Environmental assessment of rainwater harvesting strategies in urban areas from a life cycle perspective

By

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A thesis submitted in fulfilment of the requirements for the PhD degree in Environmental Sciences and Technology

September 2013

The present doctoral thesis has been developed with the financial support of the Spanish Ministerio de Ciencia e Innovación (MICINN) within the project 'Análisis ambiental del aprovechamiento de las aguas pluviales urbanas' (Ref. CTM2010-17365), and thanks to the Catalan Agència de Gestió d'Ajuts a la Recerca for the pre-doctoral fellowship awarded by Sara Angrill.

"When the well is dry,
we learn the worth of water"

Benjamin Franklin

The present thesis entitled *Environmental assessment of rainwater harvesting strategies in urban areas from a life cycle perspective* has been carried out at the Institute of Environmental Science and Technology (ICTA) at Universitat Autònoma de Barcelona (UAB) under the supervision of Dr. Joan Rieradevall and Dr. Xavier Gabarrell, from the Insitute of Environmental Science and Technology (ICTA) and the Department of Chemical Engineering at the UAB, and Dr. Alejandro Josa, from the Department of Geotechnical Engineering and Geosciences and the Institute of Sustainability at the Universitat Politècnica de Catalunya (UPC).

Bellaterra (Cerdanyola del Vallès), September 2013

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List of acronyms, abbreviations and notation

1.4 DB eq.	1.4 dichlorobenzene equivalent emissions
ADP	Abiotic depletion potential
AP	Acidification potential
C	Compact density model
CFC-11 eq.	Trichlorofluoromethane equivalent emissions
CML	Institute of Environmental Sciences (Leiden)
CO_2	Carbon dioxide
CO_2 eq.	Carbon dioxide equivalent emissions
D	Diffuse density model
EP	Eutrophication potential
FU	Functional unit
GIS	Geographic Information System
GWP	Global warming potential
HNO_3	Nitric acid
HTP	Human toxicity potential
ICTA	Institute of Environmental Science and Technology (UAB)
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
ODP	Ozone layer depletion potential
PO_4^{3-} eq.	Phosphate equivalent emissions
POCP	Photochemical oxidation potential
R	Roof tank strategy
RWH	Rainwater harvesting
Sb eq.	Antimony equivalent emissions
SO_2 eq.	Sulphur dioxide equivalent emissions
Sostenipra	Sustainability and Environmental Prevention
U	Underground tank strategy
UAB	Universitat Autònoma de Barcelona

Acknowledgments

Durant els darrers quatre anys fent recerca he tingut l'oportunitat d'investigar en l'àmbit de les aigües pluvials, recurs que he après a estimar al llarg d'aquest temps. Aquesta recerca també m'ha permès aprendre i desenvolupar metodologies quantitatives per l'estimació d'impactes ambientals. A més, he pogut treballar amb persones de moltes disciplines diferents que han fet la meva experiència encara més enriquidora. Per tant, voldria començar agraint els meus directors de tesi, Dr. Xavier Gabarrell, Dr. Joan Rieradevall i Dr. Alejandro Josa, per haver-me donat l'oportunitat de desenvolupar-la i pel suport rebut al llarg d'aquests anys i els coneixements adquirits.

Voldria agrair també a totes aquelles persones que m'han mostrat el seu suport al llarg d'aquest camí: A tots els companys del grup de recerca Sostenipra (aquells que encara estan i els que han anat marxant), a la meva gent de Tarragona que sempre han estat quan els he necessitat i als amics ambientòlegs amb els que el temps continua passant volant quan som plegats.

En especial vull dedicar aquesta tesi al meu avi, perquè sempre ha estat un model com a persona i a nivell personal la meva estrella guia.

També agrair a la meva família el suport i l'amor incondicional que m'han proporcionat. A la meva mare, perquè només n'hi ha una i perquè m'ajudes a ser forta cada dia. A la meva germana Maria per la felicitat que irradia i que sempre m'ha motivat. A la meva avia perquè m'ha proporcionat tot l'amor que he necessitat.

Per últim agrair a Manu haver-me acompanyat en aquest camí. Gràcies per ser com ets, per alegrar-me els dies i cuidar de mi, i per ser també la veu de la meva consciència quan ho he necessitat.

Summary

In the context of transition towards urban sustainability one of the major challenges facing modern societies is the provision of water, a resource that is increasingly recognized as a valuable resource while the quantity and quality available is decreasing. The growing evidence of water scarcity worldwide enhance the need to work on synergies among the different existing water sources and urban scales in order to develop more integrated, efficient and equitable water networks.

In this sense, this dissertation focuses on the use of rainwater as a local endogenous resources to achieve a more circular metabolism able to close water flows and capable of accomplish urban water self-sufficiency. This can help to reduce the collection and treatment infrastructure needs for drinking water as well as the management and treatment of wastewater while having a greater control of floods in urban environments. However, there is still a lack of knowledge on which is the most adequate rainwater harvesting (RWH) strategy for each urban scale on one hand, while on the other the quantity and quality of runoff has yet not been addressed under the local climatic and environmental conditions of Mediterranean areas (more specifically in Spain).

The aim of this research was to answer this question by investigating, evaluating and validating the potential and advantages of using rainwater to achieve, with the lower impact possible, the improvement of the water cycle in urban areas located within the Mediterranean climate.

In order to evaluate the eco-efficiency of several RWH strategies for newly built neighbourhoods and to determine the environmentally optimum strategy, the necessary rainwater collection, storage and distribution infrastructures were designed and then environmentally assessed through a Life Cycle Assessment (LCA) approach. In addition, several variables that directly affect RWH infrastructures were selected and conveniently assessed; these include the urban density model, the building scale, the tank location within the building, the building height and at last the water supplying strategy. The results evaluate the environmental performance of each scenario and indicate the most environmentally friendly option for rainwater harvesting at different scales.

The assessment of the potential RWH quantity and quality in an urban environment was developed by means of an experimental case study. To develop it, seven different catchment surfaces were selected within the UAB campus for which an experimental RWH installation was adapted and run over a period of 22 months of experimental campaign. The selection of catchment areas was done according to two criteria: surface material and type of use of the surface. The quantity assessment consisted of the calculation of the runoff –rainfall regression models, the estimation of the global RC and of the initial abstraction, while quality assessments comprised a significant variety of physicochemical and microbiological parameters. From a statistical approach all results were tested for significance and correlated.

The resulting environmental criteria are thought so to define the optimal strategies and uses of rainwater that best leads towards the sustainability of urban areas as well as the most eco-efficient redesign of urban water grids in the context of climate change. These results may provide useful guidance in urban planning and design by integrating environmental criteria into the decision-making processes.

Preface

The present doctoral thesis was developed within the research group on Sustainability and Environmental Prevention (Sostenipra) at the Institute of Environmental Science and Technology (ICTA) of the Universitat Autònoma de Barcelona (UAB) from October 2009 to September 2013 (including the period of the Master in Environmental Studies).

The dissertation is mainly based on the following book chapters and papers either published or under review in peer-reviewed indexed journals:

- Angrill, S., Farreny, R., Gasol, C.M., Gabarrell, X., Viñolas, B., Josa, A., & Rieradevall, J. (2012) Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate. The International Journal of Life Cycle Assessment, 17(1), 25-42.
- Angrill, S., Segura, L., Rieradevall, J., Gabarrell, X., & Josa, A. (2013) Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate. Water Resources Management (Submitted September 2013).
- Angrill, S., Morales-Pinzón, T., Josa, A., Rieradevall, J., & Gabarrell, X. (2013) Rainwater harvesting from urban spaces and traffic roads: quantity and quality assessments in Spain. Water Research (Submitted September 2013).

In addition, during the dissertation period the opportunity has been given to work in other papers, which were published in peer-reviewed journals and are also related with the goals of the dissertation:

- Morales, T; Angrill, S; Rieradevall, R; Gabarrell, X; M.Gasol, C and Josa, A. (2011) LCM of rainwater harvesting systems in emerging neighbourhoods in Colombia. Towards life cycle sustainability management 2011, Part 4, 277-288.
- Mendoza JMa, Sanyé Ea, Angrill Sa, Gonzalez-Garcia Sb, Garcia Rc, Rieradevall Ja,d, Feijoo Gb, Moreira MTb. Smart urban elements for promoting sustainable mobility in cities. (Submitted on October 2013).

The following oral communications and posters presented to congresses and conferences also form part of this doctoral thesis:

- Sustainable Building Conference SB10Mad (2010) 'Sustainable construction. Revitalization and rehabilitation of neighbourhoods'. Palacio de congresos, Madrid (Spain). Water self-sufficiency in Mediterranean neighborhoods. Case study of the municipality of Sitges (Spain). [Angrill S, Farreny R, Gabarrell X i Rieradevall J]. Participation: Poster.
- Youth Water Professionals National Conference (YWP 2010). Agbar Foundation, Barcelona. Water self-sufficiency in Mediterranean neighborhoods. [Angrill S, Farreny R, Gabarrell X and Rieradevall J]. Participation: Poster.
- International Conference on EcoBalance 2010. Miraikna, Tokyo, Japan. 'Eco-efficiency of Rainwater Harvesting in the Design of Mediterranean Neighborhoods.' [Angrill S, Farreny R, M.Gasol C, Viñolas B, Morales T, Gabarrell X, Josa A and Rieradevall J]. Participation: Poster.

- International Conference on Life Cycle Assessment (CILCA 2011). Coatzacoalcos, Mexico. 'Environmental impact of rainwater harvesting integration in new construction compared with renovated buildings. Application to urban planning for emerging neighbourhoods in Bogotá.' [Angrill S, Morales T, Cerón I, Gabarrell X, Josa A and Rieradevall J]. Participation: Oral communication.
- Life Cycle Management (LCM 2011).Dahlem cube, Berlin, Germany. LCM of rainwater harvesting systems in emerging neighborhoods in Colombia'. [Morales-Pinzón T, Angrill S, Rieradevall J, Gabarrell X, M.Gasol C and Josa A]. Participation: Oral communication.
- Ecotech & Tools 2011 (Ecotech-Sudoe). Environmental & Integrated Assessment of Complex Systems. Montpellier SupAgro, Montpellier, France. 'Environmental assessment of rainwater harvesting strategies in Mediterranean neighbourhoods of different densities'. [Angrill S, Viñolas B, Rieradevall J, Gabarrell X and Josa A]. Participation: Poster.

The doctoral thesis is based on the methodology and results developed under the framework of the following project:

- *Análisis ambiental del aprovechamiento de las aguas pluviales urbanas* (Ref. CTM2010-17365). 2011-2013. A Project funded by the Ministerio de Ciencia e Innovación (MICINN) of Spain. The Project was developed in the Universitat Autònoma de Barcelona (ICTA - Institute of Environmental Science and Technology) under the coordination of Dr. Xavier Gabarrell.

Structure of the dissertation

The structure of the dissertation is organised into four main parts and seven chapters. For clarity, the structure of the doctoral thesis is further outlined in Figure 0. This flow chart can be used throughout the reading of this manuscript as a *dissertation map.*

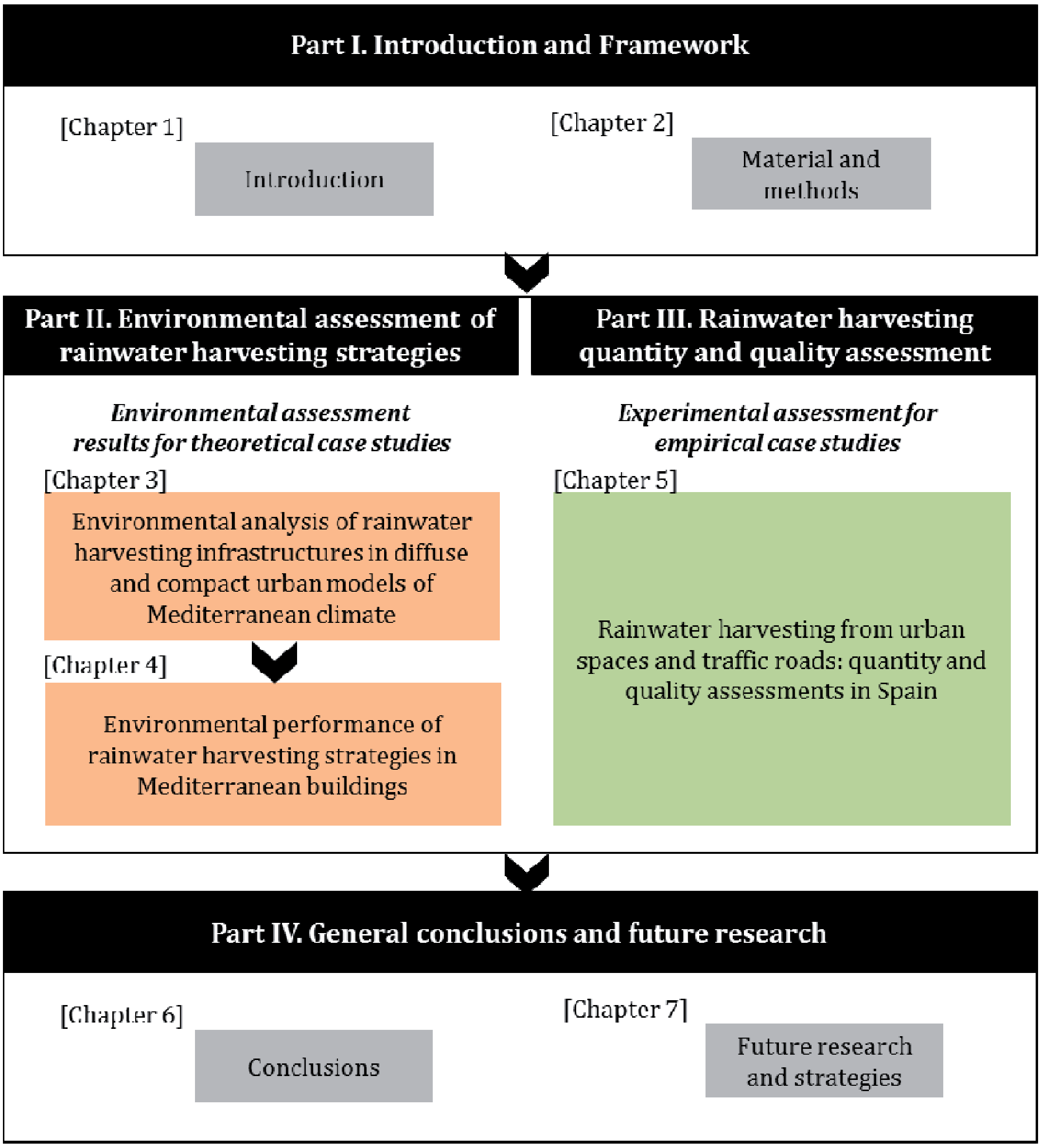


Figure 0. Map structure of the dissertation.

Part I. Introduction and framework

Part I is composed of two chapters. **Chapter 1** *[Introduction]* presents an overview of the actual water cycle in urban areas and the potential role that rainwater harvesting strategies play in these environments. Furthermore, it presents the framework of study, the life cycle approach, in relation to urban settlements. Finally, the motivation and objectives of the dissertation are also provided. **Chapter 2** *[Material and methods]* presents an overview of the dissertation's methodological aspects involved in its development. First, a description of the systems under examination is given and divided into theoretical and experimental case studies. Second, the environmental methodologies and tools used during the dissertation are presented in detail. A description of the field and laboratory works done and the data collection process are also provided in the last part.

Part II. Environmental assessment of rainwater harvesting strategies

Part II is including two chapters dealing with a main issue: the environmental assessment of rainwater harvesting strategies in Mediterranean areas.

Environmental assessment results for theoretical case studies

Chapter 3 [*Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate*] analysis the environmental performance of RWH infrastructures applied to diffuse and compact urban density models under Mediterranean climatic conditions. In this study different scales of analysis that range from a single house to a residential neighbourhood have been considered.

Environmental assessment results for experimental case studies

In **Chapter 4** [*Environmental performance of rainwater harvesting strategies in Mediterranean buildings*] assesses the environmental relevance of three different variables that directly affect RWH infrastructures: the building height, the tank location and the distribution strategy chosen.

Part III. Rainwater harvesting quantity and quality assessment

Chapter 5 [*Rainwater harvesting from urban spaces and traffic roads: quantity and quality assessment in Spain*] analysis the quantity and quality of runoff from several urban public surfaces located in a Mediterranean semi-wet urban area by means of an experimental design and a further statistical approach.

Part IV. General conclusions and future research

Part IV includes **Chapter 6** [*Conclusions*] and **Chapter 7** [*Future research and strategies*] and provides the general conclusions of the dissertation and proposes future fields of research associated with the subject.

[*Note:* Each chapter from 3 to 5 presents an article or book chapter –either published or under review. For this reason, an abstract and a list of keywords are presented at the beginning of the chapter, followed by the main body of the article].

