Life cycle and hydrologic modeling of rainwater harvesting in urban neighborhoods: implications of urban form and water demand patterns in the US and Spain

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Abstract

Water management is key in any city, but applying alternative strategies might be more or less feasible depending on the urban form and water demand. This paper aims to compare the environmental performance of implementing rainwater harvesting (RWH) systems in American and European cities. To do so, two neighborhoods with a water-stressed Mediterranean climate were selected in contrasting cities, i.e., Calafell (Catalonia, Spain) and Ukiah (California, US). Calafell is a high-density, tourist city, whereas Ukiah is a typical sprawled area. We studied the life cycle impacts of RWH in urban contexts by using runoff modeling before (i.e. business as usual) and after the implementation of this system. In general, cisterns were able to supply more than 75% of the rainwater demand for laundry and toilet flushing. The exception were multi-story buildings with roofs smaller than <200 m^2, where the catchment area was insufficient to meet the demand. The implementation of RWH was environmentally beneficial with respect to the business-as-usual scenario, especially because of reduced runoff treatment needs. Along with soil features, roof area and water demand were major parameters that affected this reduction. RWH systems are more attractive in Calafell, which had 60% lower impacts than in Ukiah. Therefore, high-density areas can potentially benefit more from RWH than sprawled cities.

Keywords: rainwater harvesting, cities, circular economy, life cycle assessment, hydrology

1. Introduction

Reliably providing potable water and maintaining drainage standards to adequate levels for urban land use are important goals of water management in any city. Yet, these goals are being challenged by urbanization and climate change. More than 50% of the global population lives in urban areas (United Nations, 2015), and extreme drought and precipitation events resulting from climate change put additional pressure on the urban water system. In this sense, cities aim to become more resilient and might take advantage of circular economy strategies applied to the built environment and production systems (Ellen MacArthur Foundation, 2017). In the case of water, rainwater harvesting (RWH) is a potential circular solution that fosters regenerative and closed-loop systems that could alleviate the pressure on both water and stormwater infrastructure. Solving these threats to our conventional infrastructure has led to an exponential increase in RWH studies (Campisano et al., 2017; Leong et al., 2017; Pacheco and Campos, 2017; Vieira et al., 2014).

Several key points on RWH systems can be drawn from prior assessments. RWH may reduce the environmental impacts of water supply systems (Ghisi et al., 2009; Proença et al., 2011) while reducing the runoff (Sample and Liu, 2014; Tavakol-Davani et al., 2015). The hydrologic and environmental performance of RWH systems depends on the balance between water demand and available rainwater, which are location-sensitive parameters affected by the building type, water use, and climate.

Harvested rainwater has been used to meet various water demands, including car and parking lot cleaning (Ghisi and de Oliveira, 2007; Villarreal and Dixon, 2005) and lawn or agricultural irrigation (Liang and van Dijk, 2011; Yuan et al., 2003), but the most commonly studied end uses are toilet flushing (Anand and Apul, 2011; Bronchi et al., 1999; Devkota et al., 2015, 2013; Furumai, 2008) and laundry (Angrill et al., 2016; Vargas-Parra et al., 2013). On average, these two end uses constitute 27% (Mayer et al., 1999; Vickers, 2001) and 10-20% (Mudgal et al., 2009; OECD, 2002) of indoor potable water use, respectively. However, indoor water demand has recently decreased due to the implementation of new technologies with increased water-use efficiency (Deoreo and Mayer, 2012).

The actual water consumption can vary based on the number of occupants, seasons, building features, habits, and efficiency of water devices. Chang et al. (2013) estimated that these parameters could affect water use by up to 87% per household in old, high-density residential neighborhoods in the US. In urban landscapes, the social dimension (e.g., water use patterns) and urban configuration play critical roles in water consumption (Fragkou et al., 2016), resulting in further variations to the economic and environmental performance of RWH systems. For example, the effects of varying demand patterns during tourist seasons have not been studied, which may be a significant component to demand patterns as, in some cities, populations can double due to tourism. Depending on policies, social perception, and the type of building (single vs. multi-family buildings, and service buildings), the water use and the efficiency of RWH systems may also vary (Domènech and Saurí, 2011; Morales-Pinzón et al., 2012b). Recent studies suggested that RWH implemented in high occupancy buildings may have lower environmental impacts than in buildings with a greater amount of area per occupant (Vargas-Parra et al., 2014). Similarly, when these buildings are connected to combined sewers, the savings in energy and greenhouse gas emissions of RWH might be larger as compared to the ones connected to separate sewers (Devkota et al., 2015). Yet, the optimal scale for implementing RWH may be groups of houses or apartment buildings (Morales-Pinzón et al., 2012a), suggesting a need for neighborhood or larger scale analyses that account for the hydrologic and environmental effects of RWH based on urban form and demand patterns.

In this study, we posed two different questions: (i) is runoff a determining factor in defining the environmental feasibility of RWH at a neighborhood scale? (ii) if so, are there differences when urban form, water demand, and sanitation design vary? We hypothesized that RWH might reduce the urban runoff and its management in wastewater treatment plants (WWTP) once it is collected by combined sewers. This might translate into environmental impact reductions in RWH systems. Additionally, the life cycle environmental impacts of RWH systems might be lower in areas where the water demand is high, such as high-density neighborhoods. To test these hypotheses, we attempt to present a preliminary assessment that compares two urban neighborhoods that are similar in terms of rainwater availability. However, they vary with respect to building types and water use patterns due to differences in urban form, urban infrastructure, and population density. Our specific objectives were i) to characterize two neighborhoods with different demand patterns and urban infrastructure, such as high-density residential areas (i.e., European coastal urban model) and sprawled distinctive building use (i.e., American urban model); ii) to design RWH systems and compare the demand met in each case; iii) to determine the effects of RWH on urban runoff, and iv) to determine how the life cycle environmental impacts of RWH systems and drainage infrastructure altered in each neighborhood.

2. Materials and Methods

The novelty of this approach is the combination of a set of methods, as depicted in Figure 1. We first selected two sites and characterized their urban form (Section 2.1). The RWH systems were sized (Section 2.2) for each study site using a 15-year time series of daily rainfall data to capture changes in seasonality. Based on the supply and demand patterns, we estimated runoff volumes pre and post RWH implementation (Section 2.3). Lastly, we used the life cycle assessment (LCA) methodology to estimate the environmental impacts for each study site in a business-as-usual (BAU) scenario (no RWH) and after implementing RWH.

