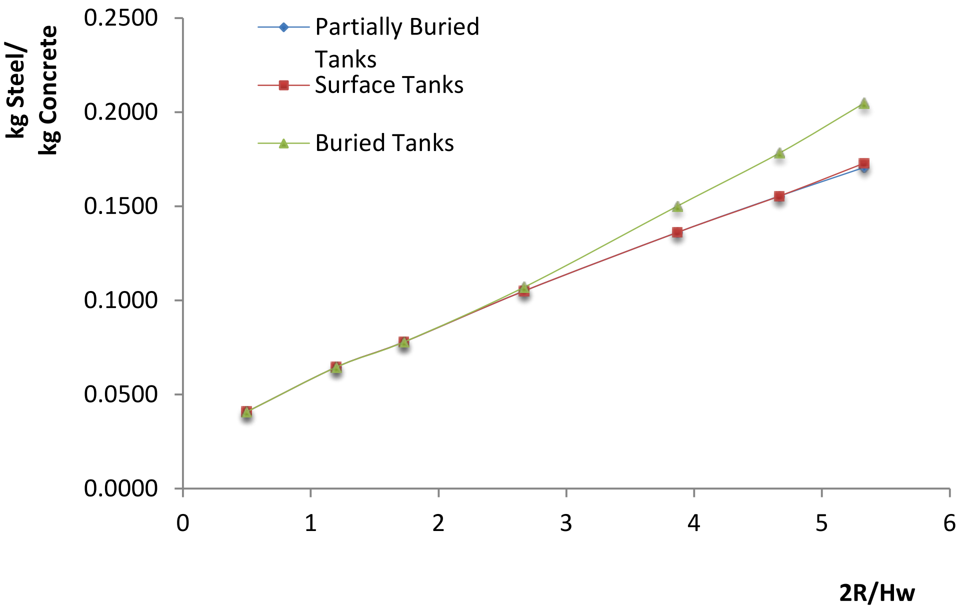
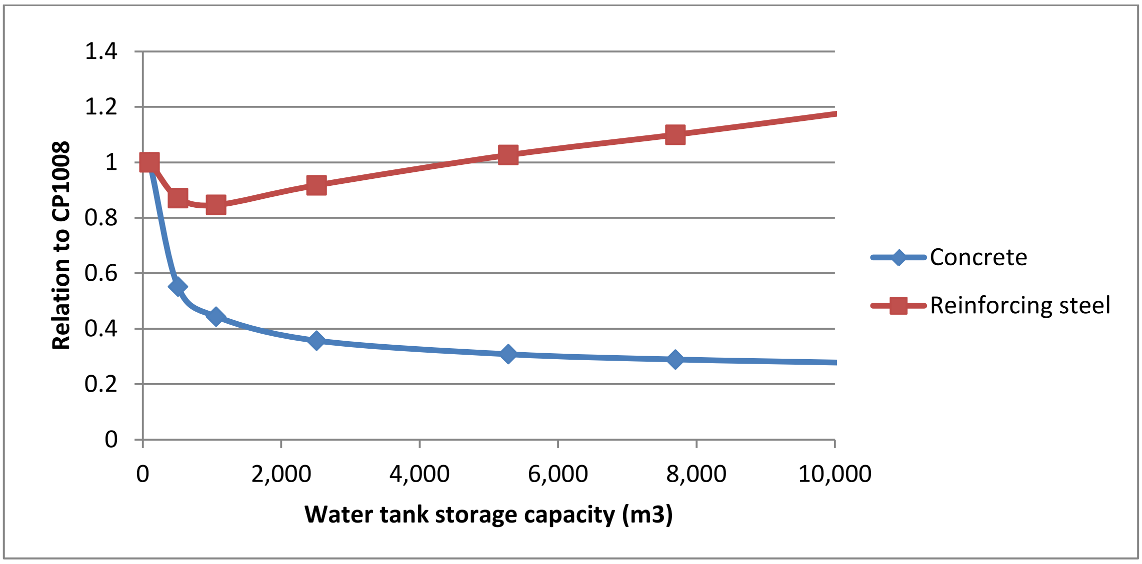
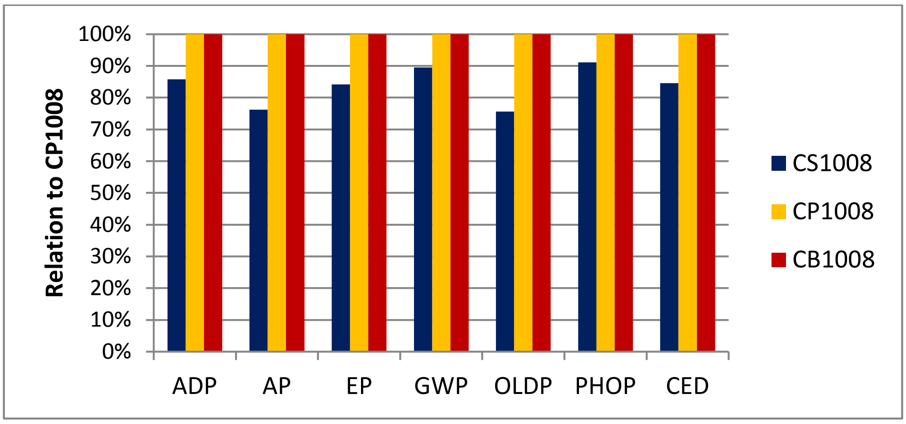