Part I

Introduction and framework

Chapter 1. Introduction

Chapter 1 presents an overview of the actual water cycle in urban areas and the potential role that rainwater harvesting strategies play in these environments. Furthermore, it presents the framework of study, the life cycle approach, in relation to urban settlements. Finally, the motivation and objectives of the dissertation are also provided.

This chapter is structured as follows:

- Urban areas and water flows.
- Rainwater harvesting and its potential role in urban areas.
- Motivation of the dissertation.
- Objectives of the dissertation.

1.1. Urban areas and water flows

1.1.1. Global environmental relevance of urban areas

Cities are constituted by a mixture of layers, networks and flows that sustain their social and economic activities. Although representing just 2.7% of the world's land area cities concentrate more than 50% of the global population – and more than 70% in Europe, America and Oceania- they are responsible for 75% of the total energy consumed worldwide and 80% of greenhouse gas (GHG) emissions (Ash et al, 2008).

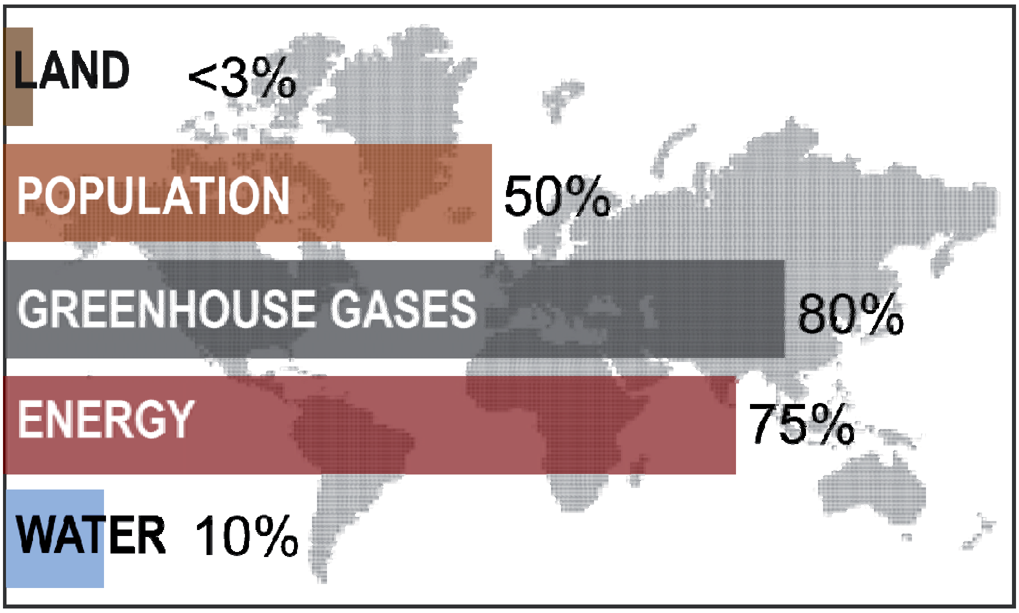


Figure 1.1. Main characteristics of cities at global scale

Source: Sara Angrill.

[1] UN (2007) Urban population, Development and the Environment. Department of Economic and Social Affairs.

[2] UN (2008) World Urbanization Prospects: The 2007 Revision Population Database.

[3] Ash C, Jasny BR, Roberts L, Stone R, Sugden A (2008) Reimagining cities - Introduction. Science 319(5864): 739-739.

[4] Aquastat. Municipal water withdrawals. 2010.

From the 18th century on, a rapid and often uncontrolled process of urbanization has been happening worldwide (Bugliarello, 2006). Nowadays we are facing the ecological consequences of this process that oversteps well beyond the boundaries of the city as imports and exports of material and energy flows (Wackernagel & Rees, 1996). Therefore, urban areas are in constant interaction with their environment at a local, regional and even international level (Fragkou, 2009).

In this sense, urban areas are also responsible for a large consumption of water to fulfill their needs, which increase consistently with population growth. In Europe alone the water required in urban areas accounts for 18% of the total abstraction and 44% of its consumptive uses (EEA, 2003). These amounts of water consumed are imported from outside the city boundaries and should present high quality standards, according to the drinking water guidelines (EC, 1998). Thus, intensive treatments are applied to water to improve its quality before its end use.

The environmental impact of a city is not just determined by its carbon footprint on its immediate environment but it has effects at regional and even global scale. For this reason a priority for urban sustainability should be to rethink urban planning which is consistent with the urban metabolism of the city in a manner that flows towards a self-sufficiency concept for a city. In this sense, many actions can be undertaken starting from a reduction of the amount of resources used and the waste produced (Girardet, 1990). In addition, the environmental problems should be addressed during the design and planning process of the urban area in order to minimize their impacts along its life cycle (Garner, 1995).

Although the main objective is to achieve a sustainable urban area, some authors suggest that the focus should be driven to a lower scale of analysis such as neighbourhoods. In this city layer more significant environmental, social and economic issues can be detected easily, and therefore more efficient and sustainable local solutions can be applied. Moreover, it is on a smaller scale and where the implementation of local governments and leader decisions are achieved.

Urban areas sustainability depends on the flows of energy, water and materials. How these resources are delivered as inputs and then changed into outputs has been intrinsically defined during the design of the urban development. Therefore, early design, headed for sustainability, of urban settlements would reduce the environmental impacts during its life cycle (Garner, 1995).

1.1.2. Water management in urban settlements

Water is a valuable need for life. The proof is that humankind has been historically involved in searching for ways to manipulate and use fresh water (Gleick, 2003). Therefore, water is part of a web of relationships that exist between natural systems and humans, and thus is a limiting variable for sustainability (WWAP, 2012).

Within cities demand for water has increased in recent decades (UN, 2006; Sharma & Vairavamoorthy, 2009). Furthermore, the urban population is expected to continue to grow during this century (Bai, 2007). This increase along with the growth of world population and excessive urbanization threatens freshwater reserves that are increasingly scarce and are non-renewable resources. Factors such as population growth, industrialization, urbanization, agricultural intensification and changes in lifestyles are putting great pressure on freshwater systems, with daily water use and pollution are the main factors, influencing the scarcity of natural resources. Thus, many cities face nowadays a real supply problem since their demand has long exceed local capacities and freshwater from distant sources needs to be imported to supply the urban needs (UN, 2003).

Centralized water supply systems are the most common strategies to provide water to the population. It includes water supply, sanitation and drainage as the main services. However, nowadays the conventional approach is being questioned since it does not comply with the ecologically sustainable development goals for urban areas (Mitchell, 2006).

The urban infrastructure has an important effect on the water cycle since it increases the imperviousness of an area by the installation of roads, parking lots and buildings. In addition, other characteristics of urban areas strongly determine water flows (i.e. urban density and the compactness). Up until now, rainwater has not been seen as an alternative option but as a nuisance. Thus, during rainfall events runoff is drained out of the city (Roesner, 1999).

In the context of transition to sustainability, one of the major challenges faced in today's societies is water. A resource that is increasingly recognized as valuable, since the quantity and quality available are decreasing. Nowadays a very static and conservatory vision of the urban water cycle prevails, while other more sustainable approaches such as rainwater harvesting or grey water reuse are possible, which may help reduce water demand.

On a wider scale, a progressive awareness for the need to rethink urban water management is emerging towards a more sustainable system. For instance, Spain is carring out strategies related to resource efficiency and urban metabolism. These guidelines are intended to deepen urban development linked to the water cycle at local level (rain water harvesting, recyled water, etc..), integrating available resources at the basin scale.

1.2. Rainwater harvesting and its potential role in urban areas

1.2.1. Rainwater harvesting as an alternative resource

Southern Europe and the Mediterranean area in particular is one of the most urbanized regions of the world on alert status for high drought stress and future climate changes. This can impact higher water scarcities, according to the latest report of the IPCC (Trenberth, 2007).

In the current context of transition to sustainability, the development and management of rainwater has many benefits. These include the following:

- Water Fountain free access attributable to non-drinking uses
- Reduced collection and treatment infrastructure for drinking water.
- Improved separative management.
- Greater control of water cycle in urbanes areas.
- Reduction of water stress and sources of pollution.
- General flood and avenue flood prevention

Sources: Trenberth et al, 2007; Zhu et al, 2004; Villarreal & Dixon, 2005.

The most widespread uses given to harvested rainwater are non-drinkable applications (i.e. toilet flushing, garden irrigation and domestic laundry use) Roebuck et al. (2010). In addition, several recent studies have quantified the average amount of water demand that RWH can meet, which is strongly dependent on the local climate and consumption patterns. These studies conclude that 45% of domestic demand can be supplied by those systems (Ratnayaka et al, 2009; Domene et al, 2004). Furthermore, it is quite simple and inexpensive to improve collected runoff quality. The most commonly used equipment is filtration and chlorination, though with more sophisticated technologies better results can be achieved (for example with solar UVA).

It should be taken into account that rainwater must be seen in water-stressed climates as a complement to water mains due to the unpredictability of rainfall intensity and frequency.

1.2.2. Rainwater harvesting potential in water-stressed urban areas

The growing evidence of water scarcity worldwide and the need for integration and cooperation to ensure sustainable, efficient and equitable use of water resources, both locally and regionally, have been highlighted by the United Nations (2007). Particularly in Mediterranean environments prolonged drought events and changes in water cycles generated by climate change, show the need for increased capacity to investigate alternative water sources in vulnerable urban areas.

To do this, urban areas present a great potential associated with collecting rain water from water proof surfaces. At present, the most widely used practice, because of the high quality associated with rainwater collection, is on building rooftops.

However, in urban areas there are numerous surfaces already designed to collect water (currently out of town) and should be reconsidered as potential rainwater conveyance infrastructures. Examples include roads, streets, squares, parks and recreation parks. The quality of the water collected has not been studied in detail so far and could be used in many applications such as watering gardens or street cleaning, which do not require high quality water.

At the same time, the increased pressure on water resources in urban areas linked to a growing demand and limited sources and in addition an increased awareness of the environmental potential of water management systems (Fletcher et al, 2008) have resulted in the use of local endogenous resources within the urban boundary (Mitchell et al, 2005). Based on these grounds, the options of RWH should be further explored more in depth in our local context.

Many strategies are emerging that integrate water supply, storm water and wastewater from a wider approach that takes into account all components of the total urban water cycle. Integrated urban water management (IUWM) takes a comprehensive approach to urban water services, viewing water supply, drainage and sanitation as components of an integrated physical system, and recognising that the physical system is part of an organisational framework within a broader natural landscape (Mitchell, 2006). The broad range of tools that are employed include water conservation and efficiency, sustainable urban drainage systems (SUDS), utilisation of nonconventional water sources, storm water and wastewater source control and pollution prevention, and non-structural tools such as education and regulations (Mitchell, 2006).

1.3. Motivation of the dissertation

The development and assessment of strategies toward an environmental transition of urban areas is a real necessity in the current context of climate change adaptation and urban expansion. Facing this situation, water management in urban settlements should be addressed in more detail and through an environmental deeper approach.

This dissertation is motivated by the following realities:

- Research on urban metabolism is still emerging, and fewer are those that deal with water resources from the perspective of sustainable development. At the same time population in urban areas grow and with that supplying problems increases too, with a particular impact in the context of climate change. Meanwhile, the application of environmental criteria in urban design has not yet considered the benefits of rainwater harvesting, a strategy that would facilitate the move towards water self-sufficiency of these areas in order to reduce external dependence and Prevent resource scarcity.
- The environmental and economic study of rainwater harvesting at different scales (from single family home neighborhood level) that includes the entire life cycle (stage both infrastructure and usage and deconstruction) has so far not been realized. This requires also the study of several variables that directly affect their implementation such as urban density, infrastructural characteristics of stormwater collection systems and supply strategies possible within each scale. These results will enhance to close the water cycle in urban areas and their sustainable development in relation to alternative systems as treated water reuse and desalination.
- Life Cycle Assessment (LCA) tools can be applied to the quantitative environmental analysis of new strategies that may arise for the use of local water resources. In addition, they can be combined with economic and social approaches to complete the sustainability analysis of these systems. However, the application of these calculation tools for urban water management is still very incipient. In addition, the scientific literature on rainwater harvesting has focused mainly on the collection techniques (Kim et al, 2005a) and runoff water quality (Evans et al, 2006; Chang et al, 2004; Kim et al, 2005b). The few cases reported focus their attention to very specifically stages of the water cycle, dropping the overall environmental assessment.
- There is a need to promote non-conventional water sources, particularly in the current context of water scarcity. Among these sources, little attention has been given to RWH in Spain, although it presents many benefits and it is considered an ancient technique that was present in the region in the past. Besides, inappropriate stormwater runoff management leads to many problems in urban areas, such as flooding and stream degradation (mostly due to combined sewer overflows), particularly in regions with heavy rainfalls concentrated in a short period of time, such as in Mediterranean climate regions.
- Water resources from storm water at local scale are not irrelevant and their optimal use could solve some of the problems associated with water management in urban areas. However, there is a lack of quality data associated with rainwater harvesting. Most of these are associated with runoff collection from roofs due to the higher quality expected of them. However, the current literature on other paved surfaces that conform as well the urban public space is insufficient for their physicochemical and microbiological characterization, and hence to determine their quality. This water, while showing lower quality than the collected from roofs may be useful for other types of uses that require non-

potable water as street cleaning or watering of gardens and parklands. Furthermore, this is a process that must be analyzed locally and depends largely on the characteristics of the environment and the climate of the place. So far few studies have been found that examine this resource at regional level in the Mediterranean area and those refer to other countries such as Greece, Italy and Cyprus. Therefore, it is necessary to determine the suitability of this resource to the potential uses that can supply through an eco-efficiency perspective in the design and redesign of future cities.

- On the other hand, the potential quantification of this resource is another issue that requires a local approach due to variability in the frequency and intensity of precipitation in each region. This study should include a wide variety of currently used pavements in urban public areas in order to have a significant impact and to be later on extrapolated to other areas. So far there is a lack of specific data on RC (runoff coefficients) for certain materials that are commonly used in urban areas. The information is further less abundant for Southern Europe (especifically Spain) and the existing literature provides a very wide range of values.
- In the scientific level, most efforts have been directed toward reclaimed water and desalination. These strategies reduce water dependence but increase energy demand contributing to global warming. However, research on the potential of rainwater harvesting in urban systems have not been addressed in depth by the scientific community with the specificity required for its implementation.
- This dissertation is motivated by the need to provide researchers, urban planners and environmental managers with criteria that facilitate the technical and environmental analysis of RWH systems from a life-cycle approach of the water resource management in urban areas. This will lead to a better understanding of the local endogenous potential of these areas and therefore to a more environmentally friendly design or redesign of urban systems towards water self-sufficiency.

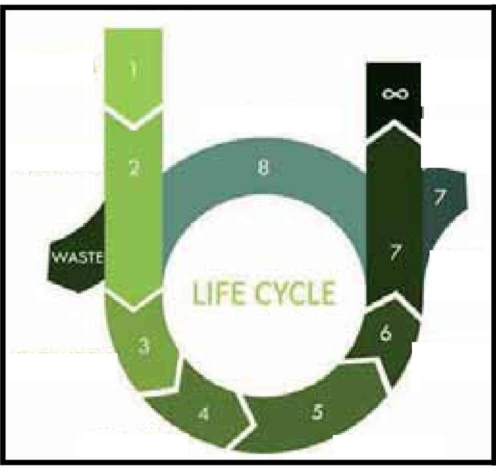
1.4. Objectives of the dissertation

The main objective of this dissertation is to investigate, evaluate and prove the potential and advantages of using rainwater to achieve, with the lower impact possible, the improvement of the water cycle in urban areas located within the Mediterranean climate. The resulting criteria are thought to be applicable for urban planning purposes.

In order to achieve this main goal, several specific objectives are outlined:

1. Estimate the potential environmental impact associated with different rainwater harvesting strategies within Mediterranean climate regions. Spanning from the simplest scale, the single dwelling, to residential neighborhoods. Determine which is the environmentally optimal strategy in different urban scenarios. In parallel to this, there is the intention to establish what are the ecodesign criteria that environmentally favors the installation of these infrastructures under each proposed scale of analysis.