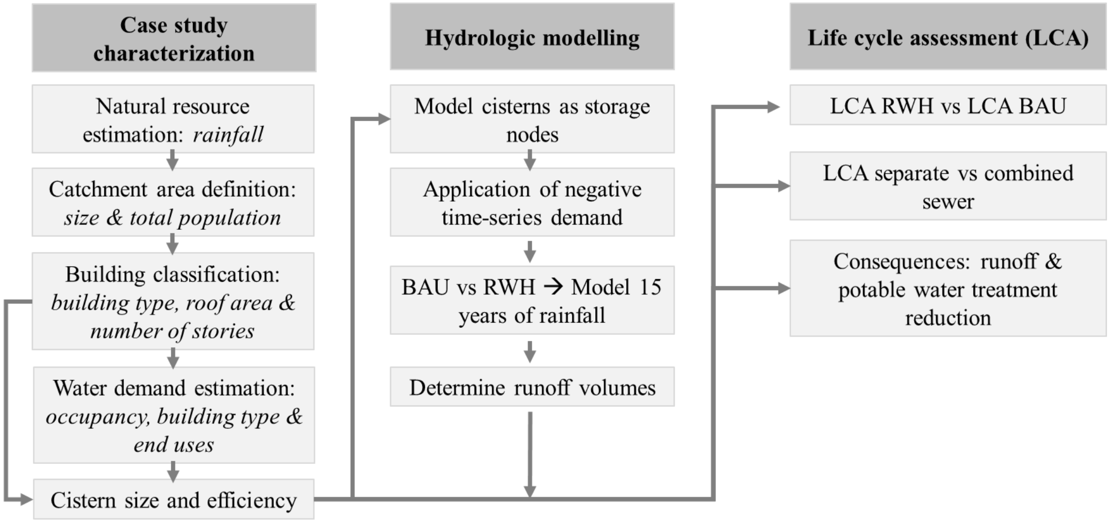

Figure 1. Schematic representation of the methodological framework

2.1. Site Selection and Description

To identify potential drivers towards the use of RWH, we selected two different cities. Because we sought to understand the potential effects of urban planning and water demand, the independent variable that drove site selection was the level of natural resources; in the present study, rainfall. Based on this first limitation, the candidate cities were required to have distinct building types, urban form, and water demand. As a result, Calafell (Catalonia, Spain) and Ukiah (California, US) were identified as they both represent the Mediterranean climate according to the Köppen Climate classification (Kottek et al., 2006) and have similar rainfall patterns. Ukiah and Calafell experience approximately 529 and 597 mm of annual rainfall, respectively. These precipitation depths reflect an average of the previous 15 years of data retrieved from Menne et al. (2012).

Ukiah and Calafell were also selected based on their distinct building patterns and urban form. In Ukiah, the urban landscape follows the predominant American design (sprawl), with varying building types, each serving an individual function and located at a predefined service/residential area based on zoning (Soule, 2006). In contrast, Calafell is typical of the European landscape, where there is no clear distinction between commercial and residential zones. It is largely configured with the ground floor consisting of commercial space and the remaining 3-4 stories serving as residential units. We selected a study area of 300-400 thousand m^2 for each city based on Calafell's downtown area and the area where most of population concentrates.

To assess the variations in urban form, we used prototypes for the diverse building types and characteristics that could be applied to the entire building stock of the studied areas (Reyna and Chester, 2015). The buildings were categorized based on their use (e.g., residential, commercial, education, etc.), roof area (<200 m^2, 201-500 m^2, 501-1,000 m^2 and >1,000 m^2), number of stories (1-5), and expected occupancy (3-100 people). Google Earth Pro was used to identify the various building types and dimensions. As a result, 500 buildings were studied in Calafell and 400, in Ukiah.

In terms of water demand, the population type might also affect the results and thus variations in the population throughout the year were considered. Ukiah is largely a residential area that would be expected to have a relatively constant population throughout the year. Here, the building occupancy was estimated according to the maximum floor area per occupant in US buildings defined by Deru et al. (2011). Alternatively, Calafell's population varies drastically in the summer due to the influx of tourists in Mediterranean coastal areas. This is especially relevant, given that in Catalonia, 70% of the population is located within a 20 km distance from the shore (Ulied and Xalabarder, 2004). In Calafell, tourism resulted in an 50-80% increase in population during the summer from 2002 to 2013 (IDESCAT, 2013). The effect of tourism was integrated into the water demand (Section 2.2.1) and a daily average was used in calculations. Additionally, we assumed four occupants per apartment in Calafell's buildings. The average year-round occupancy was 2.4 people (IDESCAT, 2013), but we doubled this occupancy to account for seasonality. The same number of occupants was assumed in all building prototypes.

Both cities were modelled considering the same water and wastewater treatment technologies to limit the dependent variables to urban form from a building perspective and occupant demand patterns. Results comparing the two locations are presented for both combined and separate sewer scenarios. While Ukiah and Calafell actually have different infrastructure (Ukiah, separate; Calafell, combined), the locations represent model cities for the analysis and lead to instructive results for the influence of urban form and demand patterns on water management systems. It is also notable that Calafell's sewer has great pumping energy requirements (0.46 kWh/m^3) (Petit-Boix et al., 2015), given that the WWTP is located 40 m above the sea level due to land price and aesthetics in coastal, tourist areas.

