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WATER USE IN LCA

Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate

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Abstract
Purpose At present, many urban areas in Mediterranean climates are coping with water scarcity, facing a growing water demand and a limited conventional water supply. Urban design and planning has so far largely neglected the benefits of rainwater harvesting (RWH) in the context of a sustainable management of this resource. Therefore, the purpose of this study was to identify the most environmentally friendly strategy for rainwater utilization in Mediterranean urban environments of different densities.

Materials and methods The RWH systems modeled integrate the necessary infrastructures for harvesting and using rainwater in newly constructed residential areas. Eight scenarios were defined in terms of diffuse (D) and compact (C) urban models and the tank locations ((1) underground tank, (2) below-roof tank, (3) distributed-over-roof tank, and (4) block tank). The structural and hydraulic sizing of the catchment, storage, and distribution subsystems was taken into account using an average Mediterranean rainfall, the area of the harvesting surfaces, and a constant water demand for laundry. The quantification of environmental impacts was performed through a life cycle assessment, using CML 2001 Baseline method. The necessary materials and processes were considered in each scenario according to the lifecycle stages (i.e., materials, construction, transportation, use, and deconstruction) and subsystems.

Results and discussion The environmental characterization indicated that the best scenario in both urban models is the distributed-over-roof tank (D3, C3), which provided a reduction in impacts compared to the worst scenario of up to 73% in diffuse models and even higher in compact ones, 92% in the most dramatic case. The lower impacts are related to the

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better distribution of tank weight on the building, reducing the reinforcement requirements, and enabling energy savings. The storage subsystem and the materials stage contributed most significantly to the impacts in both urban models. In the compact density model, the underground-tank scenario (C1) presented the largest impacts in most categories due to its higher energy consumption. Additionally, more favorable environmental results were observed in compact densities than in diffuse ones for the Global Warming Potential category along with higher water efficiencies.

Conclusions The implementation of one particular RWH scenario over another is not irrelevant in drought-stress environments. Selecting the most favorable scenario in the development of newly constructed residential areas provides significant savings in CO_2 emissions in comparison with retrofit strategies. Therefore, urban planning should consider the design of RWH infrastructures using environmental criteria in addition to economic, social, and technological factors, adjusting the design to the potential uses for which the rainwater is intended.

Recommendations and perspectives Additional research is needed to quantify the energy savings associated with the insulation caused by using the tank distributed over the roof. The integration of the economic and social aspects of these infrastructures in the analysis, from a life cycle approach, is necessary for targeting the planning and design of more sustainable cities in an integrated way.

Keywords Carbon emissions · Environmental impact · Laundry demand · LCA · Reinforcement · Sustainable cities · Urban planning · Water management

1 Introduction

1.1 Alternative water management systems: RWH

Water scarcity is recognized as an increasingly severe problem with global implications (Sazakli et al. 2007). The distribution of water reserves is far from homogeneous, both geographically and temporally. Consequently, many regions face water scarcity problems, affecting not only those located in arid areas but also those in which demand exceeds water supply. This situation will become even worse in Mediterranean climate regions (the Mediterranean basin, the western United States, southern Africa, northeastern Brazil, Chile, and the south-southwest of Australia) that are projected to experience a reduction in their water resources in the coming decades due to the effects of climate change (Bates et al. 2008).

Urban areas are among the most vulnerable systems as they bear great environmental pressures, are associated with large ecological footprints, and are dependent to a great extent on water from distant sources, which is transported by means of large infrastructures. Approximately 50% of the world's population is concentrated in these areas and over 70% of the population in North America, Europe, and Oceania (UN 2010). Frequent droughts together with population growth in urban environments contribute to increases in water demand to meet mainly domestic uses. Water scarcity and the reduction of conventional resources promote greater dependence on imported water to supply these needs (Fragkou et al. 2008) with the subsequent use of more distant sources or those of lower quality (van Roon 2007).

At present, the most developed technological strategies in Mediterranean climates for coping with increasing water demand and scarcity have focused on alternative water resources by means of desalination techniques and water recycling processes. Nevertheless, the possibility of collecting and using rainwater has frequently been ignored, despite presenting many benefits to consider: Rainwater harvesting (RWH) provides access to a free water source that can be easily sent to non-potable water uses, mitigates the pressure on aquifers and surface courses, reduces water stress and pollution to surface waters, helps to prevent floods caused by soil sealing resulting from urbanization while reduces loads on sewers allowing larger storage volumes for high intensity summer rainfall events (Zhu et al. 2004; Flower et al. 2007; Kim et al. 2005; Parkinson et al. 2005; Villarreal and Dixon 2005; RiverSides 2009; Sharma and Vairavamoorthy 2009; Slys 2009; Fewkes 2000; Konig 2001; Kellagher and Maneiro Franco 2005; Vaes and Berlamont 1999). Additionally, the use of rainwater on a large scale is perceived as an adaptive strategy to climate change against the reduction of water availability (Trenberth et al. 2007).

RWH systems have been historically applied to a variety of uses in population settlements and isolated homes (Gould and Niessen-Peterson 1999), and recently, there has been an increasing interest in the use of water resources generated within the urban boundary for drinking water supply substitution (Farreny et al. 2011a). In urban regions, rainwater has been demonstrated as a viable water source for the cleaning of roads and outdoor surfaces, the irrigation of gardens, the flushing of toilets, laundry, and other activities related to potential non-potable uses (Nolde 2007). These techniques have been widely developed in China, Brazil, Australia, Germany, India, and Japan (Zaizen et al. 2000; Hills et al. 2001; UNEP 2002).

1.2 Environmental assessment of RWH at an urban scale

The early environmental assessments on water resources and technologies for facing water demand and scarcity in urban environments have focused on a regional or basin level. In this context, recent publications have described the sustainability of water recycling systems Levine and Asano (2004), and others have examined the opportunities for increasing the water supply in Spain and California, comparing the current desalination techniques with water transfers and other alternative water recovery systems (Raluy 2009; Muñoz et al. 2010; Stokes and Horvath 2006). However, sustainable water management has so far not been considered as a distinctive issue in urban planning (Hiessl et al. 2001), and there is a lack of the environmental data needed to determine the best strategy to optimize water management at local level.

The application of environmental criteria to the study of RWH utilization is so far underdeveloped. In this sense, life cycle assessment (LCA) is proposed as a useful tool to obtain quantitative data that can be useful in decision-making processes. The state of the art of LCA application in the quantification of environmental impacts associated with the design and planning of urban areas and sustainable water management has to date focused only on specific stages of the water cycle and treatment processes or on the environmental evaluation of different components of these infrastructures. This body of work includes the analysis of different water systems in Europe (Crettaz et al. 1999), alternative water supply methods in urban environments (Tillman et al. 1998; Beavis and Lundie 2003; Raluy 2009), the determination of impacts associated with water management before and after use Lassaux et al. (2007), the analysis of alternative water infiltration systems (Friedrich 2002), distribution infrastructures (Herz and Lipkow 2002), and different methods of rainwater disinfection (Das 2002). Moreover, sustainability indicators applied to wastewater (Lundin 2003) and urban water systems Lundin and Morrison (2002) have been defined. A study in Sweden evaluating water management infrastructures through LCA showed that the installation phase is primarily responsible for the greenhouse gas emissions caused by the main water supply network, even though it can be foreseen that in future scenarios the stages of maintenance and renewal would be the major contributors (Venkatesh et al. 2009). The emissions associated with the construction of a single pipe were estimated to account for over 80% of the total impact during its life cycle (Strutt et al. 2008). The proposed use of alternative materials including recycled steel in the production of these concrete structures can reduce emissions by 25% (Venkatesh et al. 2009).