2. Determine the urban density, the type of cover, surface and optimal building height for the implementation of this infrastructure in an urban Mediterranean environment; based on the combination of environmental results obtained and the payback period of the infrastructure.
3. Adapt and integrate environmental tools such as the LCA in the investigation of endogenous local water resources, which address the entire life cycle of infrastructure examined.
4. Quantifying the potential quantity and quality of rainwater resources (physical-chemical and microbiological) based on different urban subsystems, to orientate the design (or redesign) of Mediterranean cities in the context of adaptation to climate change.
   - Technological characteristics of subsystems of rainwater harvesting to evaluate and experimental implementation.
   - Identification and analysis of physicochemical and microbiological quality of rainwater harvested in various urban subsystems, according to their use and pavement material.
   - Quantification of the resource for each subsystem. Estimation of the runoff coefficients (RC) and the initial abstraction of each surface.
5. Propose actions to optimize the supply of surplus and unused rainwater, according to the demand requirements to reduce water dependence in urban areas from a perspective of eco-efficiency and innovation in this vector.
6. Propose strategies for the integration of the results obtained in relation to the analyzed rainwater systems in the projection of new eco-neighborhoods in water-stressed environments such as the Mediterranean area.



Chapter 2. Material and methods

Chapter 2 presents an overview of the dissertation's methodological aspects involved in its development. First, a description of the systems under examination is given and divided into theoretical and experimental case studies. Second, the environmental methodologies and tools used during the dissertation are presented in detail. A description of the field and laboratory works done and the data collection process are also provided in the last part.

This chapter is structured as follows:

- Methodological aspects and tools
- Systems of study and experimental works

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2.1. Systems of study and experimental works

The research was conducted in two parallel ways. On one side several theoretical scenarios were proposed in order to study how different variables such as the urban model, the tank location, the building height and the demand strategy chosen affected the environmental assessment of RWH systems installed in newly constructed buildings. The scale of analysis ranges from a single house to a residential neighbourhood.

On the other, an experimental design was developed with the aim to assess under local climatic conditions the RWH quantity and quality conveyed from different common urban spaces. The selection of the studied surfaces was done according to the most used pavement materials and current uses of public and open urban areas.

2.1.1. Theoretical case studies

This section describes the theoretical case studies considered in Chapter 3 and 4 of the dissertation, which were all located under a Mediterranean climate given that RWH has been acknowledged as an adaptative strategy to climate change.

(i) Diffuse and compact urban models

In Chapter 3 of the dissertation two different scales of analysis were chosen to assess RWH systems in urban environments. The scales of study chosen were building and block scales. This selection is related to the storage rainwater tank scale since the objective of the research is to assess the environmental ecoefficiency of different RWH strategies.

Since the use of rainwater for laundry is one of the most widespread uses in Europe the RWH facilities were designed to supply the maximum demand of water for each home laundry, quantified as 25 m^3/(dwelling·year) (Leggett et al, 2001).

Also, 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 per year. This amount is representative of a Mediterranean climate, in which the average rainfall oscillates between 600 and 750 mm per year (Aschmann, 1973).

A detailed diagram of the selected study variables is provided in Figure 2.1.

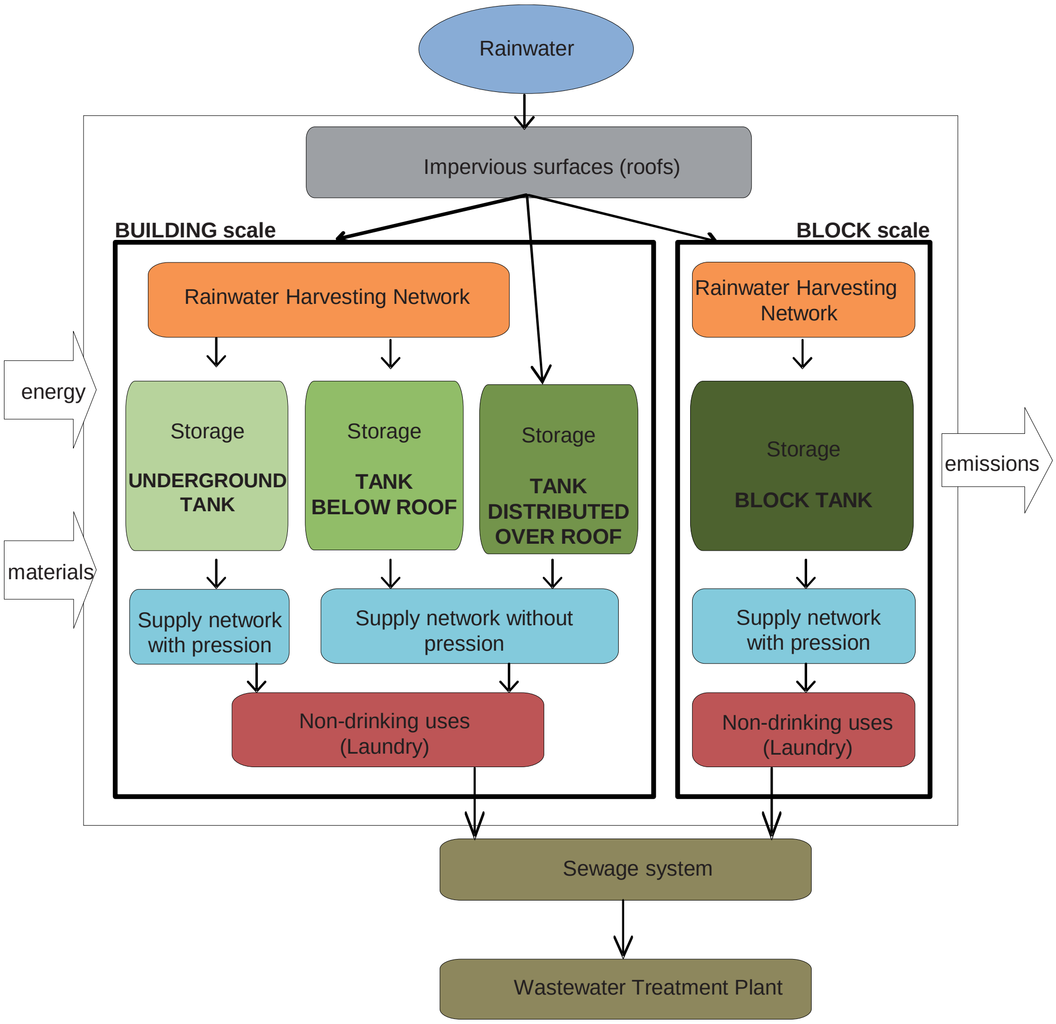


Figure 2.1. Diagram of the selected RWH variables and strategies of study at building and block scales.
Source: Sara Angrill.

The system consists of an urban area (block) of 100 × 100 m² 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: the urban density and the location of the RWH infrastructures.

In order to analyse the widest spread for current RWH practices three tank locations were chosen: An underground tank, a tank positioned below the roof and a tank positioned above the roof.

Additionally, two contrasting urban density models were selected in order to determine how this variable affects the environmental impact of RWH systems in Mediterranean climates. Thus, diffuse and compact urban models were proposed. For both urban models the building and block scales were also considered.

The diffuse density model was based on a two-story detached single-family house (250 m²/floor) in a 90% unbuilt area. The block-scenario distribution considered the construction of four houses on 10,000 m² (Fig. 2). The compact density model proposes a five-story building (24 apartments, 700 m²/floor) in a 30% unbuilt area.

The block scenario consists of the integration of 10 residential buildings on 10,000 m2. (Fig. 2).

The location of the RWH infrastructures determined four scenarios of analysis for each urban density. These were 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 the roof and tank over the roof).

The main characteristics of this case study are shown in Figure 2.2.

Figure 2.2. Characteristics of the study area based on diffuse and compact urban models and four different tank locations.
Source: Sara Angrill.

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; ABS, 2010; U.S. Census Bureau, 2010).

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.

(ii) Distribution strategies at building scale

Chapter 4 goes further, and taking into account the results found in Chapter 3, two more variables with environmental implications and which directly affect RWH systems are therefore assessed. In this case study the focus is on the building scale and thus, the additional variables correspond to the height of the building and the chosen water distribution strategy.

Firstly, to determine the contribution of the height of the building on the impact of the RWH systems and to compare medium with very high-density buildings, four different construction heights were proposed: a six-story building (30 apartments), a nine-story building (48 apartments), a twelve-story building (66 apartments) and a fifteen-story building (84 apartments).

The building design consists of a newly constructed residential building with 690 m^2 of floor area (additional structural data are given in Annex I.I). For this floor area a 'U' shape was chosen because it enables widening the surface of the facade in relation to the floor area. Inside the building every floor was distributed into six apartments that were given 100 m^2 of floor area each. The first floor, or ground floor, was not considered as habitable but was intended for commercial or other activities.

In addition, two tank locations were analyzed: a tank distributed over the roof (R) and an underground tank (U). The roof tank is distributed over 633 m^2 of roof area (92% of the total roof) and has a depth of 4 cm, while the underground tank (5 m x 3 m x 1.7 m) has a rectangular base.

For both of these locations (R and U), three different water distribution alternatives were proposed:, a common and shared laundry room located on the ground floor (A), supply to the nearest apartments to the tank (B) and distribution to all the apartments in the building (C).

A graphical sketch of the different variables considered in the assessment is provided in Figure 2.3.

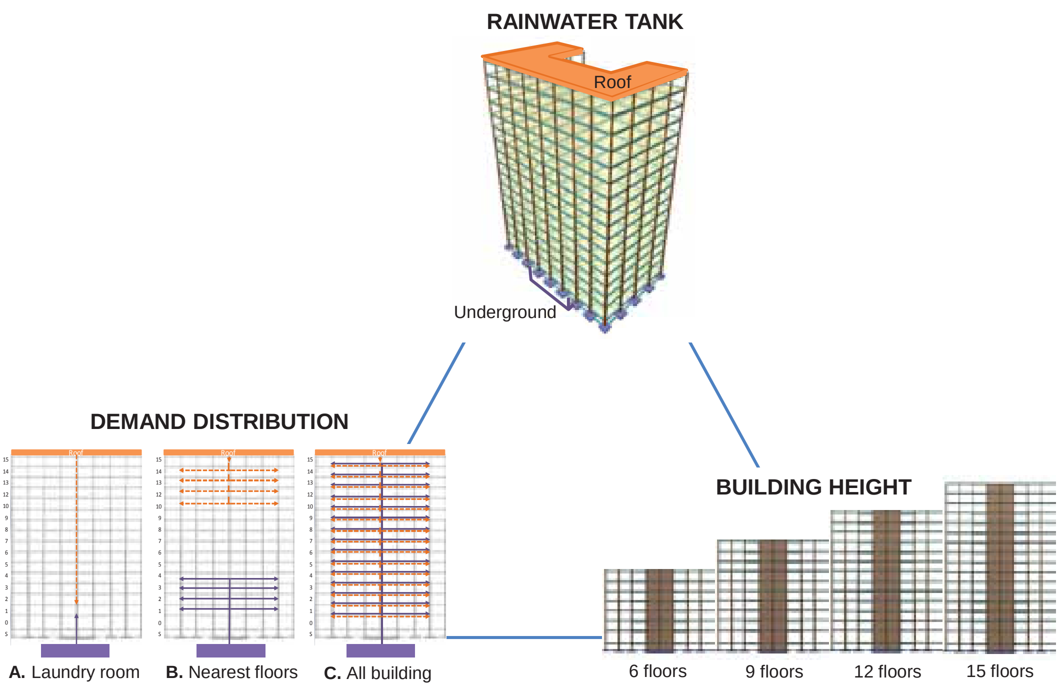


Figure 2.3. General diagram of the three variables considered in the environmental assessment of RWH at building scale: building height, tank location and demand distribution.
Source: Sara Angrill.

2.1.2. Experimental case study

The research presented in Chapter 5 of the dissertation is based on an experimental case study performed at the Universitat Autònoma de Barcelona (UAB) campus, located in Bellaterra (Cerdanyola del Vallès, Barcelona, Spain) between June 2011 and April 2013.

In this study seven different catchment surfaces were selected within the university campus in order to collect real data from a public urban area transited by pedestrians and vehicles and from an urban area accessible to the researcher. The location of each surface is presented in Figure 2.4.

Figure 2.4. General diagram of the three variables considered in the environmental assessment of RWH at building scale: building height, tank location and demand distribution.
Source: Sara Angrill.

The selection of catchment areas was done according to two criteria: surface material and type of use. The seven surfaces have been grouped on pedestrian paths or areas (PA), traffic roads (R) and car parks (P), which correspond with the blue, red and green colors in the following figures, respectively. For each surface the most common materials found in pavement construction were selected, which consist on asphalt (A), concrete (C) and precast concrete tiles (T).

The main characteristics of each surface are summarised next by means of a series of schemes (Figures 2.5 to 2.11).

Figure 2.5. Main characteristics of the asphalted pedestrian area study surface.

Source: Sara Angrill.

Figure 2.6. Main characteristics of the tiled pedestrian area study surface.

Source: Sara Angrill.

CPA **Concrete pedestrian area**

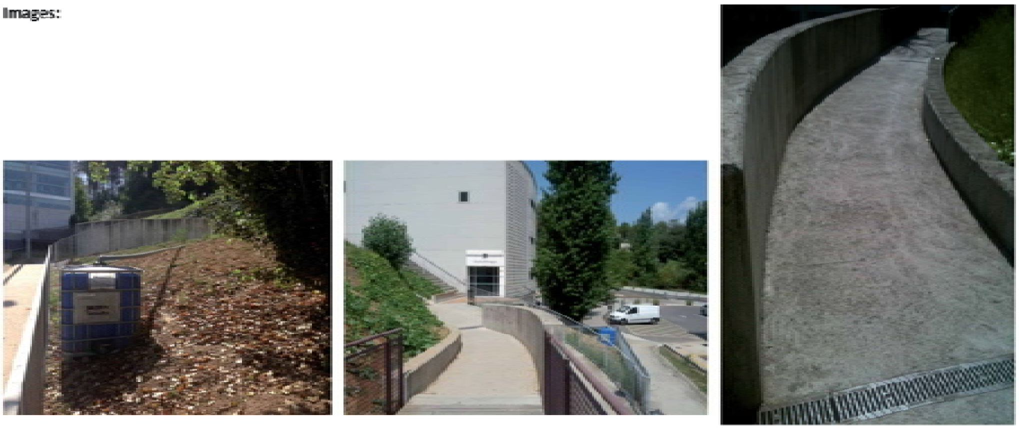
Description:
Concrete walking path located in the center of the university campus and usually very busy. Urban surface without trees but a building nearby.

Characteristics:

Roof	Material	Use	Slope (º)	Roughness	Orientation (º)	Catchment area (m2)	UTM Coord.
CPA	Concrete	Pedestrian area	5º	Rather rough	305º NW	19.8	425200,0 E; 4595040,0 N

Location:
University Campus UAB (Bellaterra, Barcelona, Spain)

Images:



Monitored rainfall events:

Roof	# monitored events	ADWP range (days)	Rainfall range (mm)
CPA	12	3 - 30	2.4 - 24.6

Figure 2.7. Main characteristics of the concrete pedestrian area study surface.

Source: Sara Angrill.

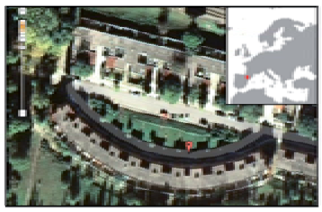
AR **Asphalted road**

Description:
Asphalted road located in a dormitory neighborhood with low traffic intensity. There are small trees and two-storey houses nearby the catchment surface.

Characteristics:

Roof	Material	Use	Slope (º)	Roughness	Orientation (º)	Catchment area (m2)	UTM Coord.
AR	Asphalt	Road	2º	Rough	12º N	40.2	424818,0 E; 4594934,0 N

Location:
University Campus UAB (Bellaterra, Barcelona, Spain)



Images:

Monitored rainfall events:

Roof	# monitored events	ADWP range (days)	Rainfall range (mm)
AR	12	3 - 30	2.4 – 66.8

Figure 2.8. Main characteristics of the asphalted road study surface.

Source: Sara Angrill.

CR Concrete road

Description: Concrete road located at the entrance of an underground parking with usual traffic fluency. One side of the catchment surface is bounded by a building façade.

Characteristics:

Roof	Material	Use	Slope (°)	Roughness	Orientation (°)	Catchment area (m2)	UTM Coord.
CR	Concrete	Road	45°	Rather smooth	180° S	142.7	424657,0E; 4594777,0N

Location:

University Campus UAB (Bellaterra, Barcelona, Spain)

Images:

Monitored rainfall events:

Roof	# monitored events	ADWP range (days)	Rainfall range (mm)
CR	16	3 - 29	2.4 – 38.2

Figure 2.9. Main characteristics of the concrete road study surface.

Source: Sara Angrill.

AP Asphalted parking

Description:
Asphalted parking with high traffic intensity located at the entrance of a faculty. It is a urban environment surrounded by small trees and a building nearby.

Characteristics:

Roof	Material	Use	Slope (°)	Roughness	Orientation (°)	Catchment area (m2)	UTM Coord.
AP	Asphalt	Parking	3°	Rough	45° NE	21.2	425235,0E; 4594914,0N

Location:

University Campus UAB (Bellaterra, Barcelona, Spain)

Images:

Monitored rainfall events:

Roof	# monitored events	ADWP range (days)	Rainfall range (mm)
AP	15	3 - 45	2.4 – 66.8

Figure 2.10. Main characteristics of the asphalted parking study surface.