2.2. RWH Systems Design

2.2.1. Cistern Sizing

We assumed that the harvested rainwater would be used for toilet flushing and laundry. Only these two end uses were studied because they i) reflect high indoor water uses (10-20%), ii) present a low viral infection risk from using non-potable water (Lim et al., 2015), and iii) have not been assessed jointly in urban centers, but only as separate end uses and at a single building scale (Angrill et al., 2012; Devkota et al., 2015, 2013; Vargas-Parra et al., 2014). The water demands for each building type in Ukiah (Vickers, 2001) and Calafell (Molina et al., 2004) were estimated based on the water use for toilet flushing and laundry (see **Table S1** in the Supporting Information), use frequency (i.e., every day for flushing and once a week for laundry) and building occupancy. We assumed that rainwater was the primary source for both toilet flushing and laundry use, only supplemented by potable water when the harvested rainwater was insufficient to meet this demand. The cistern was sized using the Yield After Spillage (YAS) approach, which results in a conservative estimate of tank yield (Fewkes and Butler, 2000; Mitchell, 2007). Mitchell (2007) stated that using 10 years of precipitation data or more does not significantly affect the yield. In this case, a 15-year time series of daily rainfall data (from 2000 to 2014) was used to size the rainwater cisterns. The use of daily rainfall data captures seasonal variation in rainfall. The volumetric reliability (V_r) of a rainwater cistern, which is also a measure of the water saving efficiency of the tank, is used to size the tank. V_r can be calculated using Equation (1).

$$V_r = \frac{\sum Y_t}{\sum D_t} \qquad \text{Equation (1)}$$

where, V_r: volumetric reliability; Y_t: volume of rainwater supplied; D_t: daily water demand.

Based on the initial storage volume (V_{t-1}), rainfall inflow on first day (I_t) and daily water demand (D_t), the volume of rainwater supplied (Y_t) was calculated for the first time step t using Equation (2). After usage on the first day, the volume of water remaining in the cistern at the end of time step t (also called V_t) was calculated using Equation (3). Daily spillage was calculated by comparing the daily demand and supply using Equation (4). The initial storage volume (V_{t-1}) for the second time step would be the volume of water at the end of the first time step (V_t). The remaining time steps were estimated by applying the same procedure. The volumetric reliability of the rainwater tank was estimated by dividing long-term daily supply by long-term daily demand. The volumetric reliabilities of the series of rainwater tanks assumed in the first step were then assessed using Equation (1). The size of the cistern was considered optimal when incremental increases in the tank size resulted in a change in volumetric reliability of 1% or less. Therefore, the cistern was not meant to store all rainwater from wet season for a later use during dry season and instead was calculated for a volumetric reliability or water saving efficiency of the tank. Utilizing volumetric reliability as the metric for cistern sizing accounts for both supply and demand patterns. This point is especially relevant in Calafell, where there are seasonal fluctuations in both rainfall and demand patterns from a large tourism economy.

$$Y_t = \min(D_t,\ V_{t-1} + I_t) \qquad \text{Equation (2)}$$

$$V_t = \min(V_{t-1} + I_t - Y_t,\ C - Y_t) \qquad \text{Equation (3)}$$

$$V_t = V_{t-1} + I_t + P_t - E_t - S_t - L_t - Y_t \qquad \text{Equation (4)}$$

where, V_t: volume of rainwater in the tank at the end of time step t; V_{t-1}: volume of rainwater in the tank at the end of previous time step t; I_t: inflow or roof runoff; C: capacity of the rainwater tank; P_t: incident precipitation received by the tank; E_t: evaporation; S_t: amount of spillage due to tank overflow; L_t: seepage or leakage.

In addition to these calculations, the cistern sizes and volumetric reliabilities obtained by operating the parameters defined in Equations (1) to (4) were compared with equivalent results exported from the Plugrisost® model (Gabarrell et al., 2014). This software estimates tank sizes at a dwelling, apartment, building, or neighborhood scale, and requires similar input parameters (i.e., daily precipitation, roof area, water demand and end use). This comparison aided in validating the results.

2.2.2 Pump Design and Pump Energy Calculation

The cistern was assumed to be located on the ground floor. Therefore, a pump was required to transport the rainwater from the cistern to the toilets and laundry in their respective floors. The energy delivered to the pump was estimated using **Equation 5** while the pump's lifetime energy requirements were calculated using **Equation 6**. Pressure head provided by the pump (h_p) was set equal to the pressure provided by infrastructure (assumed 35.2 m of water - 50 psi). Elevation head provided by pump (h_e) was set equal to the building height.

$$P = \Upsilon \times Q \times (h_e + h_p) \times \frac{[1+\alpha]}{\eta} \qquad \text{Equation (5)}$$

$$E = P \times 365\frac{days}{year} \times 24\frac{hours}{day} \times 0.001\frac{kW}{W} \times 75\ years \qquad \text{Equation (6)}$$

where, P: power delivered to pump (W); E: annual energy required by the pump (kWh); Q: flow rate (m^3/s); h = he + hp: sum of elevation head and pressure head provided by the pump (m); η: combined mechanical and electrical efficiency of the pump (assumed 65 %; Çengel and Cimbala (2005)); ϒ: specific weight of water (N/m^3); α: percentage of energy lost due to friction (assumed 0.3%; Cheng (2002)).

2.2.3 Dual Piping Calculation

When rainwater is insufficient to meet the demand, the already existing potable water supply pipeline can be used, ending up in a dual set of piping, although for this study, the potable line is out of the scope because it is considered as an already existing asset. As the height of the buildings was different, the length of the piping was also different for each building. This length was estimated assuming that one primary pipe runs all the way to the top floor and that each toilet was approximately one meter away from this pipe. In addition, the horizontal pipe length from the cistern to the main pipe was assumed equal to the width of the building (Devkota et al., 2013). The length of piping required for laundry was assumed to equal the height of one floor plus half of the building's side length. A pipe made of PVC was considered. In Ukiah, the laundry room was assumed to be located in the basement, whereas every apartment had a laundry room in Calafell.

2.2.4 Auxiliary RWH Components

Additional components were needed to supply the rainwater as well as to consume tap water. A foundation made of concrete supported the rainwater cistern. The concrete pad was designed with the side of the square pad extending 0.3 m beyond the diameter of the cistern on each side. The thickness of the concrete was assumed to be 0.1 m. A floating filter made of plastic and filter media was provided inside the rainwater cistern to separate out the floating matter in the tank, such as dead leaves, tree branches, and other rooftop debris that were not diverted at the gutters. We assumed that this filter was enough to treat rainwater used after a relatively long storage period. Other pipes and fittings (overflow pipe, bends, valves, tees, under drain) were made of PVC because of their low impacts as compared to regular plastic and cast iron pipes. The laundry water and detergent demands were calculated based on two wash loads per week per household and considering the detergent requirements applied by Vargas-Parra et al. (2014). A transportation distance of 100 km was considered (Sanjuan-Delmás et al., 2014) to transport the construction materials from the manufacturing plant to the installation point.