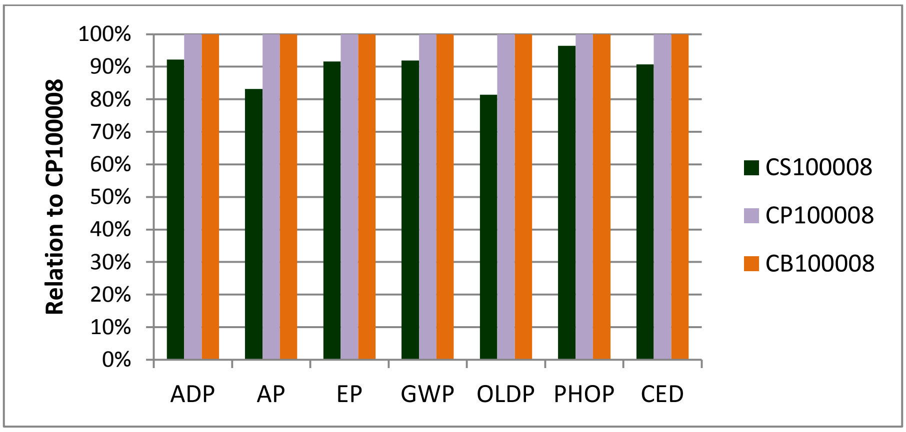
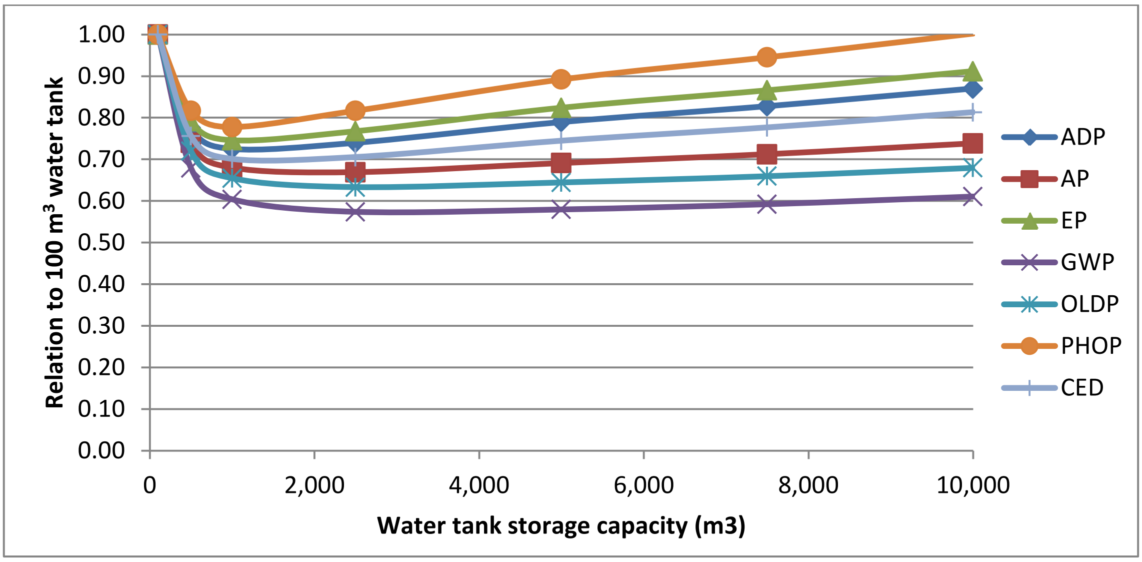
8
Heights (m)
CS100
CS500
CS1000
CS2500