Source: Sara Angrill.

CP Concrete parking

Description:
Concrete parking with restricted access and therefore low traffic intensity. It is a urban environment without trees but some buildings nearby.

Location:

University Campus UAB (Bellaterra, Barcelona, Spain)

Characteristics:

Roof	Material	Use	Slope (º)	Roughness	Orientation (º)	Catchment area (m2)	UTM Coord.
CP	Concrete	Parking	9º	Rather smooth	20º N	93	425666,0 E; 4594751,0 N

Images:

Monitored rainfall events:

Roof	# monitored events	ADWP range (days)	Rainfall range (mm)
CP	15	3 - 45	2.4 – 66.8

Figure 2.11. Main characteristics of the concrete parking study surface.

Source: Sara Angrill.

2.2. Methodological aspects and tools

The methods and tools applied along the dissertation are presented and detailed in the current section. In Figure 2.6 a diagram is provided showing the methodology that was applied to each chapter.

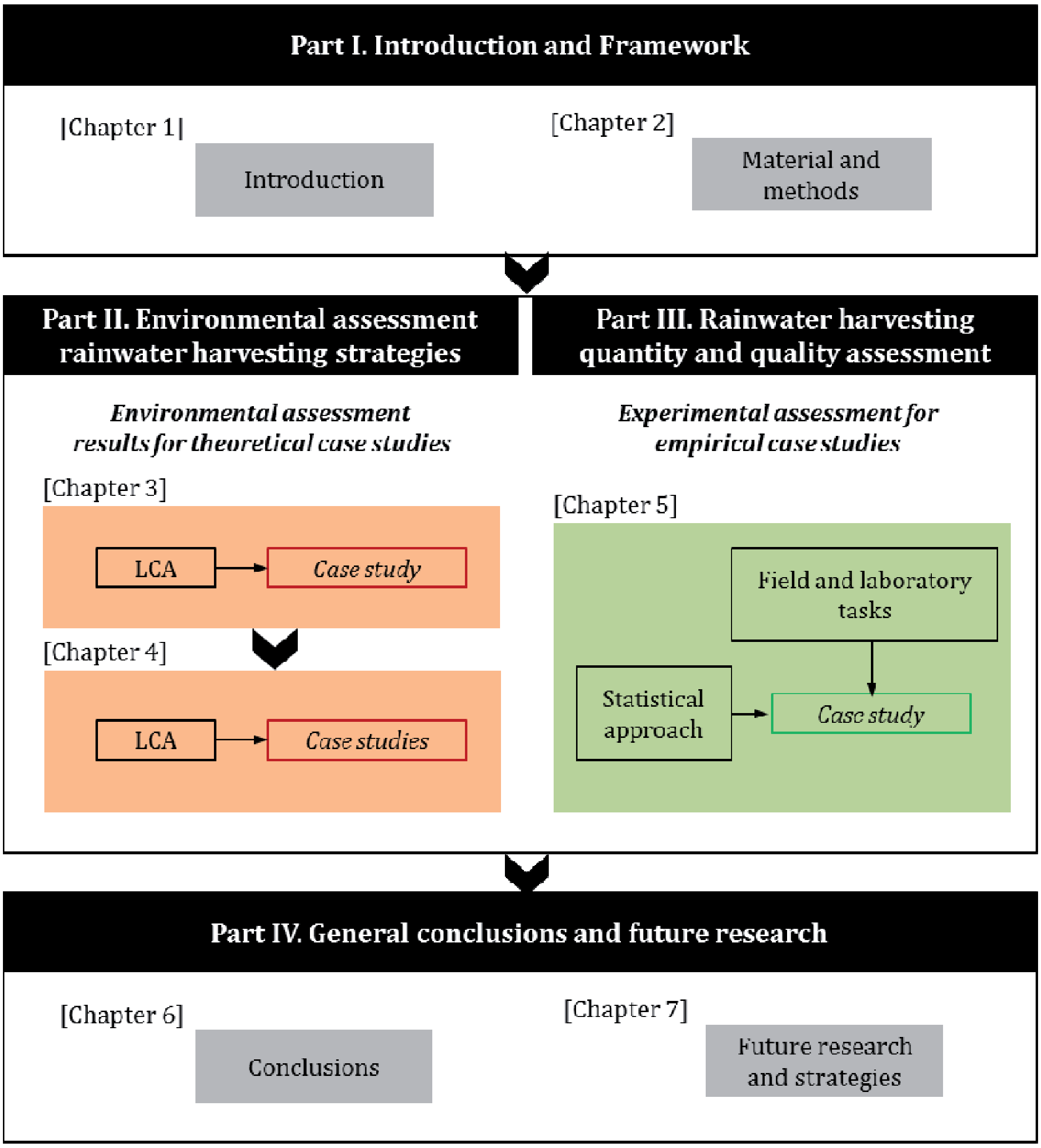


Figure 2.12. Overview of the methods used in Parts II and III of the dissertation.

Source: Sara Angrill.

2.2.1. Life Cycle Assessment

The entire Part II of the dissertation, which consists on Chapter 3 and 4, is addressed from a life cycle assessment perspective. This concept implies the consideration of the whole life cyle of a system from 'cradle to grave' with the objective to detect the critical steps of its life cycle to be able to environmentally improve them (Finkbeiner et al. 2010).

(i) Definition

Life Cycle Assessment (LCA) is a quantitative tool that assesses the potential environmental impacts associated with a product, service or system along its entire life cycle, from raw material acquisition to production, use, and disposal. It was first defined by The Society for Environmental Toxicology and Chemistry (SETAC) in 1991 as "*a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released into the environment; to assess the impact of those energy and materials used and releases into the environment; and to identify and evaluate opportunities that affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal*" (SETAC, 2001).

The LCA community together with the International Organization for Standardization (ISO) have been working together during the past decades to set standards for the LCA methodology (ISO 14040, 2006; Guinéé et al, 2002).

(ii) Methodology

The LCA procedure involves the following interdependent four phases as defined in ISO 14040 (ISO 14040, 2006) (see Figure 2.13):

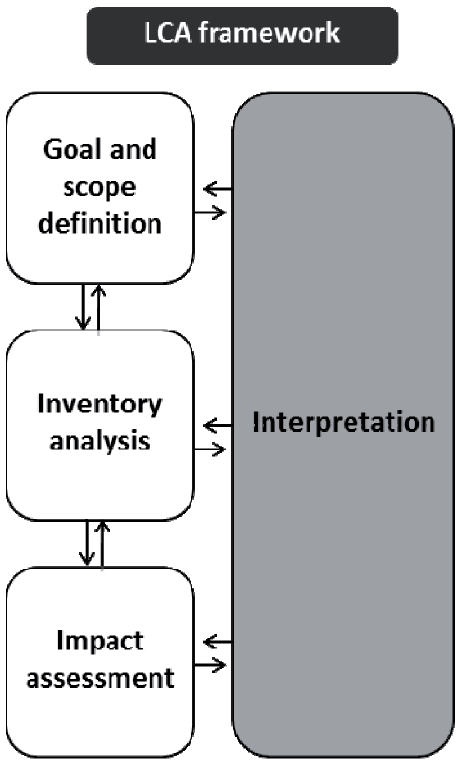


Figure 2.13. Stages of the Life Cycle Assessment.
Source: (ISO 14040, 2006).

Goal and scope

The first stage of a LCA consists of the definition detailing the goal and scope of the study. This phase include the definition of the intended application and audience of the study, the determination of the functional unit, the system boundaries, allocation procedures, the selection of the impact cathegories of analysis and the methodology used, as well as the determination of the assumptions and limitations of the current study.

According to ISO 14040 the functional unit concept refers to the performance of a product system to be used as a reference unit to which inputs and outputs can be related (ISO 14040, 2006). This is a crucial step since future comparisons to the results obtained will be greatly affected by the definition of this reference value.

During the dissertation, in both case studies analysed in Chapter 3 and 4 the functional unit defined was the collection, storage and supply of 1 m^3 of rainwater to be provided per dwelling per year, as a non-potable water source for laundry purposes.

Inventory analysis

The inventory analysis step or life cycle inventory includes the calculation and collection of data that will then be used as inputs in the impact assessment analysis. This data must be as detailed as possible to provide the most accurate results since this inventory is the basis to assess the potential impacts of the system in the latter phase. It must contain information about the entire life cycle of the system. This includes energy and raw materials, emissions to the air, water and soil, solid waste produced and all other related elements that could be quantified. The main steps are data collection, the identification of the relevant and non-relevant elements, mass and energy balance, and allocation of the system loads, since usually processes perform more than one function or discharge more than one output.

Impact assessment

The life cycle impact assessment (LCIA) translates the previous detailed inventory data into potential environmental impacts at the midpoint and endpoint by means of an impact assessment method (UNEP, 2011).
The LCIA are mandatory on the classification and characterization steps, while normalization is optional. The first phase, ie, the classification, groups all environmental data from the life cycle inventory into different impact categories according to the type of impact expected. The second phase is characterisation, which is the calculation of the potential impact of substance, using as reference specific characterisation factors that are available in literature and databases, (JRC and IES 2010), in order to reduce all impacts to a few selected equivalent compounds.

Table 2.1 presents the environmental impact categories used during this dissertation.

Table 2.1. Environmental impact categories applied during the dissertation.

Acronym	Name	Unit
ADP	Abiotic depletion potential	kg Sb eq.
AP	Acidification potential	kg SO_2 eq.
EP	Eutrophication potential	kg PO_4^{3-} eq.
GWP	Global warming potential	kg CO_2 eq.
ODP	Ozone layer depletion potential	kg CFC eq.
POCP	Photochemical oxidation potential	kg C_2H_4 eq.
HT	Human toxicity potential	kg 1.4 DB eq.

Source: Guinée et al. (2001)

Interpretation

Finally, the last step is the interpretation of the potential resulting impacts where the life cycle inventory data and the impact assessment results are crossed together. This phase should offer consistent results according to the defined goal and scope and should also reach critical steps of the inventory, to explain limitations and provide recommendations. Since LCA is an interative process the interpretation of results may involve a revision of the goal and scope as well as an examination of the collected inventory data.

(iv) Software and databases of the dissertation

In the dissertation the newest version available of Simapro software (Pré Consultants, 2012) was used to obtain the life cycle environmental impacts of all systems. This software is linked to varius international and regional databases. In the dissertation the newest version of the ecoinvent databases (Swiss Centre for Life Cycle Inventories, 2009) were mainly used.

The methodological analysis for potential impacts used was the CML Baseline 2001 (Guinée et al, 2001) associated with the impact cathegories previously presented.

2.2.2. Field and laboratory tasks

In this section the experimental methodology applied in Chapter 5 is described for the assessment of the RWH quantity and quality in several urban spaces.

(i) Experimental design

In order to assess the potential RWH quantity and quality in an urban environment a previous experimental design and selection of the catchment surfaces was used.

The seven surfaces selected have been described previously in this section and are shown again in Figure 2.14.

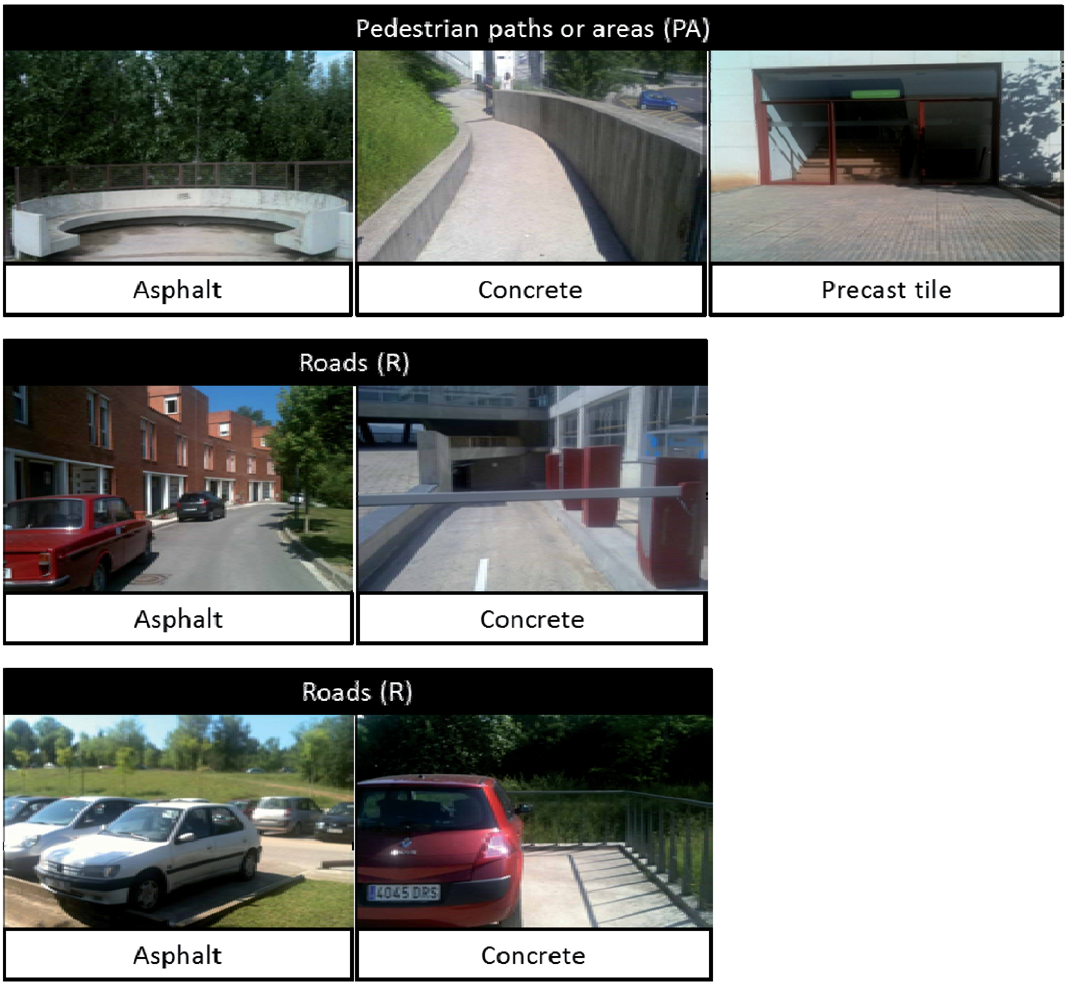


Figure 2.14. Selected urban surfaces in the UAB campus where the experimental design was installed.

Source: Sara Angrill.

A rainwater harvesting conveyance and storage system was installed on each study surface. All selected surfaces were located topographically higher than the storage tank in order to allow the storm water to flow to it using gravity, thereby avoiding any major building, construction or road works. The experimental design consisted on delimiting the catchment area and installing the system components, which consisted on a gutter and a downpipe that conducted water to one or two polypropylene storage tanks of 1 m3. A common membrane filter (0.28 mm pore diameter) was installed at the entrance of the storage tank to avoid leaves and other large objects from entering the tank. No first flush diversion was installed for any of the systems and there was no maintenance of the catchment surface during the experimental period. However, pipes and gutters were frequently cleaned out of sand, leaves and other pollutants and the storage tanks were rinsed with pressurized water twice a year.

Figure 2.15. Rainwater harvesting system experimental installation at some sampling stations at the UAB campus.

Source: Sara Angrill.

Over a time period of 22 months for the experimental campaign (June 2011 to April 2013), quality and quantity data from 25 different rain events were collected. Rainfall events of less than 2.4 mm were excluded because runoff was insufficient. Local rainfall was monitored with a rain gauge set nearby each catchment surface.

(ii) Quantity assessment

The variables recorded after each rainfall event needed to perform the quantity assessment were the following:

- Rainfall height (monitored locally with the rainfall gauges and contrasted with the weather station measures of Cerdanyola del Vallès)
- Amount of collected rainwater
- Duration of the event
- Minimum and maximum temperatures
- Predominant wind orientation and speed
- Antecedent dry weather period (ADWP)

After the measurements were taken the storage tank and rainfall gauges were emptied.

The aim of the quantity assessment was to determine the initial abstraction of each type of catchment surface and the runoff coefficient (RC) of each surface.

First of all a correlation analysis was conducted using the statistical software PASW Statistics 20 (IBM Corp, 2011) taking into account the amount of runoff depending on rainfall height.

In order to develop a model to estimate the runoff of each roof, a statistical analysis was conducted with the aid of PASW Statistics 17, from the Statistical Package for the Social Sciences (SPSS) software. This analysis included a correlation analysis followed by linear regression model, considering the amount of runoff depending on several independent variables (rainfall, ADWP and wind direction).