2.3 Hydrologic Modelling

The Personal Computer Storm Water Management Model (PCSWMM) v.5.1007 was used to estimate the surface runoff resulting from precipitation events in the neighborhoods before and after implementing RWHS. PCSWMM simulates hydrologic processes and hydraulic transport in urban environments. It also calculates the infiltration and surface storage of water at a sub-hourly time step and routes the rest as sheet flow using the non-linear reservoir algorithm. The sheet flow is then routed to storm drain inlets and to the discharge point using an implicit solution to the coupled one dimensional unsteady Saint-Venant equations (Chow et al., 1998).

The neighborhoods (i.e., catchment areas) were designated using Google Earth Pro and digitized in ArcMAP version 10.3. Three main layers were distinguished: i) buildings, serving as impervious areas for rainwater harvesting surfaces, ii) roads, performing as impermeable surface areas promoting surface runoff, and iii) green areas, which serve as infiltration/permeable surface areas. The ArcMAP digitized file was imported into PCSWMM. The three layers were assigned hydrologic properties (i.e., Manning's roughness coefficient, etc.) and the regional soil properties were identified to accurately assess the levels of runoff from the catchments. Additional soil properties (e.g., suction head, conductivity, soil type, and slope) were used in the Green-Ampt method to estimate infiltration (see **Table S2** in the Supporting Information).

To simulate the RWH scenario, storage nodes were used in the PCSWMM models to represent cisterns. Nodes were applied to each of the buildings within the catchment areas. The demand patterns (i.e., average daily demand that includes toilet flushing and laundry use) were modelled by applying a negative time series to each of the nodes. Because a change in water height in the storage node changes the volume of water coming out of the orifice located at the bottom of the storage node, it is not able to supply constant demand even if the volume of water is enough to meet the demand. Therefore, a constant negative time series was used to represent the indoor demand. In the instance when rainfall exceeded the capacity of the cistern, the additional flows were directed back to the catchment as runoff. The model computed the total amount of runoff from the catchment areas for the BAU and RWH scenarios at a single fictitious outfall assuming that the runoff from the entire neighborhood at multiple outfalls would be equal to the discharge at one outfall for the catchment areas. Reductions in the runoff generated by implementing the RWH were calculated by comparing the BAU and RWH scenarios at this fictitious outfall. The reduction in potable water supply required was calculated based on the available rainfall at the individual storage nodes, water demand, various urban forms and soil with various infiltration rates. Screenshots of the PCSWMMM models are presented in **Figure S1** in the Supporting Information.

2.4 Life cycle assessment (LCA)

The LCA method (ISO, 2006) was used to calculate the environmental impacts of implementing RWH and to compare with the BAU scenario. The functional unit was one m^3 of indoor water demand for toilet flushing and laundry services supplied with a combination of rainwater and potable water in a catchment area of 300,000 to 400,000 m^2. The average service life of the infrastructure was assumed to be 75 years, which is a typical lifetime in similar studies (Devkota et al., 2013). The environmental impacts were assessed from the raw material extraction to the operational phase. End-of-life management was excluded because of lack of data (**Figure 2**).

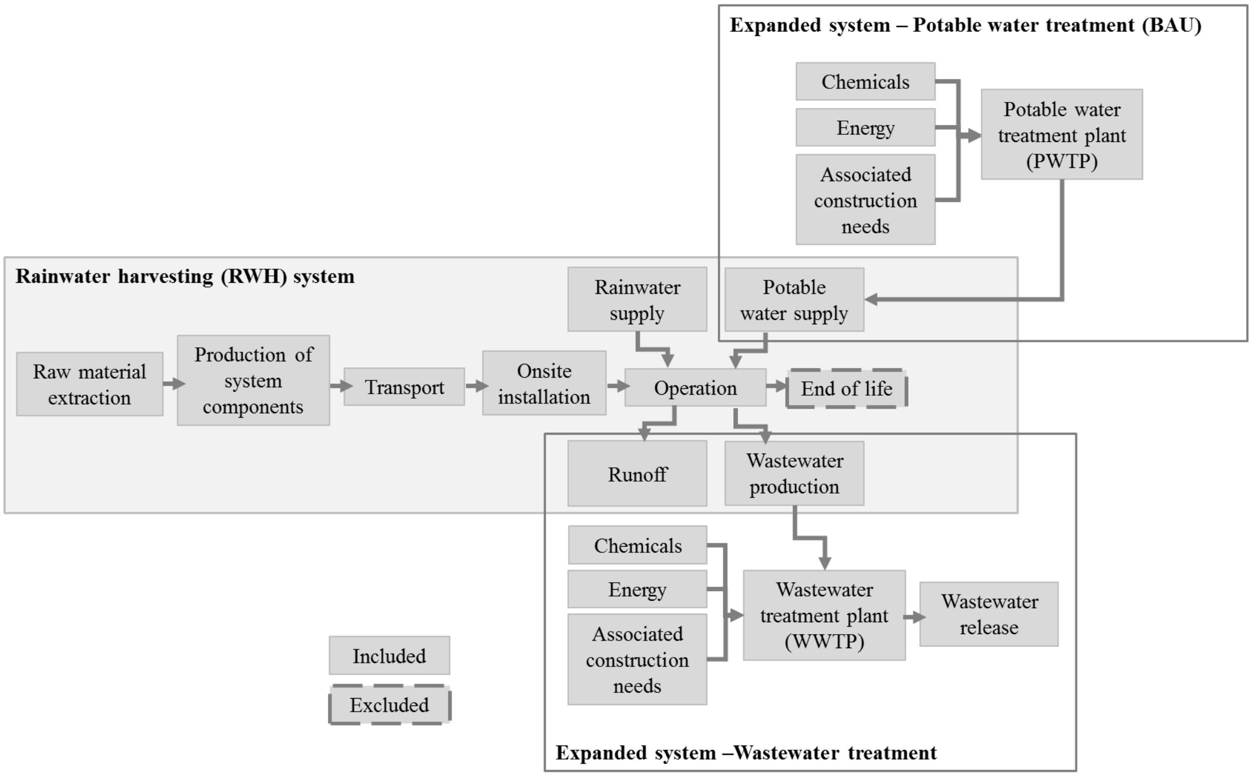

Figure 2. System boundaries for the LCA of combined supply of rainwater and potable water

Two scenarios were compared. In the BAU scenario, potable water was consumed and natural runoff was treated at a local WWTP. The RWH scenario integrated different consequences, i.e., a reduction in the demand for potable water coming from the treatment plant; a reduction in the runoff, resulting in less water treated at the WWTP; and consumption of rainwater, which is supplemented with an alternative production process (i.e., water from the treatment plant) when RWH cannot meet the water demand for toilet flushing and laundry.