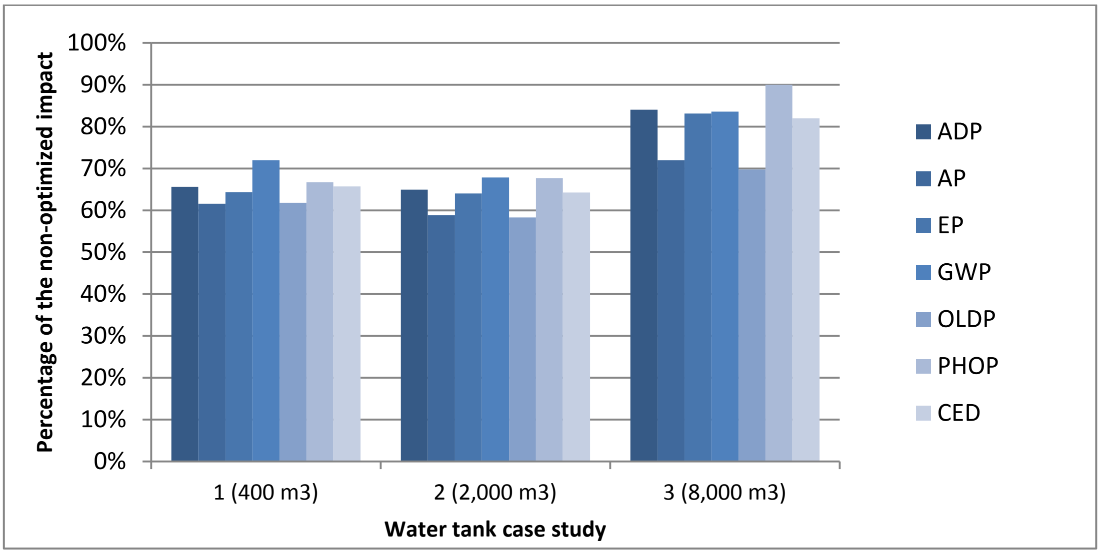

kg Steel/
kg Concrete
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
0
1
2
3
4
5
6
2R/Hw
Partially Buried Tanks
Surface Tanks
Buried Tanks