The assessment of alternative application of LCA to RWH techniques is even more recent and still largely limited to economic criteria or specific stages of these networks. The first analysis that used the LCA approach to tackle water management and urban wastewater systems in a broader way aimed to determine the potential environmental impacts associated with water management in Sydney, using a "cradle to grave" approach in the economic, social, and environmental analyses (Lundie et al. 2004). Grant and Hallmann also assessed the environmental and economic impacts of an urban domestic water tank through LCA. The outcomes of this study suggested that, in terms of energy and materials, RWH system manufacture, and operation have more impacts than a reticulated water supply, especially when a pump is needed. Despite this, the absolute impacts of the water tank are not large in proportion to other daily activities (Grant and Hallmann 2003). Additionally, a comparative LCA was performed by Bronchi et al. (1999) between conventional drinking water and rainwater from recuperation in an individual house and at a university. The results showed that it takes less energy, the storage system capacity is smaller, the demand better fits water availability, and the impacts on the environment are smaller in the rainwater recuperation scenario on larger scales (Bronchi et al. 1999).

In this context, the lack of quality inventory data along with life cycle environmental assessments of RWH systems leads to the need to evaluate these systems and to identify which environmental impacts can be attributed to these systems in certain urban models and thus determine which are the most adequate infrastructures for RWH.

2 Goal and scope

2.1 Objectives

The aim was to quantify the environmental impact of different RWH constructive solutions and to determine the most environmentally favorable strategy in different scenarios (defined according to the urban density and the location of the infrastructures) under Mediterranean climate conditions, by means of LCA.

2.2 Functional unit

The functional unit (FU) is here defined as the collection, storage, and supply of 1 m^3 of rainwater per person per year to be used as non-potable water for a constant demand of laundry use. This definition takes into account the catchment area per building, the available water to be supplied, the annual water demand per dwelling, the optimum size of the tank, different urban densities, and Mediterranean climate conditions.

2.3 Methodology

The environmental impacts associated with RWH infrastructures as applied to two models of urban density (diffuse and compact) were calculated using LCA. This methodology assesses all the environmental impacts related with a product, process, or activity through the quantification and estimation of the resources consumption and the emissions produced (ISO 14040 2006).

2.3.1 Environmental calculation tools

The LCA performs an analysis of the system from "cradle to grave," which involves four main steps: definition of the objectives and scope of the study, inventory analysis, impact assessment, and interpretation (ISO 14040 2006). The entire life cycle of the RWH infrastructures for each scenario was assessed in this case.

The inventory analysis includes both materials and processes grouped into life cycle stages (i.e., raw materials extraction and processing, transportation, construction, use, and final disposal) and into subsystems (catchment, storage, and distribution). The impact of the materials' end of life is outside the boundaries of the system because there is a lot of uncertainty about the technological development of the recycling process in 50 years time. The data regarding materials and the sizing of the infrastructures were obtained based on the conventional hydraulic design of buildings, with the aid of Cypecad v.2010 (CYPE 2010). MetaBase ITeC (MetaBase ITeC 2010) provided the information on energy consumption linked to construction/deconstruction processes.

From all stages included in the LCA methodology (ISO 14042 2000), only the classification and characterization were considered. The method 2001 Baseline v2.04 CML (Guinée et al. 2001) was used, and the selected impact categories were Abiotic Depletion Potential (ADP; kilogram Sb equivalents), Acidification Potential (AP; kilogram SO_2 equivalents), Eutrophication Potential (EP; kilogram PO_4^{3-} equivalents), Global Warming Potential (GWP; kilogram CO_2 equivalents), Human Toxicity Potential (HTP; kilogram 1.4-DB equivalents), Ozone Depletion Potential (ODP; kilogram CFC-11 equivalents), and Photochemical Ozone Creation Potential (POCP; kilogram C_2H_4 equivalents).

The ecoinvent 2.0 (Ecoinvent 2009) database, linked to the software SimaPro 7.2.0 PRé Consultants (2010), was used in the evaluation of emissions related to the majority of materials and energy. Ecoinvent 2.0 also provides data about the water flows associated to RWH processes and infrastructures classified according to different water origins (sea water, lake water, river water, underground water, or unspecified origin water), which were used to estimate the water footprint of each scenario. In the specific case of the environmental impacts of concrete, the EcoConcrete LCA software tool (CEMBUREAU et al. 2003) was used, which contains high-quality inventory data provided by European producers.

2.3.2 Structural and hydraulic calculation tools

Lifespan of the infrastructure It has been stated that a rainwater storage tank has an average lifespan of 50 years (Roebuck et al. 2010), mainly limited by changes in functionality over time and the evolution of technologies. On this basis, it was assumed that both uptake and distribution pipes would be replaced every 25 years and the submersible pump every 15 years (Roebuck et al. 2010).

Sizing of the tank The sizing of the tank was defined with the aid of the RainCycle software (Roebuck and Ashley 2006), which allows modeling the tank volume through a continuous daily water balance of supply and demand throughout the year. An optimum volume was chosen for each scenario, for which an increase in capacity did not represent significant gains in water collection. For the diffuse urban scenarios, the optimal threshold value was set such that an increase of 1 m^3 in storage volume represents an increase of less than 1% of the demand satisfied with rainwater. In the case of the compact urban density, the threshold was set at 0.6%. The percentage was lower in compact models as, in absolute terms, the threshold is set in relation to the greater volume of water rather than in proportion to the diffuse urban density.

2.3.3 Reference flows

Water demand The use of rainwater for laundry is one of the most widespread uses in Europe for non-potable water of an acceptable quality, together with garden watering and toilet flushing (Leggett et al. 2001); laundry represents 20% of the domestic demand in a standard dwelling (Griggs et al. 1997; Mustow et al. 1997).

The RWH facilities were designed to supply the maximum water demand for each home laundry, quantified as 25 m^3/(dwelling year) over the lifetime of the system. The average weekly consumption in a European household was estimated at 480 l (five wash loads per week), based on the ecoefficiency requirements necessary for the acquisition of the A+ecolabel for washing machines EC (2000). In addition, it was assumed that outdoor areas do not demand water (no irrigation needs) and that toilets reuse graywater from showers, as both uses consume similar amounts of water. Although demand is constant and equal for both density models, the amount of water available for collection and ready for consumption varies depending on the daily water balance, the size of the tank, and the roof surface available.

Rainfall The study based its calculations on the daily rainfall data from Cerdanyola del Vallès (Barcelona, Spain) from 1985 to 2007 (SMC 2007), during which precipitation averaged approximately 600 mm/year. This amount is representative of a Mediterranean climate, in which the average rainfall oscillates between 600 and 750 mm per year, although this varies over a range depending on the year and season (Aschmann 1973). In this respect, the Mediterranean climate is distributed worldwide and largely characteristic of five areas: the Mediterranean basin, California, central Chile, Cape Province in South Africa, and the south-southwest of Australia Di Castri and Mooney (1973).

2.4 Description of the system under study

The diagram of the system evaluated is presented in Fig. 1. This system consists of an urban area (block) of 100× 100 m^2 with different types of newly constructed residential buildings integrating the infrastructures required for the catchment, storage, and distribution of rainwater. A total of eight theoretical scenarios were defined in terms of two variables: urban density and location of the RWH infrastructures. Figure 2 shows the main characteristics of each scenario depending on both variables. The indirect alleviation of impacts on the urban water cycle due to RWH (supply, distribution, and sewage systems) were considered to be outside the scope of this study.

2.4.1 Urban density

Diffuse and compact urban density models were proposed to exemplify two contrasting types of cities in Mediterranean climates. The diffuse density model was based on a two-story detached single-family house (250 m^2/floor) with 90% unbuilt area. The block scenario distribution considered the construction of four houses on 10,000 m^2 (see Fig. 2). The compact density model proposes a five-story building (24 apartments, 700 m^2/floor) with 30% unbuilt area. The block scenario consists of the integration of ten residential buildings on 10,000 m^2 (see Fig. 2). The average density of people per household was estimated at 2.65 based on the average housing size of different countries located in several areas of Mediterranean climate (Eurostat 2010; Australian Bureau of Statistics 2004; U.S. Census Bureau 2010).