The life cycle inventory (LCI) data for the various components and operations in **Figure 2** were compiled for the BAU and RWH scenarios for the selected cities (see **Table S3 and S4** in the Supporting Information). The ecoinvent v3 database (Weidema et al., 2013) was used to model the environmental flows from these processes. The environmental impact assessment was performed using the ReCiPe Hierarchist method (Goedkoop et al., 2009) and the GaBi 6 software (PE International, 2014). The LCA was conducted through the classification and characterization phase. All of the ReCiPe midpoint indicators were included along with the Primary Energy Demand (Hischier et al., 2010).

3. Results

3.1 RWH System Design and Tank Sizing

The cistern sizing results for the various building classifications are provided in **Tables 1 and 2** for Calafell and Ukiah, respectively. In the case of Calafell, the population per building was constant, as the number of apartments per floor was assumed to be constant as well. As a result, the roof area was the driving parameter for defining the RWH performance. Two different tank sizes were needed (4 m^3 and 57 m^3). The smallest roof area (building type MA) required only a 4 m^3 size cistern and could only meet 20 % of the water demand. In building type MB, a larger tank was required (57 m^3) but only 76 % of the demand could be supplied. Increasing the tank size did not increase the reliability of the tank. The tank size in buildings MC and MD was the same as in building MB but it could provide almost all of the water demand due to larger roof area (>500 m^2), meaning that larger roofs result in larger reliabilities considering a constant water demand.

In Ukiah, twelve different tank sizes were needed, varying from 38 m^3 to 454 m^3. All of the prototype designs for Ukiah resulted in reliabilities greater than 80%, with the lowest being R32, which had a volumetric reliability of 83 %. Twelve of the designs exceeded 90 % reliability, with seven of them reaching 99-100 %. These results were related to variations in both the occupancy (i.e., demand) and roof area (i.e., potential supply). For example, smaller roof areas within the residential prototypes were also associated with a smaller occupancy, so the supply and demand balanced. At a neighborhood scale, these high volumetric reliabilities also led to a larger rainfall supply in Ukiah (97% reliability with 153 of rainwater supplied out of a demand of 157 m^3 per day), whereas Calafell's rainfall supply was much lower (47 % reliability with 131 of rainwater supplied out of a demand of 281 m^3/day). However, Calafell's water demand (281 m^3 per day) almost doubled Ukiah's, which might be related to the number of buildings, occupants and seasonal effect.

Table 1. Building classifications, cistern sizes, and rainwater supply efficiencies for Calafell, Spain

Building type		**Roof Area Class (m^2)**	**Design Roof Area (m^2)**	**Stories**	**Number of Buildings**	**Occupants**	**Water Demand (m^3/day)**	**Cistern Sizing**		**Rainwater supply (m^3/day)**
								Size (m^3)	**Efficiency (%)**	
Residential - Commercial Mix	MA	<200	100	5	275	16	0.57	4	20%	0.11
	MB	201-500	350	5	155	16	0.57	57	76%	0.43
	MC	501-1,000	750	5	49	16	0.57	57	99%	0.56
	MD	>1,000	1,250	5	12	16	0.57	57	99%	0.56
Total neighborhood data					**491**	**7,856**	**281**		**47%**	**131**

Table 2. Building classifications, cistern sizes, and rainwater supply efficiencies for Ukiah, California

Building type		Roof Area Class (m^2)	Design Roof Area (m^2)	Stories	Number of Buildings	Occupants	Water Demand (m^3/day)	Cistern Sizing		Rainwater supply (m^3/day)
								Size (m^3)	Efficiency (%)	
Residential	R1	<200	100	1	2	3	0.13	38	98%	0.12
	R21	201-500	350	1	280	10	0.35	76	99%	0.35
	R22		350	2	20	20	0.66	189*	87%	0.57
	R31	501-1000	750	1	14	22	0.69	151*	99%	0.68
	R32		750	2	4	44	1.4	265*	83%	1.2
	R4	>1000	1,250	1	1	36	1.1	227*	99%	1.1
Restaurant	F2	201-500	350	1	1	36	0.15	38	100%	0.15
	F3	501-1000	750	1	4	76	0.28	57	100%	0.28
Commercial	C1	<200	100	1	1	6	0.17	76	89%	0.15
	C2	201-500	350	1	12	19	0.50	114*	96%	0.48
	C3	501-1000	750	1	7	41	1.0	227*	96%	0.98
	C4	>1000	1,250	1	7	68	1.7	379*	97%	1.6
Education	E4	>1000	1,250	1	1	100	1.9	454*	96%	1.8
Hospital	HC3	501-1000	750	1	1	23	0.38	76	100%	0.38
Hotel	H4	>1000	1,250	1	1	42	0.91	189*	99%	0.90
Total neighborhood data					**356**	**5,228**	**157**		**97%**	**153**

*This size was divided into different tanks with a capacity of 100 m^3

These results are consistent with the estimations obtained with the Plugrisost® model (see **Tables S5 and S6** in the Supporting Information), meaning that the equations are replicable and present similar assumptions. However, some differences were identified in Ukiah, where two-story residential buildings presented lower efficiencies (65%). In this case, the model encourages the implementation of smaller tanks with lower efficiencies to reduce the payback time (Gabarrell et al., 2014). In general, these models produced larger tanks than previous literature (Angrill et al., 2016) because of the larger water demand and design criteria.

3.2 Runoff Reduction

Using the lifetime of the system (75 years), the life cycle runoff from the neighborhoods was 1.1E+07 m^3 and 1.43E+07 m^3 (**Figure 3**) for Calafell and Ukiah, respectively. One of the factors that might affect this 29 % difference is the type of soil. Calafell's soil profile is primarily sand, with higher infiltration rates, while Ukiah has more clayey soils with lower infiltration rates (see **Table S2** in the Supporting Information).