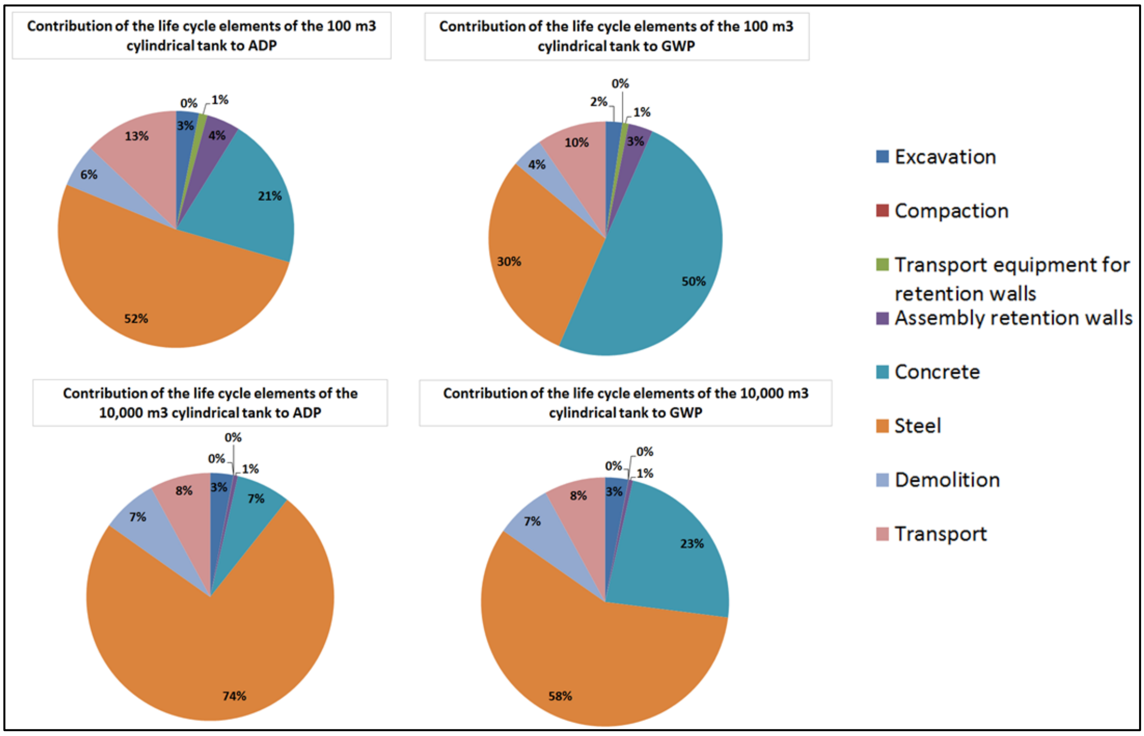

1.4
1.2
1
0.8
0.6
0.4
0.2
0
Relation to CP1008
0
2,000
4,000
6,000
8,000
10,000
Water tank storage capacity (m3)
Concrete
Reinforcing steel


Relation to CP1008
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
ADP
AP
EP
GWP
OLDP
PHOP
CED
CS1008
CP1008
CB1008


Relation to CP100008
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
ADP
AP
EP
GWP
OLDP
PHOP
CED
CS100008
CP100008
CB100008


1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Relation to 100 m³ water tank
0
2,000
4,000
6,000
8,000
10,000
Water tank storage capacity (m3)
ADP
AP
EP
GWP
OLDP
PHOP
CED


Percentage of the non-optimized impact
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1 (400 m3)
2 (2,000 m3)
3 (8,000 m3)
Water tank case study
ADP
AP
EP
GWP
OLDP
PHOP
CED


Contribution of the life cycle elements of the 100 m3 cylindrical tank to ADP
0%
1%
3%
4%
13%
6%
21%
52%
Contribution of the life cycle elements of the 100 m3 cylindrical tank to GWP
0%
2%
1%
3%
10%
4%
30%
50%
Contribution of the life cycle elements of the 10,000 m3 cylindrical tank to ADP
0%
0%
1%
3%
8%
7%
7%
74%
Contribution of the life cycle elements of the 10,000 m3 cylindrical tank to GWP
0%
0%
1%
3%
8%
7%
23%
58%
Excavation
Compaction
Transport equipment for retention walls
Assembly retention walls
Concrete
Steel
Demolition
Transport