2.4.2 Infrastructures

The location of the RWH infrastructures determined four scenarios of analysis for each urban density. These were

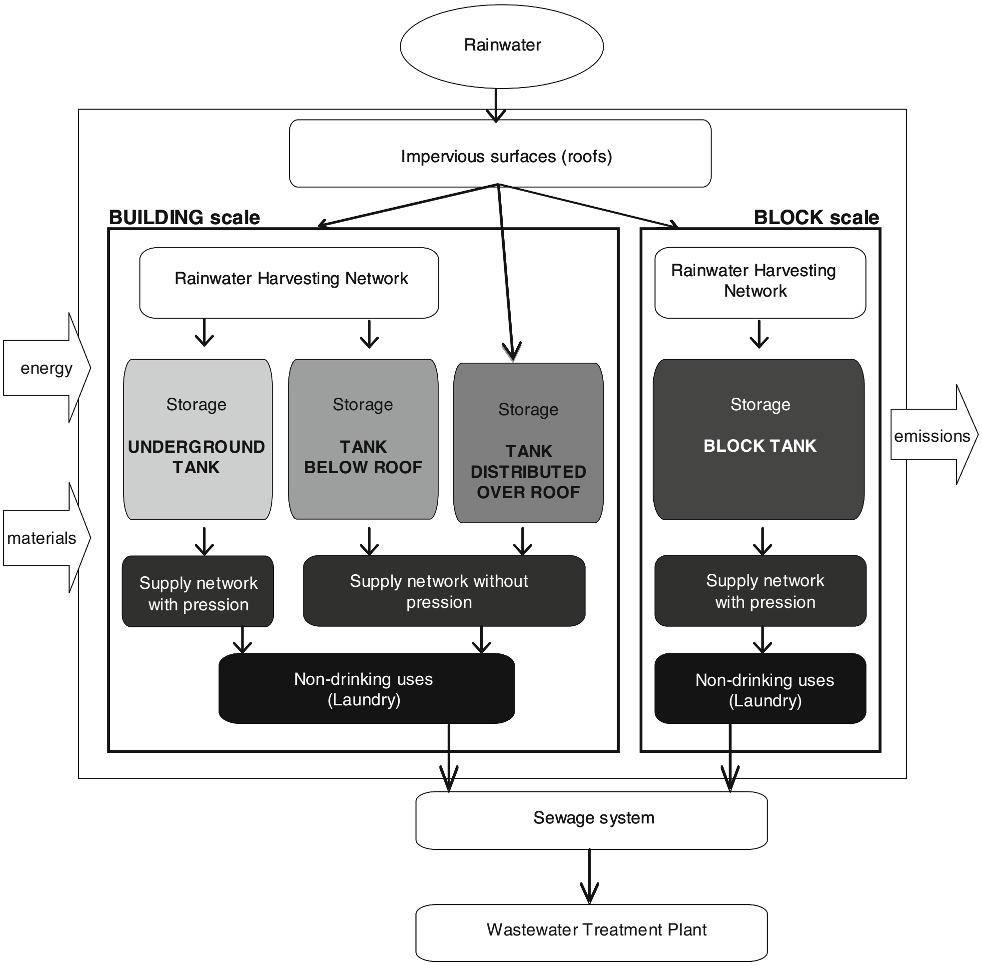

Fig. 1 RWH diagram and system boundaries at the building scale depending on the location and type of tank and at the block scale with community tanks for non-potable domestic uses

Fig. 2 Characteristics of the study area based on the two urban densities defined and the location of the tanks at the building and block scale

based on the scale of the infrastructure (building and block) and the location of the rainwater storage tank in the building (underground tank, tank below roof, and distributed over the roof).

2.4.3 Rainwater infrastructure scenarios

The combination of the density variable with the location of the infrastructures provided a total of eight scenarios for analysis. Each of these integrates the RWH infrastructures, which can be divided into three subsystems: catchment, storage, and distribution. Table 1 shows the characteristics of the main structural components for the different subsystems considered.

2.4.4 Definition of the subsystems

A direct-feed system with water-main back-up supply was assumed, including a rooftop runoff collection and conveyance (catchment subsystem), accumulation in a reservoir

Table 1 Structural characteristics of the main components of the eight analyzed scenarios based on the household density, the scale of the infrastructures, and the location of the tank in the RWH system

		Diffuse neighborhood				Compact neighborhood			
	Tank scale Tank location	D1 Building Underground	D2 Building Below roof	D3 Building Distributed over roof	D4 Block Underground	C1 Building Underground	C2 Building Below roof	C3 Building Distributed over roof	C4 Block Underground
Harvesting	Gutter (m)	47.4	47.4	–	189.6	90	90	–	620
	Down pipe (m)	6.9	6.8	–	125.5	16.5	15.2	–	371
Storage	Tank dimensions (m^3)	5	5	9	20	21	21	37.8	209
		(1.7×1.7×1.7)	(2.2×2.3×1)	(10×10×0.09)	(2.7×2.7×2.7)	(2.8×2.8×2.8)	(4.6×4.6×1)	(30×14×0.09)	(5.9×5.9×6)
Distribution	Supplying pipe (m)	5.7	4.4	4.4	153.3	26.5	13.5	13.5	431
	Pump (units)	1	0	0	2	1	0	0	2

(storage subsystem), and supply to the consumption point of use in the dwelling (distribution subsystem) (Environmental Agency 2008).

Catchment Rainwater is harvested only from roofs (flat), for which gutters and downpipes are necessary in all scenarios except those with the tank distributed over the entire roof (D3 and C3). In the block scenarios (D4 and C4), the tank collects water from the roofs of all the buildings in the block (see Fig. 2). The roof runoff coefficient was estimated at 0.9 (Singh 1992). It was assumed that the water harvested is of suitable quality for the intended use (Göbel et al. 2007; Farreny et al. 2011b). Rainwater overflows, necessary to wash the tank during rainfall peaks (Lawson et al. 2009), are directed into the sewage system.

Regarding the diffuse urban scenarios requiring conveyance components (D1, D2, and D4), a galvanized steel gutter is placed on the roof (125 mm diameter, 0.5 mm thickness) and connected to the downpipe. The downpipes are made of a three-layer wall polypropylene (125 mm diameter, 8 kN/m^2 ring stiffness, and 5.9 mm thick). In the compact urban scenarios where a catchment is needed (C1, C2, and C4), only the downpipe dimensions were varied (160 mm diameter, 8 kN/m^2, 7.5 mm thick) as there is more water to be collected (see Table 1).

Storage The storage subsystem consists of a rainwater storage tank, the design of which varies depending on its location and scale (see Fig. 2 and Table 1):

1. Underground tank (scenarios D1 and C1): located at the base of the downpipe with respect to the foundation
2. Below-roof tank (scenarios D2 and C2): placed at the center of the roof on a pillar to provide structural support, just below the lowest point of the roof
3. Distributed-over-roof tank (scenarios D3 and C3): covers much of the extension of the roof. This tank has an additional basal water volume of 4 cm depth which is not intended for consumption but necessary for its operation. The strategy was designed so that rainwater flows between the slabs of the roof and is stored directly in the tank, alleviating the need for catchment components
4. Block tank (scenarios D4 and C4): located underground in the center of the block

The concrete used in the tank construction and the structural reinforcement elements has a characteristic compressive strength of 20 to 25 MPa. The reinforcement consists of the extra structural material required in the building to withstand the weight of the water-filled tank and is therefore necessary in scenarios with the tank over or below the roof (D2, D3, C2, and C3). The necessary structural reinforcement was calculated based on the difference between the structure with and without the tank.

Steel (80% recycled, yield strength of 500 MPa) was also considered in the construction of the tank and the reinforcement (in those scenarios requiring it). The formwork is made of phenolic particle board (between 3 and 5 m in height and 3 cm thick), which can be reused up to 20 times (Alsina 2010, personal communication, Alsina Formwork Solutions (http://www.alsina.es/en/index.php)).

Distribution This subsystem consists of a pump (if necessary) and the rainwater supply pipes to its end-use point. The distribution is from the tank to the center of each building floor (see Fig. 2). The supplying pipe in the diffuse density model is made of polypropylene copolymer (25 mm diameter and 4.2 mm thick). For the compact urban density model, only the pipe dimensions were varied (90 mm diameter and 8.2 mm thick) as there is more water to be distributed (see Table 1).