After implementing RWH, the runoff depends on the cistern capacity (Petrucci et al., 2012). Higher cistern capacities can hold the rainwater for longer duration and reduce the runoff. However, when supply is greater than demand, runoff reduction might not be achieved, because once filled, the cistern cannot further store the rainfall. In Calafell, the supplied rainwater was not able to fulfill the demand in buildings with roofs smaller than 500 m^2 (**Section 3.1**). In Ukiah, in contrast, the residential buildings with roof area greater than 1,000 m^2, restaurants, hospitals and hotels had overflow from the rainwater cistern, indicating that these buildings were able to meet urban water demands (**Table 2**). One effective way to manage rainwater and further reduce the runoff may be distributing the overflow water to the nearby buildings that are in need. However, this approach would be site-specific and the effect of additional piping and space availability could be a concern. Alternatively, overflow may be directed to permeable areas, rather than paved surfaces, to increase infiltration.

In this sense, the use of RWH significantly reduced the runoff in these neighborhoods (5.83E+06 m^3 and 9.27E+06 m^3, respectively). Calafell, which has a higher building density (12 buildings/ha), presented a higher reduction (47%) in runoff than Ukiah (35%), with comparatively lower density (9 buildings/ha). Different parameters might affect this outcome.

First, the higher building density in Calafell (i.e., the urban form) resulted in a higher rainwater collection. This indicates higher rainwater supply, reduced potable water demand, and lower runoff. The commercial-residential mix buildings in Calafell were also responsible for the increase in water demand to flush the toilets and laundry. The higher the demand, the lower the runoff would be if the rainwater available for capture was enough to fulfill the demand. In addition, the building roof area was another defining parameter in Calafell's RWH performance (Section 3.1). As a result, the main factors affecting runoff were roof area and water demand, which is linked to the building density, occupancy and use patterns.

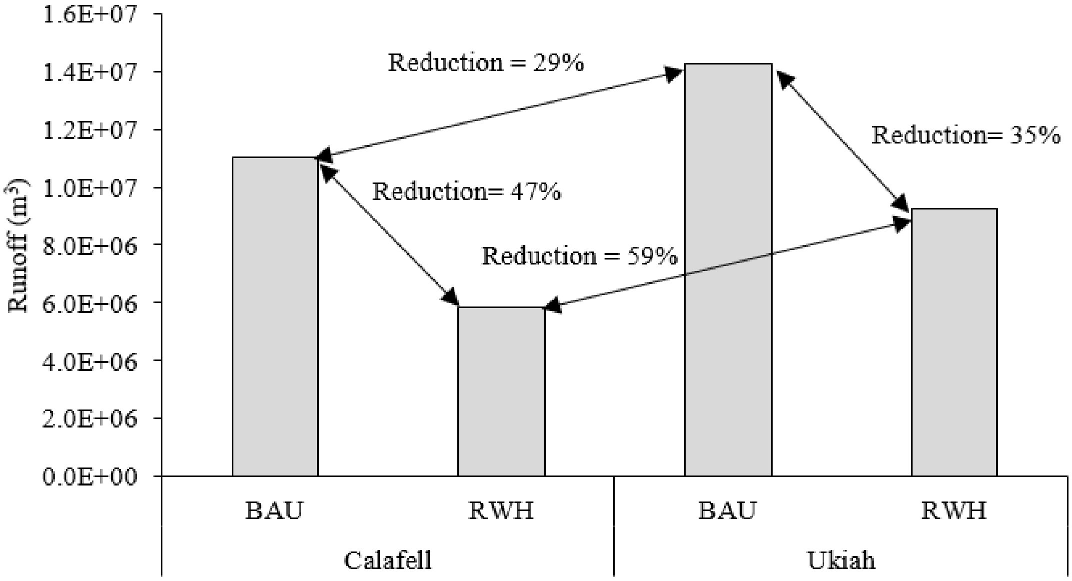

Figure 3. Life cycle runoff (75 years) from different neighborhoods before and after implementing RWH

Additionally, the water demand to flush the toilets in Calafell increased up to 58% during the tourist season (June-August), while the demand for Ukiah remained constant throughout the year. The increase in demand during the tourist season was also one of the reasons for greater rainwater requirements and runoff reduction in Calafell. For most of the buildings, rainwater was able to meet the water demand in Calafell (**Section 3.1**), which shows that RWH is effective in extreme periods.

3.3 Environmental performance of BAU and RWH

There were different environmental trends in each city when BAU and RWH were compared. The absolute results related to 1 m^3 of water demand are shown in **Table 3**. Overall, the implementation of RWH showed environmental improvements, with up to 14 of the 17 impacts assessed resulting in a positive environmental performance with respect to BAU in each case. In general, the implementation of RWH appeared to be more desirable in Calafell. For instance, the impacts on climate change were reduced by 21% through RWH (i.e., 0.5 kg CO_2 eq/m^3). This is due to a higher water demand, as Calafell's impacts were up to 60% lower than those of Ukiah in terms of m^3 of water demand.

The potential environmental improvements that resulted from RWH, especially in Calafell, were largely attributable to the reduced runoff treatment in a combined sewer network and the reduced potable water treatment (**Figure 4** – see complete set of indicators in **Figures S2 and S3** in the Supporting Information). For instance, in the BAU scenario, runoff treatment represents between 60 and 70% of the effects on climate change and primary energy demand, whereas in RWH a reduced contribution can be achieved (20%). This outcome can be related to the runoff reduction in both cities after implementing RWH, given that in Calafell there was 47% less runoff whilst in Ukiah it was 35% (Section 3.2). Additional features of interest were the contribution of the storage tank to the environmental impacts of RWH systems, which accounted for up to 50% of some impact indicators. The tank modeling principles were conservative; however, reducing their size to decrease their environmental contributions also generates more runoff that should be treated. These tradeoffs should be better assessed in future research. Additionally, the location of Calafell’s WWTP posed a concern in the assessment due to the energy needed for pumping wastewater. However, this parameter was irrelevant and represented less than 1% of the total impacts.

Furthermore, RWH resulted in up to 30% of CO_2 savings when considering a combined sewer, which performed better than separate sewers as predicted by Devkota et al. (2015) (**Figure 5**). This result was related to the runoff treatment in the case of combined sewers, whereas we considered that runoff can be re-used for non-potable purposes when discharged into a separate sewer.