Once verified, linear regression models were performed with the recorded dataset to estimate the initial abstraction of each surface, and later on, were used for the calculation of the RC of each surface. Data regarding the local rainfall profile was provided by the weather station of Cerdanyola del Vallès (automatic station owned by the Meteorological Service of Catalonia) for the last 10-year period.

(iii) Quality assessment

After each monitored rain event two water samples (V=0.5 L each) were taken from the rainwater contained in the storage tanks. One sample was used to perform the physicochemical analysis and the other to determine the microbiological, hydrocarbons (HC) and metal content. After that, the tank was emptied to prepare for the next rainfall event. Samples were kept refrigerated until their delivery to the laboratory.

The physical-chemical analyses were carried out by the Laboratori de Medi Ambient linked of the Environmental Assessment and Management Technical Office belonging to the Diputació de Barcelona. The microbiological, hydrocarbons and metal analyses were developed by a certified laboratory (Applus Agroenvironmental, Sidamon, Lleida, Spain).

The physicochemical parameters analysed together with the detection thresholds and techniques used are presented in Table 2.2:

Table 2.2. Quality parameters analysed in the experimental case study, detection thresholds and applied techniques.

Parameter	Units	Threshold	Measurement technique
Physical-chemical parameters			
pH	upH	-	pH meter
EC	µS/cm	0	Conductivity meter (at 20ºC)
SST	mg/L	2	Membrane filtration of 47 mm diameter and 1.2 micron pore
TOC	mg C/L	0	IR spectrometry
COD	mg O2/L	10	Colorymetry
HCO3-	mg/L	0	Segmented flow colorimetry (SFC)
Cl-	mg/L	2,0	Conductivity detector
SO42-	mg/L	5,0	
NO2-	mg/L	0,05	UV-Visible detector at a wavelength of 214 nm
NO3-	mg/L	1,00	
PO43-	mg/L	0,31	Segmented flow colorimetry (SFC)
NH4+	mg/L	0,10	
Microbiological parameters			
Colonies at 22ºC	ufc/mL	0	Seed and count in culture mediums
Colonies at 37ºC	ufc/100mL	0	
Total coliforms	ufc/100mL	0	
Fecal coliforms	ufc/100mL	0	
Pseudomonas aeruginosa	ufc/100mL	0	
Clostridium perfringens	ufc/100mL	0	
Enterococcus	ufc/100mL	0	
Hidrocarbons			
TPH	mg/L	2,0	Gravimetry

Metals			
Cr	μg/L	4	Plasma emission spectrometry
Ni	μg/L	7	
Cu	μg/L	10	
Zn	μg/L	7	
Hg	μg/L	1,0	
Cd	μg/L	2,0	
Pb	μg/L	25,0	
Fe	μg/L	15	
As	μg/L	5	

Source: Sara Angrill.

The data analysis was conducted with the aid of the software PASW Statistics 20. Descriptive statistics were obtained for each parameter and type of surface expressed as maximum and minimum values, the mean (with standard deviation) and the median.

Then, the dataset was subjected to a variance and correlation analysis. The variance analysis detected if differences in the mean or median concentration of compounds in the studied surfaces were statistically significant. Since data did not satisfy the one-way ANOVA test conditions (data distribution did not follow a normal distribution) the test of Kruskall-Wallis, suitable for k-independent samples, was performed.

Finally, a correlation analysis was conducted to determine the degree of association between water quality parameters among themselves and its association with the storm characteristics (total rainfall height and ADWP). This analysis was performed for the whole set of surfaces by means of the Spearman Rho correlation coefficient.

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Part II

Environmental assessment of rainwater harvesting strategies



Chapter 3. Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate

Chapter 3 is based on the following paper:

Angrill, S., Farreny, R., Gasol, C.M., Gabarrell, X., Viñolas, B., Josa, A., & Rieradevall, J. (2012) Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate. The International Journal of Life Cycle Assessment, 17(1), 25-42.

Abstract

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.

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 (underground tank (1), below-roof tank (2), distributed-over-roof tank (3) and block tank (4)). The structural and hydraulic sizing of the catchment, storage and distribution subsystems were 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 (LCA), 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.

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 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.

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.

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

Water resource, Sustainable cities, Laundry demand, Urban planning, LCA, Environmental impact, Carbon emissions, Reinforcement.

3.1. Introduction

3.1.1. 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; Vairavamoorthy and Sharma 2009; Slys 2009; Pia 2009; 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 Nissen-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).

3.1.2. 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 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 1998; Beavis and Lundie 2003; Raluy 2009), the determination of impacts associated with water management before and after use (Lassaux 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 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.

3.2. Goal and scope

3.2.1 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.

3.2.2 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.

3.2.3. 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).

(i) 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 2009 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, kg Sb eq.), Acidification Potential (AP, kg SO2 eq.), Eutrophication Potential (EP, kg PO43- eq.), Global Warming Potential (GWP, kg CO2 eq.), Human Toxicity Potential (HTP, kg 1.4-DB eq.), Ozone Depletion Potential (ODP kg CFC-11 eq.) and Photochemical Ozone Creation Potential (POCP, kg C2H4 eq.).

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.

(ii) 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 $1m^3$ 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.

(iii) 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 2003). 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 per 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 Money 1973).

3.2.4. Description of the system under study

The diagram of the system evaluated is presented in Fig. 3.1. 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. Fig. 3.2 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.

(i) 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 (Fig. 3.2). 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 10 residential buildings on 10,000 m^2 (Fig. 3.2). 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; ABS 2010; U.S. Census Bureau 2010).

(ii) Infrastructures

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

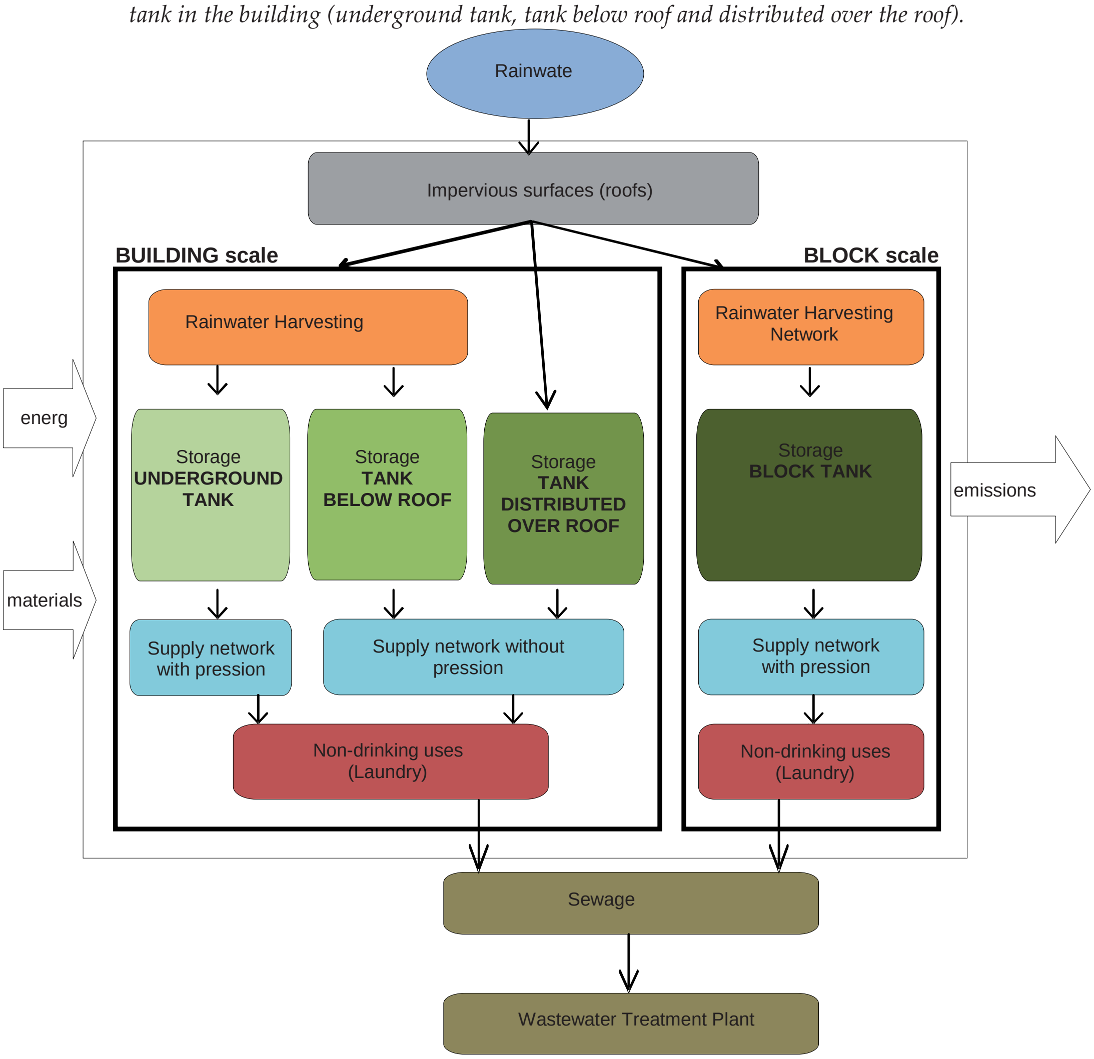

Figure 3.1. RWH diagram and system boundaries at the building scale depending on the location and type of tank and at the block scale with community tanks for non-potable domestic uses
Source: Own elaboration

(iii) 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 3.1 shows the characteristics of the main structural components for the different subsystems considered.

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

Figure 3.2. Characteristics of the study area based on the two urban densities defined and the location of the tanks at the building and block scale
Source: Own elaboration

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 (Fig. 3.2). 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 (Table 3.1).

Storage The storage subsystem consists of a rainwater-storage tank, the design of which varies depending on its location and scale (Fig. 3.2, Table 3.1):

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 m and 5 m in height and 3 cm thick), which can be reused up to 20 times (Alsina 2010).

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 (Fig. 3.2). 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 (Table 3.1).

Table 3.1. 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			
	D1	**D2**	**D3**	**D4**	**C1**	**C2**	**C3**	**C4**
Tank scale	Building	Building	Building	Block	Building	Building	Building	Block
Tank location	Undergr.	Below roof	Distrib. over roof	Underg.	Undergr.	Below roof	Distrib. over roof	Undergr.
Structural data								
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	5	5	9	20	21	21	37.8	209
Tank dimensions (m^3)	(1.7x1.7 x1.7)	(2.2x2.3 x1)	(10x10 x0.09)	(2.7x2.7 x2.7)	(2.8x2.8 x2.8)	(4.6x4.6 x1)	(30x14 x0.09)	(5.9x5.9 x6)
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

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 kW 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 minutes 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.

(v) 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.

3.3. Results

3.3.1. Inventory data

The inventory data are presented in Table 3.2, 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 (Table 3.2).

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.

Table 3.2 Inventory of materials and energy per FU disaggregated into subsystems, components and stages (Life cycle stages are Materials [M], Construction [C], Transportation [T], Use [U], Deconstruction [D])

Life cycle stages			Data per FU	D1	D2	D3	D4	C1	C2	C3	C4
Catchment	M	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
	C	Power consumption	Diesel (MJ)	2.5E-01	0	0	1.7E+00	6.1E-02	0	0	1.6E-01
	T	Materials to site	Van <3,5t (tkm): 30km	2.9E-03	2.9E-03	0	5.1E-03	5.9E-04	5.7E-04	0	7.4E-04
		Waste to manager	Van <3,5t (tkm): 50km	5.1E-03	5.1E-03	0	8.9E-03	1.0E-03	1.0E-03	0	1.3E-03
	D	Demolition energy	Diesel (MJ)	2.5E-01	0	0	1.7E+00	6.1E-02	0	0	1.6E-01
Storage	M	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 20-25MPa (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 reinforce-ment	Reinforcing steel frame (kg)	0	1.4E-01	5.7E-03	0	0	1.1E-02	3.3E-03	0
			Concrete 20-25MPa (kg)	0	7.6E+00	5.6E-01	0	0	9.4E-01	3.5E-01	0
	C	Power consumption	Diesel (MJ)	6.7E-01	0	0	7.6E-01	2.8E-01	0	0	2.9E-01
	T	Materials to site	Truck >32t, (tkm): 30km	0	0	0	2.3E-01	8.2E-02	8.7E-02	0	7.7E-02
			Truck 7,5-16t, (tkm): 30km	2.6E-01	3.7E-01	2.6E-01	0	0	0	9.6E-02	0
		Waste to manager	Truck >32t, (tkm): 50km	4.6E-01	6.4E-01	4.5E-01	4.0E-01	1.4E-01	1.5E-01	1.7E-01	1.4E-01
	D	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	M	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
	C	Power consumption	Diesel (MJ)	2.5E-01	0	0	1.7E+00	6.1E-02	0	0	1.6E-01
	T	Materials to site	Van <3,5t (tkm): 30km	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 <3,5t (tkm): 50km	1.2E-03	1.2E-04	1.2E-04	1.6E-03	7.6E-04	2.2E-04	2.2E-04	7.7E-04
	U	Pumping consumption	Electricity (kWh)	4.9E-01	0	0	9.7E-01	4.2E+00	0	0	2.1E+00
	D	Demolition energy	Diesel (MJ)	2.5E-01	0	0	1.7E+00	6.1E-02	0	0	1.6E-01

3.3.2. 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.

(i) Environmental impacts of diffuse-density models

The results of the environmental analysis of impacts regarding the diffuse density scenarios are presented in Figure 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 Ozone Depletion Potential (ODP), in which scenario D4 (block tank) was the best choice (Fig. 3.3). Conversely, the scenario with the most significant negative impacts in most of the seven categories analyzed was D2 (tank below cover), except for Acidification Potential (AP) in which D4 showed a greater contribution.

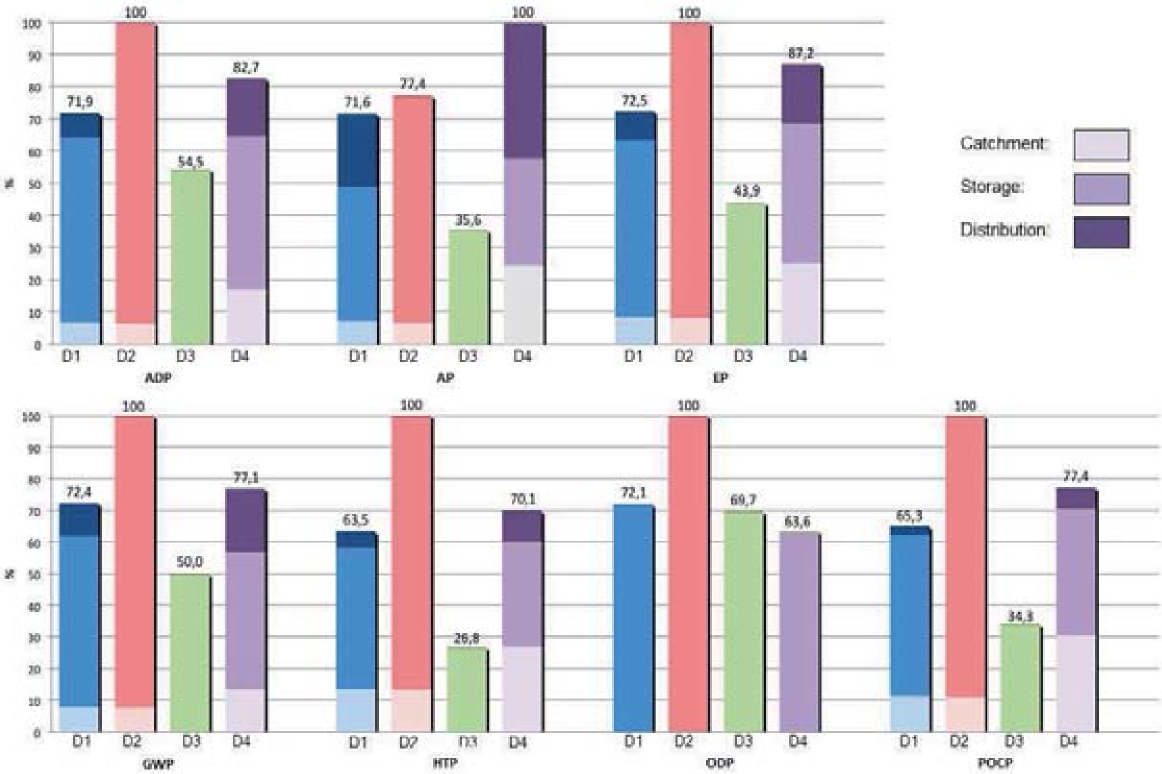

Figure 3.3. Proportional comparison of the total environmental impacts of the diffuse-density scenarios by impact category and contributions of the subsystems.
Source: Own elaboration

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 (Fig. 3.3). 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.