The scenarios with a tank placed over or below the roof (D2, D3, C2, and C3) do not require a pumping system (the distribution system has sufficient pressure to supply water to a washing machine by gravity flow). In scenarios with underground tanks (D1 and C1), a stainless steel submersible pump (0.25 and 2.2 kW for the diffuse and compact density scenarios, respectively) was located inside the tank. Additionally, two pumps were considered at the block scale tanks (in scenarios D4 and C4), required to pump a larger volume of water at a greater distance. The power consumption over the lifespan of the system was calculated based on 10 min of pumping per wash load, based on the average time required to fill a washing machine.

Regarding the calculation of the necessary pumping energy required in the diffuse model scenarios with underground tanks (D1 and D4), pipe section head losses of 25% of the height were assumed. The pump selected must overcome a total head loss of 8 m with a maximum flow of 19 l/min. In the compact model scenarios (C1 and C4), head losses of 6.5% of the height in the pipeline were assumed. In this case, the pump must overcome a total head loss of 16.5 m with a maximum flow of 465 l/min. Construction elements and minor components such as complementary boxes, stopcocks, valves, elbows, and filters were excluded from the analysis.

2.4.5 Life cycle stages

The phases considered in the inventory of the system were materials, transportation, construction, use, and deconstruction of each of the three subsystems. The materials stage comprises the extraction, production, processing, and storage of materials used in the RWH infrastructures, calculated per scenario in both urban models.

In the construction stage, the energy costs related to infrastructure construction include land excavation and opening and closing of trenches. However, for both the diffuse and compact scenarios with tanks over or below the roof (D2, D3, C2, and C3), the use of machinery in the construction of the catchment and distribution subsystems was not considered. Additionally, standard losses of 5% of the total materials were assumed.

The transport stage includes both local material transportation to the building site (estimated at 30 km) and waste transport to a local disposal facility (an average distance of 50 km). The types of vehicles (trucks and vans) selected are representative of the EURO5 engine technology. The use stage consists of the power demand in the distribution subsystem for those scenarios with pumping needs (D1, D4, C1, and C4).

The pipeline deconstruction energy was also not considered in the demolition phase for the scenarios with tanks over and below the roof (D2, D3, C2, and C3). In addition, it was assumed that the energy required in the demolition and construction stages of the other scenarios (D1, D4, C1, and C4) was the same for both subsystems because it is linked with land excavation and the reopening and closing of trenches.

3 Results

3.1 Inventory data

The inventory data are presented in Table 2, disaggregated for the diffuse and compact urban scenarios. It describes the amounts of materials and the energy consumption per FU grouped into subsystems, components, and life cycle stages.

The storage subsystem had the greatest material requirements, which are due to the tank and the structural reinforcement required (only in scenarios with tanks over and below the roof), comprising more than 97% of the total costs of each scenario. Within this subsystem, concrete was the major constituent in each scenario analyzed. Structural reinforcement components were also relevant in D2. The proportions of materials required in the catchment and distribution subsystems were almost negligible with respect to the total.

Additionally, the construction energy of the storage subsystem was significant in scenarios D1 and C1 with the underground tanks, for total contributions of 57% and 70%, respectively. In contrast, the deconstruction stage was the main contributor in scenario C2, requiring 21 times more energy than the distributed-over-roof tank scenario (D3) and 17 times more than C1 and C4 (see Table 2).

In the diffuse urban models, pumping power consumption during the use stage in the block scenario (D4) was twice as much as in the building-scale scenario (D1). In contrast, at compact densities, the inverse was found; the consumption of C1 was up to five times greater than C4.

3.2 Impact assessment of systems

The results of the environmental impact assessments were analyzed separately for the diffuse and compact urban models (Figs. 3 and 4), disaggregated according to the total impact and the contribution of the subsystems defined for each impact category. The contributions of each life cycle stage in each scenario and the absolute values of the impact characterizations are shown in Table 3.

3.2.1 Environmental impacts of diffuse density models

The results of the environmental analysis of impacts regarding the diffuse density scenarios are presented in Fig. 3 showing the total relative values of the impacts of every scenario with reference to the option with the most negative impacts and the relative contributions of the subsystems—catchment, storage, and distribution—in each scenario.

In the diffuse urban model, the best environmental results were obtained in D3 (distributed-over-roof tank) except for the impact category of ODP, in which scenario D4 (block tank) was the best choice (see Fig. 3). Conversely, the scenario with the most significant negative impacts in most of the seven categories analyzed was D2 (tank below cover), except for AP in which D4 showed a greater contribution.

Impacts of subsystems in diffuse density scenarios For almost all the scenarios analyzed, the storage subsystem had the highest environmental impacts in six out of seven categories analyzed, except for scenario D4 in the AP category, in which the distribution subsystem was the main contributor to the total value (see Fig. 3). The impact contributions of the catchment and distribution subsystems varied depending on the scenario. It is worth noting that the total impact for scenario D3 was lower than the others because it does not require a dedicated harvesting subsystem. The environmental impacts per FU related to each scenario and the relative weights of the life cycle stages considered in the diffuse and compact density models are presented in Table 3.

Impacts of stages in diffuse density scenarios The results regarding the diffuse density scenarios show that the

Table 2 Inventory of materials and energy per FU disaggregated into subsystems, components, and stages

	Life cycle stages		Data per FU	D1	D2	D3	D4	C1	C2	C3	C4
Catchment	Materials	Pipe material	Galvanized steel (kg)	7.6E−02	7.6E−02	0	7.5E−02	1.2E−02	1.2E−02	0	8.6E−03
			PP (kg)	2.1E−02	2.1E−02	0	9.5E−02	7.1E−03	6.6E−03	0	1.6E−02
	Construction	Power consumption	Diesel (MJ)	2.5E−01	0	0	1.7E+00	6.1E−02	0	0	1.6E−01
	Transportation	Materials to site	Van <3.5 t (tkm):30 km	2.9E−03	2.9E−03	0	5.1E−03	5.9E−04	5.7E−04	0	7.4E−04
		Waste to manager	Van <3.5 t (tkm):50 km	5.1E−03	5.1E−03	0	8.9E−03	1.0E−03	1.0E−03	0	1.3E−03
	Deconstruction	Demolition energy	Diesel (MJ)	2.5E−01	0	0	1.7E+00	6.1E−02	0	0	1.6E−01
Storage	Materials	Tank	Recycled wood formwork (kg)	7.0E−03	5.1E−03	0	4.2E−03	1.5E−03	1.1E−03	0	7.2E−04
			Concrete 20–25 MPa (kg)	8.3E+00	3.9E+00	7.5E+00	7.3E+00	2.6E+00	1.7E+00	2.7E+00	2.5E+00
			Reinforcing steel frame (kg)	3.2E−01	5.1E−01	9.7E−02	2.4E−01	8.8E−02	2.2E−01	2.0E−02	9.2E−02
			Waterproof sheet (kg)	0	0	8.5E−02	0	0	0	3.0E−02	0
			Brick wall (kg)	0	0	3.4E−01	0	0	0	6.8E−02	0
			Lining mortar (kg)	0	0	4.1E−02	0	0	0	8.2E−03	0
		Structural reinforcement	Reinforcing steel frame (kg)	0	1.4E−01	5.7E−03	0	0	1.1E−02	3.3E−03	0
			Concrete 20–25 MPa (kg)	0	7.6E+00	5.6E−01	0	0	9.4E−01	3.5E−01	0
	Construction	Power consumption	Diesel (MJ)	6.7E−01	0	0	7.6E−01	2.8E−01	0	0	2.9E−01
	Transportation	Materials to site	Truck >32 t (tkm):30 km	0	0	0	2.3E−01	8.2E−02	8.7E−02	0	7.7E−02
			Truck 7.5–16 t (tkm):30 km	2.6E−01	3.7E−01	2.6E−01	0	0	0	9.6E−02	0
		Waste to manager	Truck >32 t (tkm):50 km	4.6E−01	6.4E−01	4.5E−01	4.0E−01	1.4E−01	1.5E−01	1.7E−01	1.4E−01
	Deconstruction	Demolition energy	Diesel (MJ)	3.5E−01	4.8E−01	2.4E−01	3.2E−01	1.1E−01	1.8E+00	8.7E−02	1.1E−01
Distribution	Materials	Pipe	PP-copolymer (kg)	3.0E−03	2.4E−03	2.4E−03	2.0E−02	7.1E−03	4.1E−03	4.1E−03	1.3E−02
		Pump	Stainless steel (kg)	1.9E−02	0	0	9.5E−03	7.3E−03	0	0	1.5E−03
	Construction	Power consumption	Diesel (MJ)	2.5E−01	0	0	1.7E+00	6.1E−02	0	0	1.6E−01
	Transportation	Materials to site	Van <3.5 t (tkm):30 km	6.7E−04	7.1E−05	7.1E−05	8.9E−04	4.3E−04	1.2E−04	1.2E−04	4.4E−04
		Waste to manager	Van <3.5 t (tkm):50 km	1.2E−03	1.2E−04	1.2E−04	1.6E−03	7.6E−04	2.2E−04	2.2E−04	7.7E−04
	Use	Pumping consumption	Electricity (kWh)	4.9E−01	0	0	9.7E−01	4.2E+00	0	0	2.1E+00
	Deconstruction	Demolition energy	Diesel (MJ)	2.5E−01	0	0	1.7E+00	6.1E−02	0	0	1.6E−01