Table 3. Comparison of the annual environmental impacts of Calafell and Ukiah for the BAU and RWH scenarios for combined sewer networks

Impact categories		**Units**	**Per m^3 of water demand**					
			Ukiah		**Calafell**		**Calafell/Ukiah**	
			BAU	**RWHS**	**BAU**	**RWHS**	**BAU**	**RWHS**
Climate change	CC	kg CO_2 eq	3.8E+00	4.3E+00	2.4E+00	1.9E+00	**65%**	**44%**
Fossil depletion	FD	kg oil eq	1.1E+00	1.2E+00	7.2E-01	5.4E-01	**67%**	**47%**
Freshwater ecotoxicity	FET	kg 1,4-DB eq	3.2E-02	2.8E-02	2.0E-02	1.4E-02	**61%**	**49%**
Freshwater eutrophication	FE	kg P eq	4.5E-03	4.1E-03	1.2E-03	1.8E-03	**26%**	**44%**
Human toxicity	HT	kg 1,4-DB eq	9.4E-01	8.2E-01	5.5E-01	3.9E-01	**59%**	**47%**
Ionising radiation	IR	kg U^{235} eq	4.1E-01	3.1E-01	2.9E-01	2.4E-01	**70%**	**76%**
Marine ecotoxicity	MET	kg 1,4-DB eq	2.3E-02	2.1E-02	1.3E-02	9.9E-03	**57%**	**48%**
Marine eutrophication	ME	kg N eq.	9.0E-02	7.6E-02	4.8E-02	3.4E-02	**54%**	**44%**
Metal depletion	MD	kg Fe eq	4.5E-01	8.0E-01	2.5E-01	3.0E-01	**55%**	**37%**
Natural land transformation	NLT	m^2	1.2E-04	1.2E-04	9.7E-05	1.0E-04	**80%**	**84%**
Ozone depletion	OD	kg CFC-11 eq	1.4E-07	1.6E-07	8.1E-08	7.7E-08	**56%**	**48%**
Particulate matter formation	PMF	kg PM10 eq	8.1E-03	7.5E-03	5.0E-03	3.4E-03	**62%**	**45%**
Photochemical oxidant formation	POF	kg NMVOC	1.5E-02	1.5E-02	9.6E-03	6.6E-03	**62%**	**44%**
Terrestrial acidification	TA	kg SO_2 eq	2.8E-02	2.6E-02	1.6E-02	1.2E-02	**57%**	**44%**
Terrestrial ecotoxicity	TET	kg 1,4-DB eq	8.5E-04	7.8E-04	5.0E-04	3.6E-04	**58%**	**47%**
Water depletion	WD	m^3	7.1E+00	5.8E+00	4.5E+00	3.5E+00	**64%**	**61%**
Primary energy demand	PED	kWh	2.1E+01	2.2E+01	1.3E+01	1.1E+01	**62%**	**49%**

🟩	Best option in each city

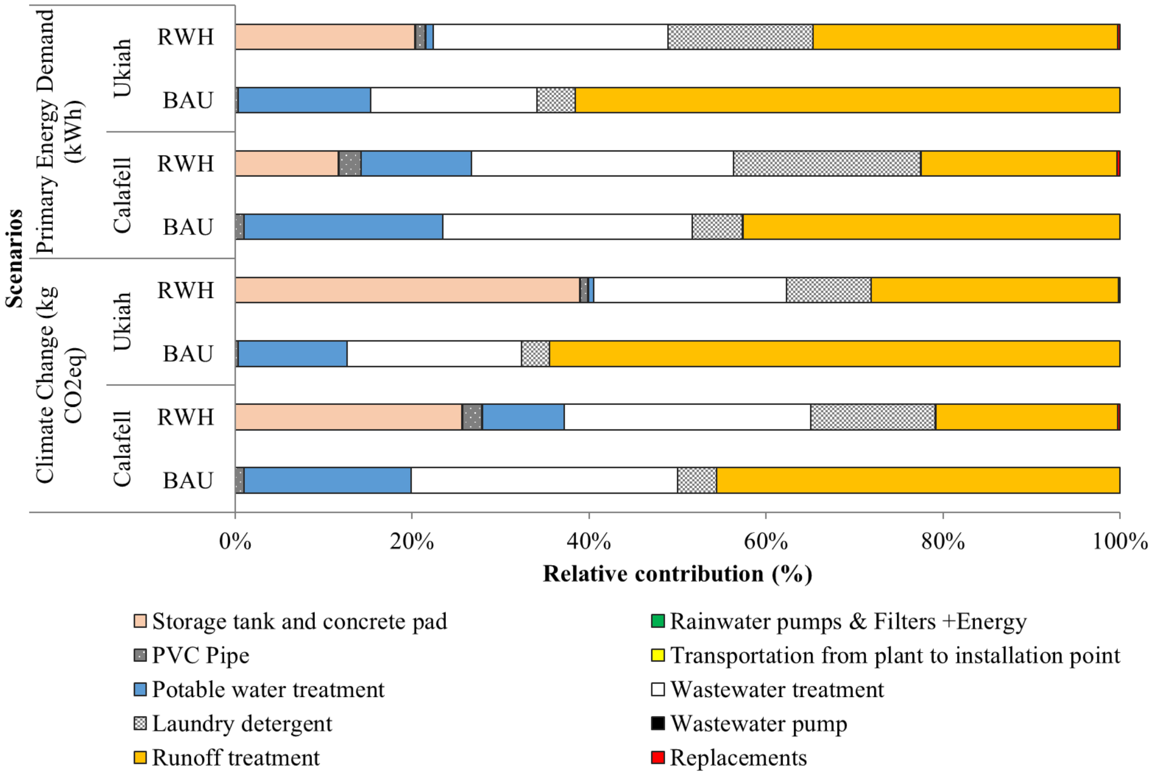

Figure 4. Relative contribution of the system components to climate change and primary energy demand for each scenario with combined sewer networks