Table 3.3. Characterization of results per FU and life-cycle stage contributions in the diffuse (D) and compact-density (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-11eq.]		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
	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
2	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	6.23E-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

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 3.3.

Impacts of stages in diffuse-density scenarios The results regarding the diffuse-density scenarios show that the materials stage was by far the major contributor in all of them (Table 3.3). 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.

(ii) 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 (Fig. 3.4). The environmentally worst option was C1, as it presented higher impacts in six categories (all except ODP).

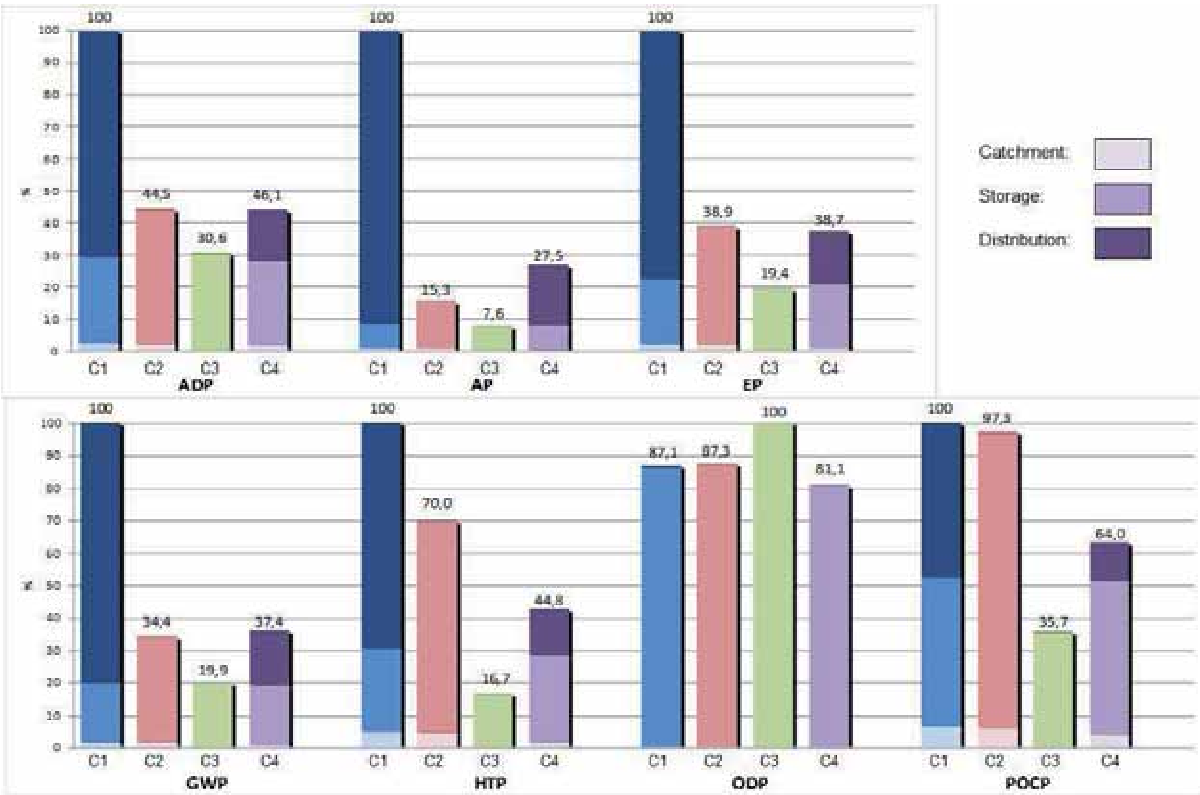

Figure 3.4. Proportional comparison of the total environmental impacts of the compact-density scenarios by impact category and contributions of the subsystems.
Source: Own elaboration.

Impacts of subsystems in compact-density scenarios The greatest impacts were related to the storage subsystems in C2, C3 and C4 (Fig. 3.4). 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 (Table 3.3). 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 (Table 3.3).

(iii) 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 3.3). 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 Global Warming Potential (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 analogues 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.

3.4. Discussion

3.4.1. 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 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 (Fig. 3.3). 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 building. 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 (Fig. 3.3) and the materials-processing stage (Table 3.3), 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 (Schuurmans 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; Josa et al. 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 (Fig. 3.3). 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.

3.4.2. 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 (Fig. 3.4). 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 (Fig. 3.4). 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 (Fig. 3.4) during the use period of the infrastructure (Table 3.3), 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) (Table 3.3). However, in the compact urban-density model (C2) the structural reinforcement was not as relevant as in the diffuse model (D2).

3.4.3. 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.

3.4.4. Comparison of the impacts with conventional networks and alternative water techniques

Table 3.4 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 (kg CO_{2eq}/m^3 of water supplied) and the energy demand during use stage (kWh/m^3). All data refer to Mediterranean regions in order to allow comparisons with the maximum reliability.

Table 3.4. GWP and energy demand impact comparison of three water management systems: RWH, drinking main water-supply systems and alternative technologies

		GWP ($kgCO_{2eq}/m^3$)	Energy demand (kWh/m^3)
RWH	C3 (gravity syst.)	0.64	0.00
	C4 (pumping syst.)	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

As can be seen from Table 3.4 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 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 3.4) 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.

3.5. 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 macro scale of the same order of magnitude and to include additional adjustments in order to make a consistent comparison.

3.6. 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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Chapter 4. Environmental performance of rainwater harvesting strategies in Mediterranean buildings

Chapter 4 is based on the following paper:

Angrill, S., Segura, L., Rieradevall, J., Gabarrell, X., & Josa, A. (2013) Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate. Water Resources Management (Submitted September 2013).

Abstract

This research suggests environmental criteria for the design and use of rainwater harvesting (RWH) infrastructures in residential blocks of flats in Mediterranean climates. The criteria account for the tank location (distributed over the roof and underground), the building height (6, 9, 12 and 15 floors) and the distribution strategy (shared laundry, supply to the nearest apartments and distribution throughout the building) linked to a constant demand for laundry. A life cycle assessment was conducted to estimate the environmental contribution of each scenario. The distribution strategy chosen was found to be the most important variable in the optimization of RWH systems. Roof tank strategies present fewer impacts than their underground tank equivalents because they enhance energy and material savings, and their reinforcement requirements can be accounted for within the safety factors of the building structure without the tank. A distribution strategy that concentrates demand in a laundry room was the most ecoefficient option resulting in impact reductions from 25% to 54%, depending on the building height. Therefore, a behavioral change regarding demand should be promoted in compact, dense urban settlements. These results may set new urban planning standards for the design of construction buildings from the perspective of sustainable water management.

Keywords

Sustainable buildings, Water management, Laundry demand, Urban planning, LCA, Environmental impact.

4.1. Introduction

4.1.1. Rainwater harvesting in urban areas

The rapid urbanization and the constant expansion of urban areas during the last decades have led to increasing water shortages. This situation is being aggravated in water-stressed climates, such as the Mediterranean, which present high risks for droughts and frequent floods (Ngigi 2003). Rainwater harvesting (RWH) has been utilized for centuries to fulfill household and agricultural requirements (Pandey et al. 2003) and is currently being increasingly practiced in areas with very different rainfall patterns, such as Jordan (Abdulla and Al-Shareef 2009), India (Glendenninga and Vervoort 2010), South Africa (Mwenge Kahinda and Taigbenu 2011), Brazil (Guisi et al. 2007), the United States (US) (Jones and Hunt 2010), Australia (Zhang et al. 2009), China (PUB 2012) and the United Kingdom (UK) (Roebuck et al. 2010).

The main benefits associated with RWH include flood risk reduction, self-sufficiency and decreased dependency on distant water sources, reduction of stormwater flows treated in wastewater treatment plants or transported from far away, and reduction of non-point water pollution (Zhang et al. 2009; Coombes et al. 2002; Villarreal and Dixon 2005; van Roon 2007; Fletcher et al. 2008; Rahman et al. 2010). Rainwater can supply different water qualities for fit-for-purpose water uses. Although untreated harvested rainwater is often unsuitable for drinking due to the presence of microbes and pathogens (Sazakli et al. 2007; Zhu et al. 2004), numerous studies guarantee rainwater quality for toilet flushing, laundry and gardening irrigation (Lye 2009).

4.1.2. RWH strategies in urban areas: Scale and tank location

Urban morphology trends are converging on more compact cities, where population densities together with building height play a significant role (Oliver-Solà et al. 2011). In this context, RWH systems have the potential to be an important contributor to urban water self-sufficiency.

Until now, the selected parameters to design RWH infrastructures and to determine their potential have been the catchment area, the rainfall pattern, the degree of roof slope, the runoff coefficient (RC) and the roof materials (Farreny et al. 2011a). Housing type and density also affect RWH system efficiency, as does occupancy and non-potable demand. The installation of decentralized technologies in multi-family buildings may be favored by economies of scale and cost sharing arrangements (Nolde 2007). The collection efficiency is also larger in high density urban areas because the water consumption pattern per hectare is greater and, therefore, all water collected is more likely to be consumed (Herrmann and Schmida 1999). However, the percentage of demand met is usually lower than in low density neighborhoods because the latter usually present larger catchment surfaces per dwelling and, therefore, per consumer. From this point of view, several studies on RWH applied to multi-family buildings have been performed in Sweden (Villarreal and Dixon 2005), Malta (Reitano 2011), Germany (Herrmann and Schmida 1999) and UK (Ward et al. 2010), to cite just a few.

The relevance of the tank location as a design criterion for RWH infrastructures was previously examined together with urban density (Angrill et al. 2012). For diffuse and compact urban areas in the Mediterranean climate, tanks located over flat roofs in newly constructed buildings were the most favored environmental option. That was due to the equal distribution of the weight of the tank along the building structure and the ability to distribute the rainwater using gravity, avoiding the need for pumping. However, underground or external tank locations are currently the most frequently practiced strategies.

Another factor that may influence RWH sustainability from the environmental, social and economic point of view is demand distribution within the building (Domènech and Saurí 2011).

4.1.3. Precedents for the assessment of environmental impacts of RWH systems

Until now, there has been limited research on long-term sustainability of RWH systems, in particular for multistory residential buildings. Proper planning for water supply that considers material, energy and emissions implications requires a Life Cycle Assessment (LCA) approach, where the impacts of these infrastructural systems are evaluated holistically through the entire life cycle (Stokes and Horvath 2006). In the literature, few studies use LCA tools to determine the critical points of the urban water cycle (Lundie et al. 2004; Herz and Lipkow 2002; Lassaux et al. 2007; Venkatesh et al. 2009) and even fewer assess the installation of RWH in urban environments (Morales-Pinzón et al. 2012a). Of those, most are focused on particular stages and components of the RWH system's life cycle (Bronchi et al. 1999; Crettaz et al. 1999; Grant and Hallmann 2003).

This research aims to identify additional criteria for sustainable RWH systems from an environmental point of view and intends to provide sustainability guidelines for urban planners in the design of newly constructed neighborhoods of different densities. To fulfill future demands, water policies should focus on integrated water management, increasing the range of supply alternatives and acting upon demand (Saurí 2003).

4.2. Methodology

4.2.1. Objectives

The goal of this research was the selection of the environmentally optimum RWH strategy in newly constructed residential buildings in Mediterranean climatic conditions linked to a constant water demand for laundry. Two tank locations were analyzed: a tank distributed over the roof and an underground tank. For both of these locations, three different water distribution alternatives were proposed (supply to the nearest apartments, shared laundry room and distribution to all the apartments in the building). At the same time, four building heights were set (6, 9, 12 and 15 floors) to determine the contribution of the height of the building on the impact of the RWH systems.

4.2.2. Description of the system under study

(i) Reference flows

Rainfall: An annual rainfall of 620 mm was considered as the average for the last twenty years of rainfall data collected for Barcelona (Spain) (AEMET 2011). This amount was considered representative of a Mediterranean climate for which the average rainfall varies within a range of 600 to 750 mm per year. This climate is characteristic of several regions in the world such as California, southern Chile, Cape Province in South Africa, the Mediterranean basin and the south-southwest of Australia (Di Castri and Mooney 1973).

Water demand: The use of rainwater for laundry is one of the most common practices for nonpotable water, together with garden watering and toilet flushing (Leggett et al. 2001); laundry represents 20%

of the domestic demand in a standard dwelling (Elzen et al. 2004). The annual demand for each home laundry was set at 15.5 m^3/(dwelling·year). Based on the following assumptions, the RWH infrastructure defined was intended to supply the maximum demand possible, taking into account the average rainfall and its frequency. The average weekly consumption for European households is set at 300 l per week (assuming four wash loads per week) based on the ecoefficiency requirements necessary for the acquisition of the A+ ecolabel for washing machines (Comission Regulation EU 2010).

(ii) Building characteristics

The building design consists of a newly constructed residential building with 690 m^2 of floor area (additional structural data are given in Annex I.I). The selection of this wide floor area facilitates different building heights to fit this structure without being out of proportion. For this floor area a 'U' shape was chosen because it enables widening the surface of the facade in relation to the floor area. Moreover, it allows the underground tank to be placed beside the building foundation (on the inside face of the U). This shape is widely common in buildings since it can be found in many architectural collections and was also summarized by Meng and Forberg (2007).

Every floor was distributed into six apartments that were given 100 m^2 of floor area each. The first floor, or ground floor, was not considered as habitable but was intended for commercial or other activities.

(iii) Definition of scenarios

According to the results obtained in previous studies (Angrill et al. 2012), two different tank locations were chosen, a tank distributed over the roof (R) and an underground tank (U), with the aim of determining the best tank location under different demand distribution strategies and building heights.

To examine the influence of building height and to compare medium with very high-density buildings, four different construction heights were proposed: a six-story building (30 apartments), a nine-story building (48 apartments), a twelve-story building (66 apartments) and a fifteen-story building (84 apartments).

For each tank location (R and U), three possible distributions of the demand within the building were selected: a community laundry room located in the ground floor (A), concentration of the demand in the nearest floors to the tank (B), and distribution to all the apartments in the building (C). Laundry rooms are common in the service sector (e.g. university dormitories, hotels and other kind of shared facilities) (Riesenberger and Koeller 2005). In contrast, nowadays in residential buildings most dwellings use to have their own washing machine (Elzen et al. 2004). An alternative distribution that stands between strategies A and C, strategy B, takes into account the position of the tank and the rainwater supply and demand. This water distribution strategy concentrates demand on the upper floors (therefore in the upper apartments) in the R scenarios and on the lower floors in the U scenarios (Figure 1), taking into consideration the distribution to a fixed number of floors, set at four in all cases.

Figure 4.2. Front view of the three distribution strategies proposed for the roof (R) and underground (U) tank scenarios represented on the fifteen-story-building structure: A (laundry room), B (nearest floors) and C (all building)

Source: Own elaboration

(iv) Description of systems

The most relevant structural data used in the inventory and in the definition of the functional unit (FU) is presented in Table 1.

Regarding the *catchment stage,* it was considered that rainwater is harvested only from roofs (flat), for which standard galvanized-steel gutters and polypropylene (PP) downpipes are necessary in the U scenarios to conduct water from the roof to the tank. In the R scenarios, water is collected by infiltration between the roof pavement tiles and is stored directly in the tank, hence the catchment and storage stages coincide (Table 1). It was assumed that 90% of the total rainfall incident on the roof would enter the tank as the initial abstraction of the tiles was assumed to be very low (i.e., roof-RC was estimated at 0.9) (Farreny et al. 2011a).

A rainwater tank is the main component of the *storage stage*, the shape and measures of which vary depending on its location in the building, but its volume remains constant for all scenarios within this study (Table 1). While the underground tank is intended to be located at the inside face of the 'U' shape of the building, the roof tank covers the entire extension of the roof. The concrete used in the tank construction and the structural reinforcement of the building has a compressive strength of 30 MPa. This reinforcement consists of the extra structural material required in the building to withstand the weight of the tank and the weight of the water volume and is therefore necessary in the R scenarios. Steel (80% recycled, yield strength of 500 MPa) was also considered in the construction of the tank (underground tank) and the reinforcement (roof tank).