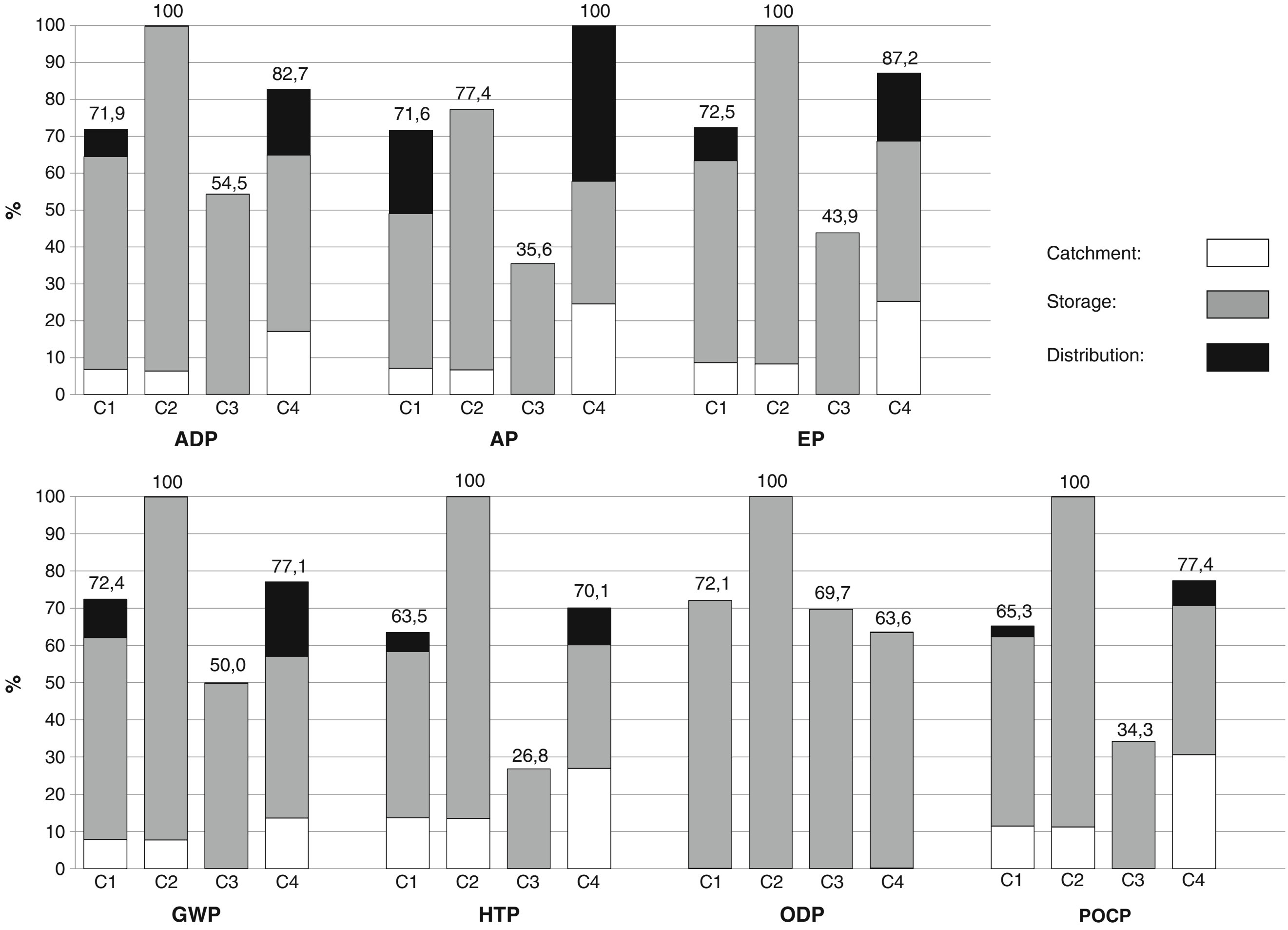

Fig. 3 Proportional comparison of the total environmental impacts of the diffuse density scenarios by impact category and contributions of the subsystems

materials stage was by far the major contributor in all of them (see Table 3). This stage was particularly relevant in scenarios D2 and D3, representing more than 93% of the impacts over the total absolute value of each scenario. The use stage was relevant in D4 and to a lesser extent in D1. Its contribution varied depending on the impact category analyzed, reaching 33% of the total contribution to AP in the D4 scenario.

3.2.2 Environmental impacts of compact density models

Figure 4 shows the relative contributions of the total environmental impacts with regard to the compact urban model depending on the highest-impact scenario and the weight attributed to the subsystems for each constructive option. These results suggest that the best performance in environmental terms was achieved by the tank distributed over the roof (C3) except for ODP, in which it was the scenario with more impacts (see Fig. 4). The environmentally worst option was C1, as it presented higher impacts in six categories (all except ODP).

Impacts of subsystems in compact density scenarios The greatest impacts were related to the storage subsystems in C2, C3, and C4 (see Fig. 4). The distribution subsystem was the main contributor in C1 except for the ODP category, in which the storage had the highest impacts in all scenarios.

Impacts of stages in compact density scenarios The results from the compact urban model analysis highlight the materials stage as the most relevant factor in construction scenarios C2 and C3, with more than 85% of the total impacts (see Table 3). Furthermore, the use stage in scenario C1 had the greatest environmental impacts in five out of the seven categories; the exceptions were ODP and POCP, in which the materials were the main contributors to the life cycle impacts of the RWH infrastructures and were more significant in the former category (see Table 3).