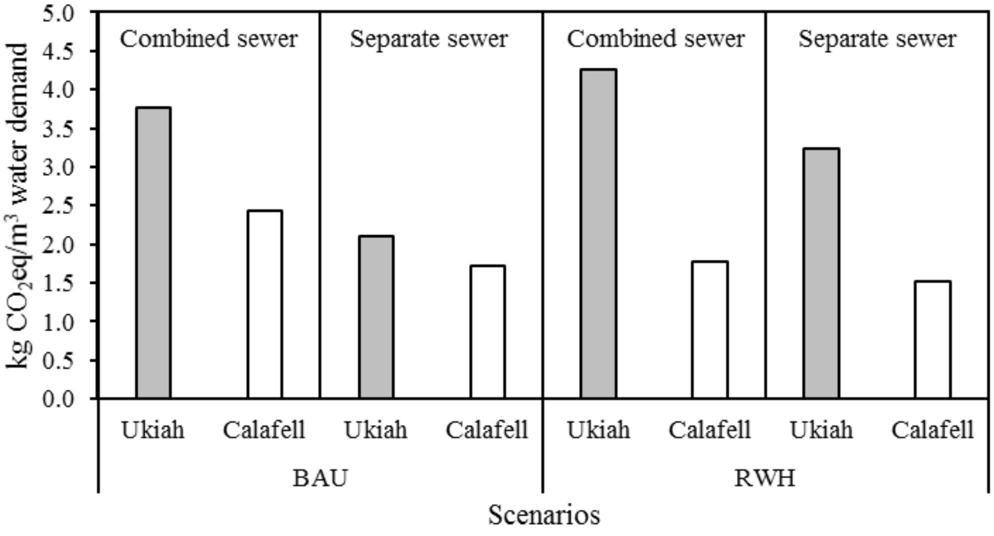

Figure 5. Comparison of the CO_2eq. emissions of the BAU and RWH scenarios in Calafell and Ukiah considering combined and separate sewer networks

4. Discussion

In this paper, we attempted to answer our two main questions related to RWH. By integrating runoff into the LCA of RWH, we tested that the implementation of these systems reduces the runoff volume and, consequently, the environmental impacts associated with its treatment. In this sense, the environmental benefits of RWH at the urban scale were assessed and they provided with new data that might help decision makers in dealing with flooding and water scarcity at the same time. We showed that RWH has a dual functionality. Harvesting rainwater reduces the runoff volume while providing a service to the residents (e.g., water for laundry and toilet flushing) and improving the environmental footprint of water procurement. RWH might also play a direct role in preventing combined sewer overflows (CSO), which are discharges of untreated wastewater that result from excess runoff in combined sewers. In this sense, RWH might avoid impacts on water bodies, such as eutrophication. These systems might also reduce the economic costs and environmental impacts of adapting urban sanitation to increased water flows and replacing damaged properties after flooding (Petit-Boix et al., 2017). However, we could not model these effects because we assessed long-term average rainfall, whereas CSOs and flooding are episode-specific.

To answer our second question related to urban form, water demand and infrastructure, we attempted to compare two distinctive cities. We observed varying environmental behaviors of RWH in Calafell and Ukiah. Urban form was closely related to water demand, and our results were in line with those reported by Morales-Pinzón et al. (2012) and Vargas-Parra et al. (2013), which highlighted that RWH systems located in high-density buildings result in a better environmental profile than in low density scenarios. Here, the effects of urban form and water use play a key role. In Calafell there is a higher building occupancy, which is vertically distributed in different stories. Together with a population increase from June to August, which doubles the permanent population in the area (IDESCAT, 2013), this leads to an indoor water demand of 0.25 m^3/day per m^2 of neighborhood. This value is lower in Ukiah, being around 0.14 m^3/m^2day.

Other social consumption patterns could play a role in this outcome, such as appliance efficiency. For instance, washing machines have a greater load capacity in the US, leading to greater water demand per laundry service. However, this social aspect does not significantly affect the results because the tourism and building density are the main factors that increase water demand. Deoreo and Mayer (2012) reported a decrease in the water consumption at the households with respect to the past decade. This means that RWH might have a greater reliability in the future, as less water will be needed. Smaller tanks might provide enough water for non-potable end uses and the environmental impacts might experience more significant reductions. Additionally, when the appliance efficiency cannot be further optimized, behavioral changes might be key in reducing the water demand. Besides laundry and toilet flushing, rainwater could be used to mop the floor or water urban gardens. However, when addressing outdoor water demand, we might need to model additional parameters related to runoff and RWH design.

Considering the urban form, another intrinsic issue to assess is the tank location. In Calafell, adequate space for the estimated cistern size may not be available given the structure of the multi-story buildings and high building density, with commercial space on the ground floor and residential areas in the remaining stories. Possible options include the use of designated parking spaces located underground, which leads to competitive space requirements for parking versus water supply systems. For example, a typical parking space is 5m deep x 2m wide x 3m high, or an available space of 30 m^3. Comparing the value of such space is outside of the scope of this work, but this aspect should be included in the design of smart cities that integrate sustainable mobility and water self-sufficiency. The impact linked to the construction of the underground cistern should be assessed.

All in all, with this analysis we restated the complexity of modeling large-scale urban areas. As discussed, the variables involved in a neighborhood-based analysis involve not only technical, but also social and urban planning aspects that are usually case specific. However, we do believe that our methodological approach (i.e., hydrologic and life-cycle modeling) can be applied to any region, city or district, and other types of stormwater management systems can also be assessed (e.g., green roofs or bio-retention). We encourage the application of this method to additional areas with different climatic, urban and social features to pinpoint the potential drivers and barriers towards the use of RWH. This might also help cities decide whether RWH is an environmentally optimal solution for approaching urban circular economy that turns them into more sustainable communities.

5. Conclusion

Water supply and demand has been used in the past to evaluate the environmental performance of RWH systems. Moving a step forward, these are the main contributions of our research:

- This is the first study to assess and compare the effects of urban form and water demand on the environmental and hydrologic performance of RWH systems.
- In our case studies, soil type played an important role in reducing the runoff, but the roof area and water demand were major contributors due to their effect on RWH performance.

- Runoff treatment contributed to >70% of the total impacts of RWH systems; the higher the runoff reduction, the higher the environmental savings. Any increase or decrease runoff treatment would be responsible for the environmental feasibility of RWH.
- In Calafell, the environmental impacts of RWH were generally lower than the BAU scenario due to higher water demand, roof area and higher runoff reduction.
- This study suggests that implementing RWH could be a viable alternative to meet water needs in areas with a high building concentration and water demand.

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