Table 4.1. Inventory data of stages (catchment, storage and distribution) and supply and demand characteristics for the roof (R) and underground (U) tank scenarios and for each building height

<table>
<tr><th colspan="2"></th><th></th><th colspan="4">ROOF TANK (R)</th><th colspan="4">UNDERGROUND TANK (U)</th></tr>
<tr><th colspan="2"></th><th>Data per building</th><th>6 floors</th><th>9 floors</th><th>12 floors</th><th>15 floors</th><th>6 floors</th><th>9 floors</th><th>12 floors</th><th>15 floors</th></tr>
<tr><td rowspan="7">Stage</td><td rowspan="2">CATCHMENT</td><td>Gutter (m)</td><td>0</td><td>0</td><td>0</td><td>0</td><td>63</td><td>63</td><td>63</td><td>63</td></tr>
<tr><td>Downpipe (m)</td><td>0</td><td>0</td><td>0</td><td>0</td><td>23</td><td>31</td><td>39</td><td>48</td></tr>
<tr><td>STORAGE</td><td>Tank volume (m^3)</td><td>25</td><td>25</td><td>25</td><td>25</td><td>25</td><td>25</td><td>25</td><td>25</td></tr>
<tr><td rowspan="4">DISTRIBUTION</td><td>Distribution pipes (m) – A (Laundry room)</td><td>26</td><td>34</td><td>42</td><td>51</td><td>18</td><td>18</td><td>18</td><td>18</td></tr>
<tr><td>Distribution pipes (m) – B (Nearest floors)</td><td>211</td><td>211</td><td>211</td><td>211</td><td>222</td><td>222</td><td>222</td><td>222</td></tr>
<tr><td>Distribution pipes (m) – C (All building)</td><td>264</td><td>422</td><td>580</td><td>738</td><td>274</td><td>432</td><td>590</td><td>749</td></tr>
<tr><td>Pump (items)</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td colspan="2">Apartments per building</td><td>Number of apartments per building</td><td>30</td><td>48</td><td>66</td><td>84</td><td>30</td><td>48</td><td>66</td><td>84</td></tr>
<tr><td colspan="2">Potential RWH</td><td>Potential rainwater harvested per year and building (m^3)</td><td>385</td><td>385</td><td>385</td><td>385</td><td>385</td><td>385</td><td>385</td><td>385</td></tr>
<tr><td colspan="2" rowspan="2">Total water supply</td><td>Water supplied per year and building (m^3) – A and C</td><td>281</td><td>319</td><td>332</td><td>338</td><td>281</td><td>319</td><td>332</td><td>338</td></tr>
<tr><td>Water supplied per year and building (m^3) – B</td><td>261</td><td>261</td><td>261</td><td>261</td><td>261</td><td>261</td><td>261</td><td>261</td></tr>
<tr><td colspan="2" rowspan="2">Demand satisfied</td><td>Demand satisfied per building (%) – A and C</td><td>60</td><td>43</td><td>33</td><td>26</td><td>60</td><td>43</td><td>33</td><td>26</td></tr>
<tr><td>Demand satisfied per building (%) – B</td><td>70</td><td>70</td><td>70</td><td>70</td><td>70</td><td>70</td><td>70</td><td>70</td></tr>
</table>

The *distribution stage* consists of polypropylene pipes (PP-copolymer) that conduct water from the tank to a laundry room (distribution strategy A), to the nearest apartments to the tank (B) or to each home laundry (C) for its end-use. Therefore, pipe length varies depending on the distribution strategy and the number of floors in the building. The U scenarios require a stainless-steel pump to supply rainwater to each dwelling, which were previously selected and optimized for each distribution strategy and building height. The power consumption over the lifespan of the system was calculated based on 6 minutes of pumping per wash load. In R strategies, it was assumed that the distribution system would have enough pressure to supply water to a washing machine by gravity.

The potential rainwater harvested is the same for all scenarios because roof area and annual rainfall remain constant, and was estimated to be 385 m^3/year (Table 1). However, the storage volume was optimized and considered constant (25 m^3) for all case studies because an increase in capacity did not represent significant gains in water collection, as identified by modeling the system using

Plugrisost v1.0 (Morales-Pinzón et al. 2012b). This software allows modeling the tank volume through a continuous daily water balance of supply and demand along the year according to a 90-year rainfall series. Due to the variability of rainfall, there will always be tank overflows in certain rainfall events throughout the year and that theoretical maximum would never be reached.

Additionally, water demand increases with the number of floors in the building for distribution strategies A and C. This promotes a more efficient performance of the water storage tank by collecting more water during rain peaks, which are very typical in Mediterranean climates due to the seasonality of the climate and the frequency and intensity of the rainfalls (for further details see Annex I.II). Therefore, the more the water demand rises, the more the rainwater supply will increase as well (Table 1) (Guisi 2009). In distribution strategy B, water demand is constant for all building heights because rainwater is delivered to a fixed number of floors (Table 1). For this reason, the total water supplied per year is constant and limited by the number of apartments.

4.2.3. Functional unit

An LCA approach was used to assess the environmental impacts related to the RWH infrastructures of the 24 scenarios proposed for tank location, building height and the demand distribution variable.

The FU was defined as the catchment, storage, and supply of 1 m^3 of rainwater per building per year to be used as non-potable water for a constant demand of laundry. This definition takes into account the catchment area per building, the available water to be supplied and the annual water demand per dwelling in Mediterranean climatic conditions.

4.2.4. Structural calculations

The roof tank is distributed over 633 m^2 of roof area (92% of the total roof) and has a depth of 4 cm, while the underground tank (5 m x 3 m x 1.7 m) has a rectangular base. Both tanks were equipped with an overflow system that releases rainwater directly into the sewer pipes when the tank is full. A minimum water level was always expected to be present in the tank (either rainwater or, alternatively, water from the mains). A tank top-up system facilitates a dual supply of water by means of a valve for both tank locations.

Data regarding materials and the sizing of the infrastructures were obtained with the structural calculation software CYPE v.2011 (CYPE 2011). The assumptions of the structural analysis (type of soil, criteria for reinforcement, etc.) can significantly affect the result (e.g., the foundation type or the materials used). To reduce this effect, a sandy soil with a high strength was selected, and the reinforcement was designed to optimize the amount of materials (minimizing the steel in the structure, maintaining the layout of the floors and the concrete in the foundation to keep the underlying stress). Additional data can be consulted in Annex I.I.

The rainwater storage tank lifespan was set at 50 years (Roebuck et al. 2010), principally limited by the evolution of technologies and changes in functionality over time. The uptake and distribution pipes and submersible pump were considered to have a useful life of 25 and 15 years, respectively.

4.2.5. Environmental methods

The LCA methodology assesses, from "cradle to grave", all the environmental impacts that concern a product, process or activity through the quantification and estimation of the resources consumed and the emissions produced. It consists of four main steps: definition of the objectives and scope of the study, inventory analysis, impact assessment and interpretation (ISO 14040 2006).

The inventory includes all materials and processes along the life-cycle stages of the infrastructure. The phases considered in the inventory were materials, transportation, construction, use and deconstruction for the catchment, storage and distribution systems. The materials stage comprises the extraction, production, processing and storage of materials used in the RWH infrastructure. In the construction stage, the energy costs include land excavation and the opening and closing of trenches. However, for the R scenarios, the use of machinery in the construction and deconstruction of the catchment and distribution stages was neglected because it is considered to fall within the purview of the building structure. Transport includes both local material transportation to the building site and waste transport to a local disposal facility. The use stage consists of the power demand (spanish mix) in the distribution stage for those scenarios with pumping requirements (U). The end of life of materials was considered outside the boundaries of the system because there is uncertainty regarding the technological development of recycling in 50 years' time. The database Metabase ITeC 2011 (ITeC 2012) provided operational energy consumption information linked to the construction and deconstruction stages.

In the LCA assessment, only the classification and characterization stages were considered. The impact categories selected were as follows: Abiotic Depletion Potential (ADP, kg Sb eq.), Acidification Potential (AP, kg SO2 eq.), Eutrophication Potential (EP, kg PO43- eq.), Global Warming Potential (GWP, kg CO2 eq.), Human Toxicity Potential (HTP, kg 1.4-DB eq.), Ozone Depletion Potential (ODP kg CFC-11 eq.) and Photochemical Ozone Creation Potential (POCP, kg C2H4 eq.). The method used to assess these categories was the 2001 Baseline v2.04 CML (Guinée et al. 2001). In this framework, the ecoinvent v2.2 (Hischier et al. 2010) database, linked to the software SimaPro 7.3.2 (PRé Consultants 2012), was used in the evaluation of all materials and processes.

4.3. Results and discussion

4.3.1. Inventory data

The inventory data take into account the amount of materials and energy required in each scenario for the FU defined and the lifespan of each component. These data were grouped into life cycle stages (materials, transportation, construction, use and deconstruction) and systems (catchment, storage and distribution). The detailed inventory is given in Annex I.III.

The underground tank scenarios (U) required from 3.4 to 5.7 times the total amount of material required in the roof tank scenarios (R), depending on the building height and the distribution strategy chosen. The largest amounts of materials were present in the storage system for both tank locations. In the U strategies, the concrete required to build the tank represented 97% of the total of this stage. For the R scenarios, the brick and the waterproof sheet contributed between 44% and 66% of this system, depending on the building height. The concrete requirements linked to the reinforcement of the building accounted for 26%-49% of the total amount of the storage. This reinforcing amount refers to the extra concrete required in the foundations to support the weight of the tank and the water stored, while the steel required in the reinforcement is located mostly in the building structure (71%-100%, increasing with building height) and partly in the foundations as well.

However, in the foundations, the steel and concrete reinforcement requirements did not increase linearly with building height. For this reason, the 15-story building required a proportionally smaller amount of reinforcing materials than the 12-story building. In any case, it can be considered that the structural increase required to locate a roof tank is negligible when compared with the building structure itself because this difference accounts for less than 0.5% of the total materials required in the construction of the building. Therefore, it is not necessary to consider depreciation in new construction for the roof tank scenarios because it can be considered to be within the repayment period of the building (Farreny et al. 2011b).

4.3.2. Environmental assessment of systems

The outcome of the environmental assessment is at first presented separately for the underground (U) and roof (R) tank scenarios, crossing the different building heights and distribution strategies (Figures 2 and 3). Subsequently, the environmental performance of the best case underground tank scenario (AU) is compared with the worst roof tank strategy (CR) for each impact category (Figure 4). The contribution of each system for each possible scenario is presented in Table 2, taking the GWP category as a reference.

(i) Underground tank impact assessment

For the U scenarios, the results showed that the distribution strategy A (laundry room) is the least environmentally impacting across all impact categories. It is followed by the supply to the nearest floors to the tank strategy (B), which shows a very marked difference from the distribution to all the apartments in the building (C) (Figure 2). This last difference becomes greater with more floors in the building (between 36% and 71%, depending on the impact category), increasing with a nonlinear tendency. This outcome is related to the use stage and the energy consumption of the distribution strategy, being more and more energy-demanding and requiring more powerful pumps with increasing building height (Angrill et al. 2012).

Distribution strategies A and B showed the same trend with differences between them and the building height remaining quite constant. However, the B strategies implied an increase in impacts between 32% and 48% compared to the A strategies, depending on the impact category selected.

(ii) Roof tank impact assessment

The results showed that the least impacting strategy in all cases is having a laundry room in the ground floor (A), while the B and C strategies presented different tendencies depending on the impact category chosen (Figure 3).

Although strategy C presented a growing tendency correlative with the number of floors due to the more need of materials, the most impacting scenario was not always the 15-story building, but rather the 12-story building for EP, ODP, HTP and POCP impact categories. The same trend was observed for the B-strategy scenarios in all impact categories analyzed (Figure 3). This is due to the behavior of the reinforcement of the building. The reinforcement required to support the weight of the tank affects the upper building structure and the foundations, but these two locations have different performances when more floors are added to the building. The upper structure requires more strengthening (more steel is added) the taller the building is, following a linear growth pattern.

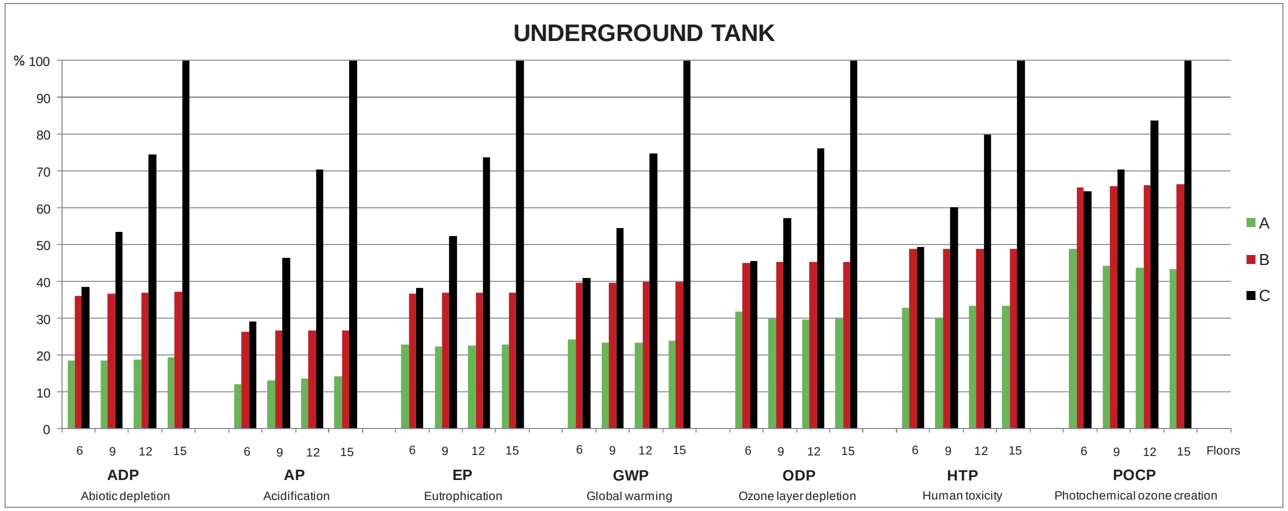

Figure 4.2. Impact assessment comparison of underground-tank scenarios (U) for each building height (6, 9, 12 and 15 floors) and distribution strategy (A-laundry room; B-nearest floors; C-all building)

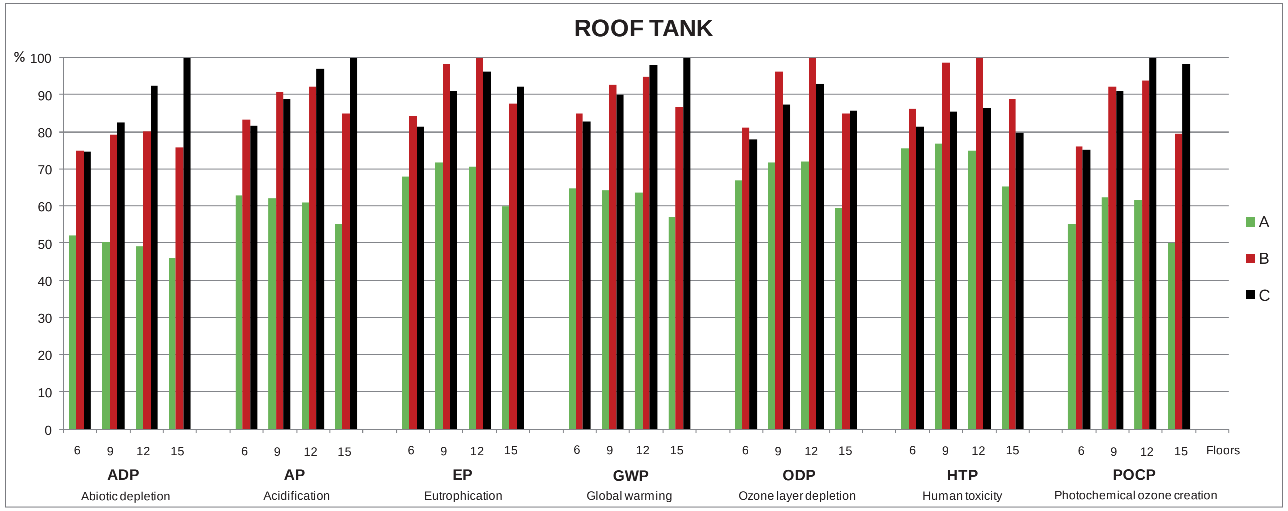

Figure 4.3. Impact assessment comparison of roof-tank scenarios (R) for each building height (6, 9, 12 and 15 floors) and distribution strategy (A-laundry room; B-nearest floors; C-all building)

In contrast, the reinforcement requirements of the foundations are directly related to the tank area, which remains constant with the building height; therefore, the added amount of reinforcement (mainly concrete) is smaller when the number of floors increases. Hence, from the 12-story building on, less reinforcing steel and concrete is required to support the weight of the tank, which, in relative terms, means that the difference of material required is smaller for the 15-story building compared to the requirements of the 12-story building.

Moreover, unlike in the U scenarios, the B strategy performed worse environmentally than the C strategy for the 6- and 9-story building scenarios (except for the ADP impact category) and in three out of seven impact categories (EP, ODP and HTP) for the 12-story building, with differences that ranged from 1% to 13%. These results are due to the nature of the water supply and demand, which remain constant with building height for the B strategies and always supply to a fixed number of apartments. By contrast, in the C strategies, the amount of water available per building increases in line with the building height, affecting the FU definition and resulting in lower relative impacts when compared to the B strategies. However, the differences in absolute terms are not significant when compared with the underground tank impact results.