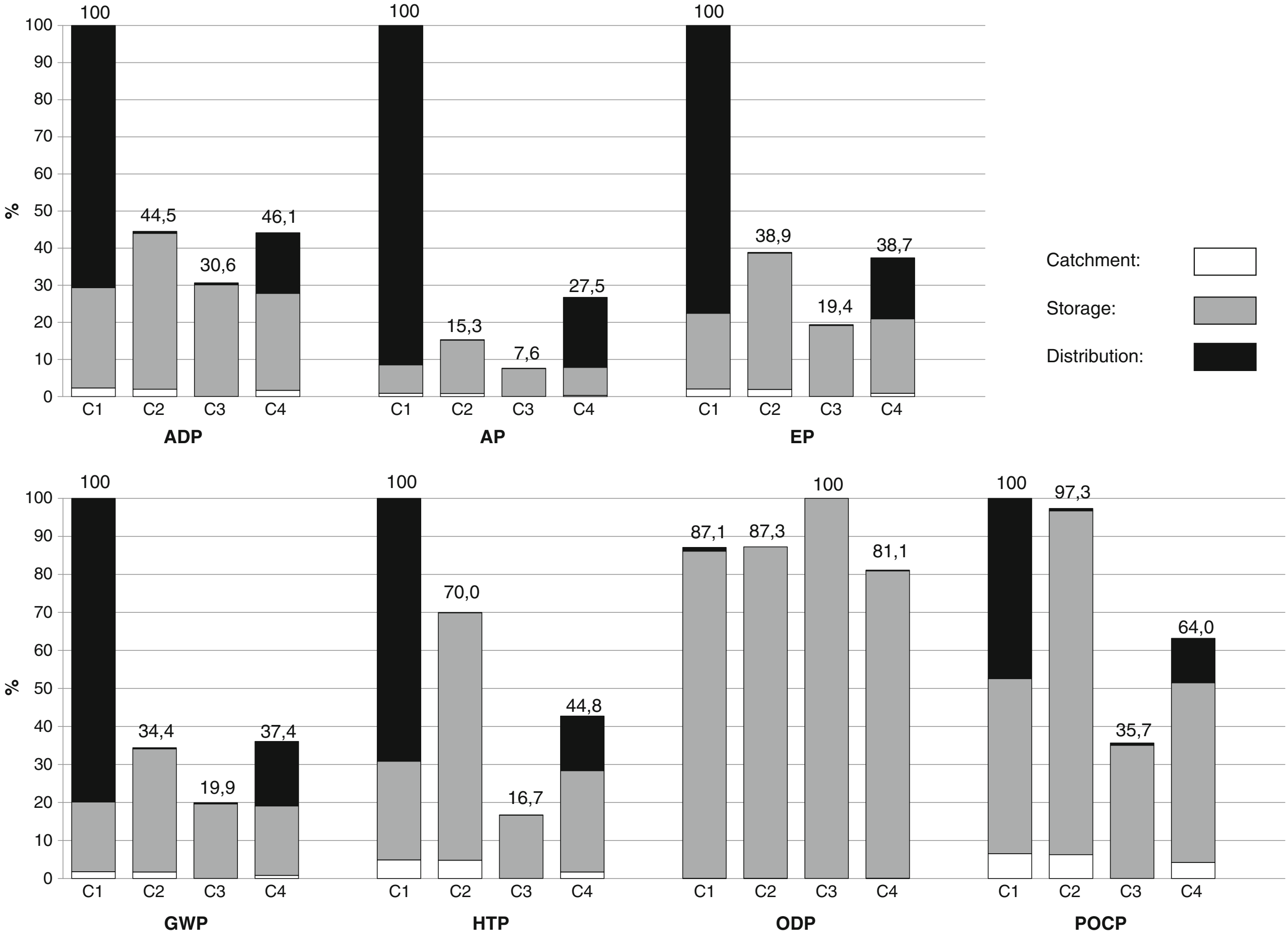

Fig. 4 Proportional comparison of the total environmental impacts of the compact density scenarios by impact category and contributions of the subsystems

3.2.3 Comparison of the diffuse and compact density impacts

From the results obtained, a more favorable environmental performance can be attributed to compact density urban models in six out of the seven impact categories analyzed. Overall, the C3 scenario showed the fewest impacts except for ODP, in which C4 presented similar contributions (see Table 3). On the contrary, the scenario with the highest impacts by far was D2 except in the AP category, in which C1 was the worst option, doubling the contribution of all the other scenarios. With regard to ODP impact category, major environmental impacts can clearly be seen mainly linked to diffuse urban scenarios rather than to compact ones.

Focusing the analysis on the GWP category, given its current political relevance, scenario C3 presented the lowest relative proportion of impacts over the main contributor (17.2%) followed by scenarios C2 (29.7%), C4 (32.3%), D3 (50%), D1 (72.4%), C1 (86.4%), and D2 (100%). Overall, the comparison of the same RWH scenarios in the diffuse and compact city models also corroborates these results. Proportionally, nearly three times greater impacts were observed among the diffuse urban scenarios D2, D3, and D4 in comparison with their analogs in compact density (C2, C3, and C4), although this varied depending on the impact category. In scenarios with the tank below the roof (D2 and C2), these differences were particularly relevant, on the order of 69% to 77% lower in C2 than in D2. On the contrary, the reverse was observed with scenarios D1 and C1 in the EP, GWP, and AP impact categories, for which the contributions of C1 were 7%, 16%, and 55% higher, respectively.

4 Discussion

4.1 Impact analysis of the diffuse density model

The environmental results related to the use of RWH systems in diffuse urban models by the installation of a tank

Table 3 Characterization of results per FU and life cycle stage contributions in the D and C models

		ADP (kg Sb eq.)		AP (kg SO_2 eq.)		EP (kg PO_4^{3-} eq.)		GWP (kg CO_2 eq.)		HTP (kg 1.4-DB eq.)		ODP (kg CFC-11 eq.)		POCP (kg C_2H_4 eq.)	
	Life cycle stages	D	C	D	C	D	C	D	C	D	C	D	C	D	C
1	Materials (%)	85.85	29.34	70.86	9.46	83.51	22.26	83.12	20.57	91.28	31.08	99.85	98.79	92.78	52.43
	Construction (%)	2.16	0,.83	1.36	0.21	1.08	0.35	0.51	0.15	0.62	0.29	0.03	0.04	0,84	0.60
	Transport (%)	3.23	0.77	3.49	0.34	5.05	1.01	5.06	0.88	1.74	0.57	0.06	0.04	3.19	1.61
	Use (%)	7.18	68.57	23.30	89.86	9.57	76.18	10.93	78.31	5.89	67.89	0.04	1.12	2.57	45.01
	Deconstruction (%)	1.58	0.49	0.99	0.12	0.79	0.20	0.37	0.09	0.46	0.17	0.02	0.02	0.62	0.35
2	Absolute value (kg)	2.99 E−02	2.68 E−02	1.22 E−02	2.70 E−02	1.50 E−03	1.61 E−03	2.69 E+00	3.21 E+00	1.52 E+00	1.13 E+00	3.80 E−05	1.22 E−05	5.49 E−04	2.68 E−04
	Materials (%)	96.16	89.98	95.32	91.71	94.94	93.48	95.06	95.58	98.45	97.38	99.94	99.81	97.35	95.81
	Construction (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Transport (%)	3.17	1.72	4.16	2.17	4.74	2.55	4.78	2.52	1.38	0.78	0.05	0.04	2.43	1.47
	Use (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Deconstruction (%)	0.67	8.29	0.52	6.12	0.32	3.96	0.15	1.90	0.16	1.84	0.01	0.16	0.23	2.72
	Absolute value (kg)	3.99 E−02	1.19 E−02	1.32 E−02	4.14 E−03	2.06 E−03	6.25 E−04	3.71 E+00	1.10 E+00	2.39 E+00	7.89 E−01	5.28 E−05	1.22 E−05	8.42 E−04	2.61 E−04
3	Materials (%)	95.81	92.27	93.73	87.66	92.76	85.75	93.67	87.33	96.59	92.04	99.94	99.90	96.01	91.63
	Construction (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Transport (%)	3.61	3.61	5.71	5.94	6.87	7.00	6.18	6.31	3.10	3.85	0.05	0.05	3.66	4.13
	Use (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Deconstruction (%)	0.59	0.57	0.56	0.57	0.37	0.36	0.15	0.15	0.30	0.36	0.01	0.01	0.33	0.35
	Absolute value (kg)	2.27 E−02	8.51 E−03	6.06 E−03	2.19 E−03	9.07 E−04	3.35 E−04	1.86 E+00	6.82 E−01	6.42 E−01	1.96 E−01	3.68 E−05	1.40 E−05	2.89 E−04	9.94 E−05
4	Materials (%)	72.85	63.82	47.22	31.34	61.73	55.67	73.10	54.73	65.67	66.69	99.52	99.62	69.58	80.87
	Construction (%)	6.76	2.78	3.51	1.18	3.24	1.38	1.73	0.61	2.04	1.00	0.13	0.06	2.56	1.43
	Transport (%)	2.00	1.64	1.88	1.22	3.08	2.57	3.32	2.30	1.38	1.27	0.04	0.04	2.76	2.61
	Use (%)	12.33	29.82	33.01	65.43	15.73	39.42	20.31	41.94	10.56	30.35	0.09	0.24	4.28	14.09
	Deconstruction (%)	6.05	1.95	3.14	0.83	2.89	0.97	1.55	0.42	1.82	0.70	0.12	0.04	2.29	1.00
	Absolute value (kg)	3.45 E−02	1.23 E−02	1.70 E−02	7.43 E−03	1.80 E−03	6.23 E−04	2.86 E+00	1.20 E+00	1.68 E+00	5.06 E−01	3.35 E−05	1.14 E−05	6.51 E−04	1.72 E−04

distributed-over-the-roof surface (D3) presented the lowest impact values. Those impacts entailed a reduction from 46% to 73% compared to the scenario with the tank below the roof (D2), the scenario with the greatest impact (see Fig. 3). The lower environmental impact associated with the tank distributed over the roof was mainly linked to the lack of a catchment subsystem, the absence of power consumption during the use stage, and a lower volume of materials related to the storage subsystem. This kind of tank allows for a better distribution of weight on the structure of the building because it covers a larger roof area and requires less structural reinforcement. Additionally, this strategy integrates existing building materials, as the top of the building serves as the base of the tank, and its multifunctional properties should also be considered given that the tank acts as a thermal insulator for the buildings (Ruíz and Briz 2010). However, these results should be compared with the environmental analysis of RWH infrastructures at the neighborhood scale to determine if this construction option is still the most ecofriendly in comparison with the construction of more centralized infrastructures.

Here, the results indicated that the major environmental impacts of all scenarios among the diffuse urban density models were associated with the storage subsystem (see Fig. 3) and the material-processing stage (see Table 3), partially due to the impact of the materials from the tank and the structural reinforcement (mainly consisting of concrete and steel). These material impacts determined the D2 scenario to be the least favorable environmentally due to the structural reinforcement required in the construction of the building to offset the weight of the tank located on the roof on a pillar. Regarding the concrete used in the construction of the tank and the reinforcement, the cement content and the transport of components turn out to be the major contributors to the environmental impacts of concrete construction (Shuurmans et al. 2005; Oliver-Solà et al. 2009). In particular, cement clinker is the component with the greatest contribution in the final impact of concrete (Josa et al. 2004, 2007). For this reason, it is important to select a concrete with a suitable cement content to fulfill the target function. In addition, coprocessing in the cement industry can be an optimum way of recovering energy and materials from waste, thus reducing the environmental impacts of concrete during its life cycle (CEMBUREAU 2009). Blengini (2009) also noted the importance of concrete and steel reinforcement in the stages of extraction and processing of materials.

Distribution was the largest contributor to the total impact in the block-tank scenario D4 (42.2%) for the AP impact category (see Fig. 3). The composition of the electricity generation mix, consisting of large gas and coal demands, is the main cause of the increased impacts related to power consumption used for pumping over the lifespan of the system. This higher energy consumption in scenario D4 was due to the existence of a single underground tank, which must redistribute water to each dwelling on the block.

4.2 Impact analysis of the compact density model

In the analysis of the compact urban scenarios, it was observed that the construction option of the tank distributed over the roof (C3) was the optimum RWH choice in environmental terms (see Fig. 4). This scenario, despite showing the highest impacts in the ODP category due to the storage subsystem, presented from 64% to 92% lower environmental impact overall than the underground tank (C1), which had the most significant negative impact (see Fig. 4). Nevertheless, the ODP category had contributions of more than 80% of the total impact in all four scenarios due to the building materials load.

C1 was the scenario with the greatest impacts among the compact density models for most impact categories except ODP; the impacts were associated with the distribution subsystem (see Fig. 4) during the use period of the infrastructure (see Table 3), mainly attributable to the pumping power required to supply water to a higher apartment density in such compact buildings. This scenario had twice the contribution of the other scenarios in most impact categories except for HTP and POCP. Therefore, in this urban density scenario, it is in the use stage where efforts should be concentrated to reduce the environmental impacts, for instance, by means of the installation of more efficient pumps.

With reference to scenarios C2 (below-roof tank), C3 (distributed-over-roof tank), and C4 (block tank), the higher impact values were generally associated with the storage, owing to the tank materials and structural reinforcement components (concrete and steel) (see Table 3). However, in the compact urban density model (C2), the structural reinforcement was not as relevant as in the diffuse model (D2).

4.3 Impact comparison of the diffuse and compact density model

Generally, the results of this study indicate that the environmental impacts of RWH systems in compact densities are almost three times lower than in diffuse densities except for the C1 scenario. The exploitation of this resource is higher in compact cities as there is a greater demand in relation to rainwater availability. As an example, the resulting impact values for the GWP category of the compact density scenarios C2, C3, and C4 were 2.2 to 4.4 times lower than in the D1 scenario with an underground tank.

The infrastructure impacts are expressed in relation to the defined FU (1 m^3 of rainwater supplied per person and year). Therefore, comparing and interpreting the total impacts obtained from the characterizations for both urban densities should be done with caution, as the RWH infrastructures were designed to provide different amounts of water depending on the urban model considered. Choosing a constant demand throughout the year, such as laundry, results in a tank that is empty more often at the beginning of each rainfall in higher density areas (Rahman et al. 2010). This hypothesis affects the sizing of the tank as the dimensions can be chosen based on the minimum amount of volume needed since the water will not remain much time in the tank.

The criteria used for choosing the tank dimensions were based on the optimum water storage yield by means of the RainCycle software (Roebuck and Ashley 2006), which models the volumetric parameters of the tank based on the potential daily rainfall supply and a constant laundry demand throughout the year. The storage volumes selected were the cause of a higher amount of overflow in the diffuse urban density. This is due to the availability of large rainwater catchment areas per inhabitant (94 m^2/inhabitant). These frequent overflow volumes could be used in other non-potable domestic uses, such as garden watering or vehicle and outdoor cleaning, thus reducing the impacts of the diffuse density scenarios per FU. In contrast, the low unitary catchment surface availability in the compact density model (11 m^2/inhabitant) combined with the high demand concentrated in a building indicates the maximization of the rainwater volume used, causing fewer overflows in the system.

The definition of variables determines that different proportion of demand can be fulfilled in each urban density: The water self-sufficiency for laundry was 98% in the diffuse urban models and 47% in the compact ones. As a result, in compact densities, more conventional municipal water is required to meet the demand. The differing roof-surface availability determines that the RW supply is greater in diffuse densities, and hence, the proportion of demand is also considerably higher. The variability of the water self-sufficiency of these systems indicates the highly site-specific nature of RWH for demand management, along with the fact that implementation issues can have a significant impact on system efficiency (Ward 2010). These results could be further improved by the study of the relationship between surface area, height, and dwelling density per building to determine the optimum RWH infrastructure for each kind of urban model.

In this context, water efficiency can be defined as the relationship between the water delivered by the system (the output, namely the collection, storage, and supply of 1 m3 of rainwater per person per year) and the amount of water required for that particular purpose (which can be estimated as the water footprint). From an environmental point of view, the scenario with a higher ecoefficiency should be the one with fewer impacts per cubic meter of water delivered. In this case, from among all the scenarios analyzed, C3 (distributed-over-roof tank) is the most ecoefficient choice. From the discussion above, it can be concluded that compact density urban models are more ecoefficient than diffuse density ones.

Another way to determine the water efficiency of each scenario is by means of its *water footprint*, defined as the volume of water used along the lifecycle of the infrastructures (Hoekstra et al. 2011). Therefore, the RWH scenario most water efficient would be the one with the lowest demand to satisfy the FU defined (which means lower water footprint values). The water footprint of the eight scenarios under study was estimated, and the results indicate that in the diffuse density neighborhood, water footprint values range from 17.7 to 4.9 m^3 of water footprint per m^3 of water supplied. In this urban model, scenario D3 and D2 present the lowest and highest water footprint values, respectively. In the compact density urban model, results indicate that C1 scenario shows the highest water footprint from among all (7.7 m^3 water footprint/m^3 water supplied) while C3 scenario is the least water intensive (1.5 m^3 water footprint/m^3 water supplied). Comparing both urban densities, it can be stated that compact neighborhoods are between 1.4 and 3.3 times more water efficient in water footprint terms than diffuse ones due to the fewer materials needed per cubic meter supplied. These results agree with the previous ecoefficiency analysis as both conclude that compact density urban models are more water efficient than diffuse ones, in particular C3 scenario is the most water-efficient strategy.

4.4 Comparison of the impacts with conventional networks and alternative water techniques

Table 4 shows an impact comparison between two of the RWH scenarios presented in this study (C3 and C4 as examples of a gravity distribution system and a pumping supplying system respectively), the drinking main water supply system (Muñoz et al. 2010), and other alternative technologies such as water transfer from the Ebro river (Spain), wastewater reclamation, desalination by reverse osmosis (RO), and wastewater treatment (Raluy 2009). The indicators selected given their importance are the GWP (kilogram CO_{2eq} per cubic meter of water supplied) and the energy demand during use stage (kilowatt-hour per cubic meter). All data refer to Mediterranean regions in order to allow comparisons with the maximum reliability.

As can be seen from Table 4, RWH systems (in particular scenarios C3 and C4) are within the same order of magnitude as the current drinking main water supply and the alternative water technologies, being much less energy-

Table 4 GWP and energy demand impact comparison of three water management systems: RWH, drinking main water supply systems, and alternative technologies

		GWP (kg CO_{2eq}/m^3)	Energy demand (kWh/m^3)
RWH	C3 (gravity system)	0.64	0.00
	C4 (pumping system)	1.20	2.10
Drinking mains water (Muñoz et al. 2010)	Water production	0.37	0.14
	Water distribution	0,44	0.20
Alternative technologies (Raluy 2009)	Water transfer from river	1.51	2.50
	Wastewater reclamation	0.62	0.50
	Desalination (RO)	1.96	4.00
	Wastewater treatment	0.91	1.04

intensive than desalination (RO) processes and water transfers from rivers. On the one hand, it is quite obvious that main water supply networks show lower energetic and infrastructural impact values since the amount of water that goes through this system is much larger than the built infrastructure that supports it. On the other, alternative systems require high amounts of energy during its use stage (Ward 2010). These results agree with the energy analysis of different water supply technologies performed by Stokes and Horvath (2006) in California. Their results indicate that desalination technologies are among the most energy-intensive technologies nowadays, causing from 2 to 18 times more carbon emissions than water importation or recycling. The comparison of the different GWP results and the energy demand during use stage altogether indicates that scenario C3 is environmentally better than all the other alternative technologies and is as well very similar to the GWP results obtained for the drinking main water supply production and distribution.

However, the comparison between RWH scenarios and the other options is somewhat impeded because the first refer to local water management strategies while drinking main water supply systems and alternative technologies take into account larger scales (regional or basin scales). Data regarding these options (shown in Table 4) do not consider the entire distribution infrastructure to the final consumer, and then a large part of the infrastructure is missing in this analysis. Besides, drinking water systems show large network losses from 15% to 30%, much higher than those obtained by RWH and the lifespan of the water production and distribution infrastructures is usually longer as well (about 70 years); this should also be adjusted to make a more consistent comparison.

5 Conclusions

The strategies for using rainwater raised in this study are located in Mediterranean environments, which are at present characterized by a growing water demand and the prospect of worsening water shortages. The implications of this situation are the need to import water from other regions or to find alternative, unconventional water sources. In this context, the use of endogenous local resources, such as rainwater, is one possible solution for increasing water supply and an adaptive strategy to mitigate the repercussions of climate change. The current study estimated the environmental impacts related to RWH systems in two contrasting urban density models (diffuse and compact) for eight defined scenarios differentiated in terms of scale and location of the storage tanks.

From the outcomes of the LCA of RWH systems, it was observed that the environmentally optimal infrastructure, regardless of urban density, locates the tank on the roof in an integrated design extended across the top of the building that evenly distributes the weight on the structure. The determining factor here is the reduced need for structural components; additionally, the absence of catchment components, the use of the gravity flow to distribute the water supply, and the adjustability of the tank to the shape of the roof are other advantages of this scenario.

The storage subsystem and the life cycle stage of extraction and processing of the tank materials and the structural reinforcement components are critical factors to consider in the environmental optimization of these infrastructures. These material components—especially the reinforcement—are important in the diffuse density model, particularly in the scenario with the tank placed on the roof on a pillar (D2), with a relative contribution of more than 95% of the total impact in all categories.

The environmental impacts associated with compact urban density models were lower than those in the diffuse density models. However, this did not show a linear trend and is conditional on the type of building reinforcement and pumping system needed as well as on the structural and hydraulic assumptions made. At compact urban densities, the distribution subsystem is the main consideration in the environmental improvement of the infrastructures. These impacts are especially relevant in the underground tank scenario at the building scale (C1) and are due to the power consumption during the use stage of the infrastructure. Water pumping to each dwelling contributes to more than the 78% of the total impact of this scenario for the GWP category. Therefore, the distribution subsystem role is particularly decisive when the pump must supply water to important heights.

The incorporation of the most favorable construction option in the definition and design of new residential areas can provide a significant reduction in CO_2 emissions. The possibility of integrating a tank distributed over the roof in the design of a building rather than constructing an underground tank in an existing one (often the only option in retrofit) generally reduces the environmental impacts up to 4.7 times in the compact urban density and 1.5 times in the diffuse.

The comparison of diffuse and compact urban systems concluded that, on the one hand, this kind of network implemented in the diffuse urban city model could allow for almost total self-sufficiency in water for laundry demand, with a simultaneous water surplus in the system; on the other hand, the adaptation of these infrastructures in compact city models would result in lower unitary environmental impacts and in higher water efficiencies, although they are characterized by a greater water deficit, with a 47% of the demand met. As a result, the selection of the environmentally optimal infrastructure for the implementation of RWH systems at an urban scale provides useful guidance in urban planning and design by integrating environmental criteria into the decision-making process. Regarding the comparison between RWH systems, conventional networks, and alternative technologies, it can be concluded that a priori rainwater can be considered a competitive resource, especially in urban areas with scarce water resources, but further studies are needed in order to consider RWH in a macroscale of the same order of magnitude and to include additional adjustments in order to make a consistent comparison.

6 Recommendations and perspectives

In the context of a Mediterranean climate, the comparison of the environmental results of RWH infrastructures with other alternative water supply strategies, such as desalination, water import, and water recycling, should be promoted through tools that consider the entire life cycle of these systems.

Conducting a comparative analysis of the materials used in the tank, structural reinforcement, pipes, and pump would be useful in evaluating the representativeness of the results obtained here and comparing them with other alternatives. The possibility of offering a potential water surplus to nearby city areas should also be explored (other residential districts, urban facilities, or public and private services). Additionally, the environmental impacts of RWH infrastructures should be assessed with regard to renovated buildings in future research, allowing a comparison of the outcomes of strategies for new building with those for existing buildings.

The optimization of the relative position of the tank in the building and the location of the points of use are other subjects which could be studied to reduce the environmental impact of RWH systems. In addition, the analysis of the optimal ratio between roof area and building height would be useful to determine the best scenario in each city model.

Further research should include an energetic analysis. In this context, it would be interesting to take into account the indirect energy savings linked to the placement of the tank distributed over the roof of the buildings as well as its function as a thermal regulator. Further studies should also integrate the economic and social analysis of the systems to evaluate the most cost-efficient option, the social perception of these infrastructures, and their repercussions on users. The results can be complemented with the corresponding quality analysis of stormwater runoff, as this is a topic of current concern among water managers and users.

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