It can be concluded that the rainfall pattern affects the design of RWH infrastructure. This analysis was conducted under Mediterranean climatic conditions, characterized by frequent dry long periods and intense rain events that can involve more than 50% the annual precipitation. These rain peaks allow an increase in the water supply together with the building height. A sensitivity analysis should be conducted to assess how local conditions affect the results and, more concretely, how they influence the distribution strategy chosen.

(iii) Comparison of roof and underground tank scenarios

Figure 4 represents the environmental performance of the best U scenario, based on a centralized laundry (AU), compared with the worst choice R scenario, with a distribution to all apartments in the building (CR), presented for each impact category.

Figure 4 shows that the absolute values for the less environmentally friendly roof-tank scenario (CR) were between a 6% and a 66% better than the best option for the underground tank (AU), depending on the building height and the impact category chosen, except for ADP. In this category, the waterproof sheet installed at the base of the roof tank to avoid infiltration, together with the PP distribution pipes, which increases in amount with building height to supply water to all the apartments (C strategy), had the most significant contribution (accounting for 85% to 91% of the total). A similar converging trend was observed for the GWP and POCP impact categories.

Absolute results indicated that, in general, the U scenarios presented greater impacts than their R equivalents in all impact categories, especially regarding distribution strategy C because, for underground tanks, the impacts increase following a polynomial trend with the number of floors in the building. This increase is associated with the pumping energy consumption for the 50 years span of the infrastructure, which the infrastructures under R scenarios that deliver water by gravity do not consume. Further, it is pointless to supply water throughout the building (C strategy) when laundry demand cannot be fulfilled 100% with rainwater in Mediterranean climates. Distributing water to a laundry room (A) is the most environmentally efficient option and is most likely the most cost-efficient option as well. The planning and implementation of RWH infrastructures should therefore take into account a proper collective demand management of the building in compact-density urban settlements.

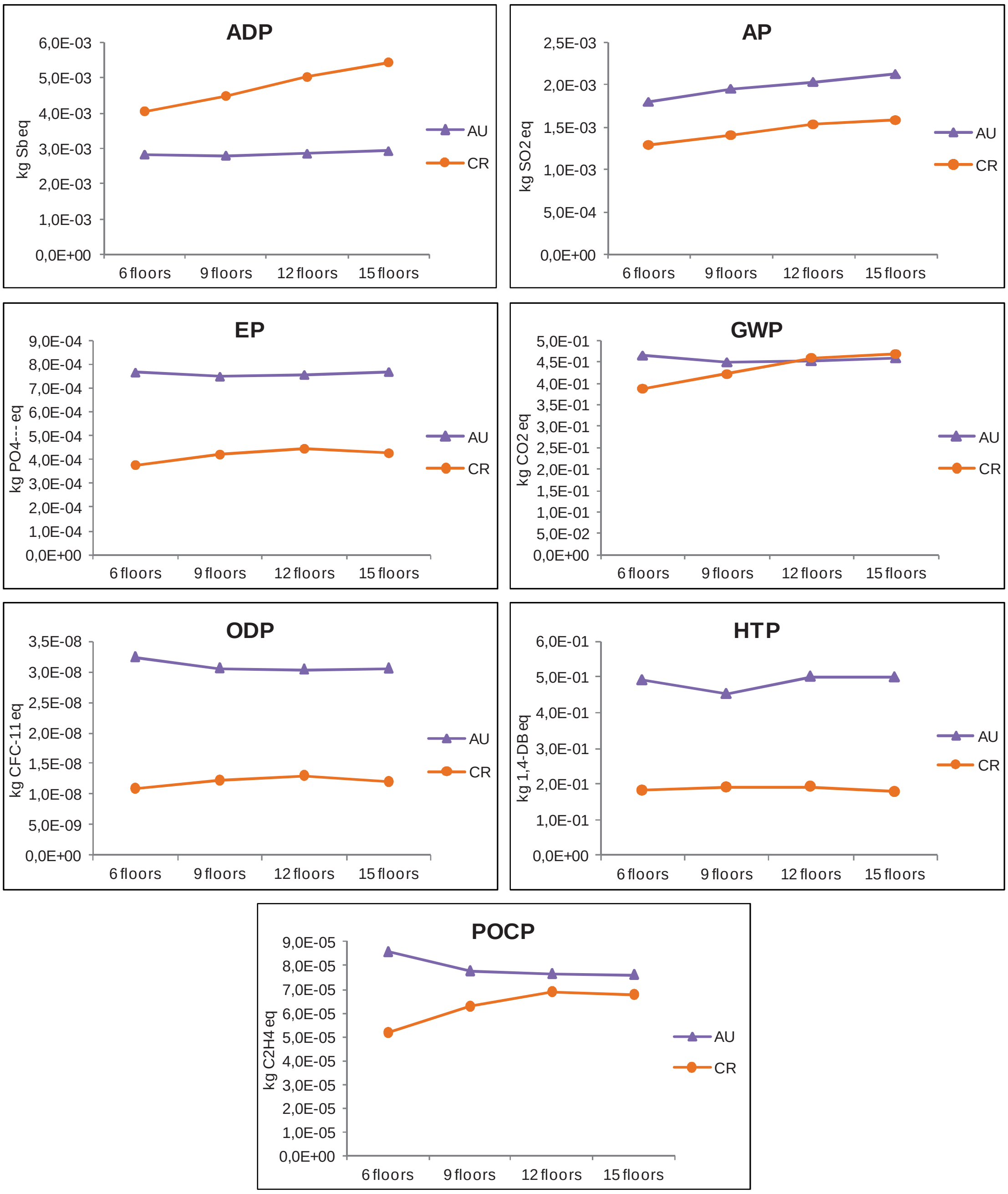

Figure 4.4. Impact assessment comparison of the underground-tank scenarios (AU) and the roof-tank scenarios (CR) for each building height and impact category
Source: Own elaboration

(iv) Contribution of the life-cycle stages

The GWP impact category was chosen because of its current importance in climate change in exemplifying the contribution of each life-cycle stage of the RWH infrastructure. Nevertheless, all impact categories analyzed showed generally similar trends.

Table 4.2. Impact contribution of all stages within each building height for each distribution strategy and tank location (R- roof and U-underground tank) according to the GWP category

Building height	Distribution strategy	A. Laundry room		B. Nearest floors		C. All Building	
		R	U	R	U	R	U
6 FLOORS	**HARVESTING** (%)	0.0	19.6	0.0	12.9	0.0	11.6
	STORAGE (%)	**96.9**	**73.1**	**79.8**	**48.1**	**75.9**	43.2
	DISTRIBUTION (%)	3.1	7.3	20.2	39.0	24.1	**45.2**
	Total absolute value (kg CO_2 eq.)	3.0E-01	4.7E-01	4.0E-01	7.6E-01	3.9E-01	7.9E-01
9 FLOORS	**HARVESTING** (%)	0.0	18.4	0.0	13.3	0.0	7.9
	STORAGE (%)	**96.4**	**66.6**	**81.5**	**47.9**	**68.8**	28.6
	DISTRIBUTION (%)	3.6	15.0	18.5	38.8	31.2	**63.5**
	Total absolute value (kg CO_2 eq.)	3.0E-01	4.5E-01	4.4E-01	7.6E-01	4.2E-01	1.0E+00
12 FLOORS	**HARVESTING** (%)	0.0	18.1	0.0	13.6	0.0	5.7
	STORAGE (%)	**95.7**	**63.6**	**81.9**	**47.7**	**62.2**	20.0
	DISTRIBUTION (%)	4.3	18.3	18.1	38.7	37.8	**74.3**
	Total absolute value (kg CO_2 eq.)	3.0E-01	4.5E-01	4.4E-01	7.7E-01	4.6E-01	1.4E+00
15 FLOORS	**HARVESTING** (%)	0.0	18.1	0.0	14.0	0.0	4.3
	STORAGE (%)	**94.4**	**61.5**	**80.2**	**47.5**	**53.7**	14.7
	DISTRIBUTION (%)	5.6	20.4	19.8	38.5	46.3	**81.0**
	Total absolute value (kg CO_2 eq.)	2.7E-01	4.6E-01	4.1E-01	7.7E-01	4.7E-01	1.9E+00

For the R scenarios, the storage life-cycle stage was the main contributor to the GWP impacts of RWH infrastructures in all building heights due to the reinforcement requirements to withstand the weight of the tank and the water (Angrill et al. 2012). The relevance of the storage stage decreased with a distribution strategy focused on the nearest floors (B) (81% contributor to the impact compared to 95% in A). The distribution stage became even more relevant with strategy C, for which the storage account loads are from 54% to 76%, depending on the number of floors in the building. This last fact is due to the progressive importance of PP distribution pipes in strategy C for taller building heights and the lesser importance of the reinforcement, which does not grow linearly with the number of floors. Indeed, it can be concluded that building height is not relevant to reinforcement requirements because these can be accounted for within the safety factors of the building structure without the tank; therefore, they are negligible when compared to the whole building.

For the U scenarios, the distribution strategy was the main contributor in scenarios where rainwater was supplied to all the apartments in the building (C). There are differences of magnitude by building height (accounting for 45% to 81% of the total), a fact strongly related to the pumping energy requirements associated with the whole lifespan of the infrastructure to deliver rainwater to taller buildings (Angrill et al. 2012).

The absolute values for the GWP category highlighted the U scenarios as the environmentally less preferable option. The roof tank scenarios reduced their impact between 33% and 42% in the A distribution strategies, depending on the building height considered, from 42% to 48% in the B strategies and even more in the C strategies (decreasing from 51% to 76%) (Table 2). We can conclude that the R scenarios would be less impacting for having a decentralized distribution to all the building (C), although it is not the most ecoefficient strategy, while for the U scenarios, a common laundry room would always be preferable.

4.4. Conclusions

The results indicate that a roof tank is in all the examined cases less environmentally detrimental than an underground tank. For instance, for a 15-story building with harvested water distribution to all the apartments, the reductions in impacts due to tank location range from 61% to 89%, depending on the impact category. A roof tank location enhances energy and material savings and most likely contributes to more energy-efficient buildings because the water in the tank may act as a thermal insulator (further studies should address this issue).

The distribution strategy chosen was found to be the most important factor in the optimization of RWH infrastructures. Within the roof tank scenarios, a distribution strategy than concentrates demand in the ground floor, enabling water to flow by gravity to the washing machines, was the environmentally optimal option resulting in impact reductions from 25% to 54% depending on the building height.

This washing strategy that concentrates all demand in a laundry room is well known in the service sector, being currently used worldwide in penal institutions, hotels, university campuses and nursing homes. However, it has never been a widespread practice in residential buildings of developed Mediterranean countries, which are highly water-demanding due to their easy access to potable water and which, simultaneously, suffer from frequent water shortages. Therefore, a behavioral change on demand should be promoted to a more sustainable and environmentally conscious society that optimizes resources and reduces its footprint.

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Part III

Rainwater harvesting quantity and quality assessment

Chapter 5. Rainwater harvesting from urban spaces and traffic roads: quantity and quality assessments in Spain

Chapter 5 is based on the following paper:

Angrill, S., Morales-Pinzón, T., Josa, A., Rieradevall, J., & Gabarrell, X. (2013) Rainwater harvesting from urban spaces and traffic roads: quantity and quality assessments in Spain. Water Research (Submitted September 2013).

5.1. Introduction

In the context of transition towards sustainability, one of the major challenges facing modern societies is the provision of water, a resource that is increasingly recognized as valuable while the quantity and quality available is decreasing (Sazakly et al, 2007; Fletcher et al, 2008). The growing evidence of water scarcity worldwide and the need for cooperation and integration to ensure sustainable, efficient and equitable water resources highlight the benefits of rainwater harvesting (RWH) as a free local source. This can help reduce the collection and treatment infrastructure for drinking water as well as the management and treatment of wastewater in addition to having a greater control of floods (van Roon, 2007; Zhu et al, 2004; Fletcher et al, 2008). In this context, there is still a lack of knowledge on the study of public urban paved spaces as potential collectors of runoff water since focus has been mainly put on roof covers until now. Moreover, the quantitative and qualitative potential of these alternative surfaces has not yet been studied yet in depth from a monitored point of view in water-stressed climates such as the Mediterranean. These are being adapted to the expected consequences of climate change. Therefore, the aim is to provide criteria for the (re)design of urban spaces from a sustainable water management perspective taking into account available urban components that have been forgotten so far.

5.1.1. RWH from urban spaces

Since roofs represent approximately half of the total sealed surface in cities, it can be assumed that at least 40% of paved urban surfaces correspond to streets, squares and other open-space public areas. Until now these spaces have been neglected for RWH purposes, although they act as runoff catchment and conveyors. In Mediterranean climates, when strong storm water events occur during the year, rainwater together with wastewater is usually sent directly to the sea. Water volume can exceed water treatment plants capacities (Llopart-Mascaró et al, 2010). Our approach is to evaluate the potential of open urban spaces to be used as RWH systems and therefore to use runoff water for public maintenance activities such as green parks and garden irrigation or street cleaning, for example.

The assessment of the quantitative potential of RWH and the quality of runoff water from different urban spaces is crucial in order to determine which functions this water is suitable for. In this sense, two characteristics of urban paved surfaces have been selected since one research hypothesis proposed that they might influence runoff quantity as well as quality. On one side, the surface material (characterized by a certain smoothness, porosity, conservation degree, others) and on the other, the surface use or activity that takes place on the surface (i.e. traffic road, pedestrian path). The main target is to set up criteria for policy makers and urban planners to select the most adequate pavement surfaces from an approach of water self-sufficiency and cyclic metabolism of urban spaces. Experimental results were intended to be compared with an analogue case study conducted by Farreny et al. (2011) where the potential quantity and quality assessment of roof surfaces was also determined in urban areas.

5.1.2. Runoff quantity and quality

The calculation of the RWH potential of a surface can be estimated multiplying the annual local rainfall by the catchment area and a dimensionless coefficient named runoff coefficient (RC) (McCuen, 2004; Viessman and Lewis, 2003). This coefficient represents the amount of water that becomes runoff from the total incident rainfall volume of the surface. This difference is lost due to leakages, surface material retention and evaporation (Singh, 1992). Therefore the RC can be used to determine the potential RWH of a certain surface. So far, RC values for roads, streets and other urban spaces range from 0.5 to 0.95 (TxDOT, 2009; Ragab et al, 2003) depending on the bibliographic source consulted (Liaw and Tsai, 2004; Ward et al, 2010).

Due to the wide variability of the data the calculation of the RC for local and specific surfaces needs to be able to predict the potential RWH with a higher accuracy, since it depends on environmental and climatic factors (rainfall intensity, winds, antecedent dry period) and on the specific characteristics of the surface (slope, material, smoothness, others) and its nearby environment.

On the other hand, the factors that influence runoff quality vary from roof geometry and material, location of the surface and maintenance, rainfall events and other meteorological factors (mainly climatic seasonality and antecedent dry period) and concentration of pollutants in the atmosphere (Abbasi and Abbasi, 2011). In this sense, the quality of storm water has become along the past decades of great interest for sanitary institutions and a barrier to the implementation of RWH systems, mainly motivated by the presence of microbial presence in runoff water (Adeniyi and Olabanji, 2005; Simmons et al, 2001). In addition, there is still a lack of information and quality data about RWH quality data from open urban spaces; which is more pronounced in southern Europe that present different rainfall regimes (frequencies and intensities) in a milder climate. Thus, the interest of monitoring several urban surfaces is to complement quantity results with quality on-site information.

This research aims to assess the quantity and quality of runoff water collected from several urban paved surfaces located in the north of Spain, therefore under a Mediterranean climate, to provide criteria on the most suitable type of surfaces for the optimization of RWH. These results might lead towards the sustainability of urban areas and the ideal redesign of the Mediterranean cities in the context of climate change.

5.2. Materials and methods

5.2.1. Case study area

Seven different catchment surfaces have been selected in the Universitat Autonoma of Barcelona (UAB) campus, located in Cerdanyola del Vallès (Barcelona, Spain), since it is a public urban area transited by pedestrians and vehicles. The area presents a semi-wet Mediterranean climate with an average annual rainfall and temperature of 514 mm and 15.5 °C, respectively (SMC, 2013). The university campus is located in a green environment nearby Collserola range and less than 1km distance from a motorway with dense traffic.

The characteristics of each surface are shown in Table 1. The selection of catchment areas has been done according to two criteria: surface material and type of use. The seven surfaces have been grouped on pedestrian paths or areas (PA), traffic roads (R) and car parks (P). For each surface use the most common materials have been selected, which consist on asphalt (A), concrete (C) and precast concrete tiles (T), the latter only applies to PA areas since it is a common material used in this type of paved surfaces. Our research hypothesis is that these two parameters (material and use of the surface) might influence significantly the quantity and quality of urban spaces runoff.

Table 5.1. Characteristics of the catchment surfaces.

Roof	Material	Use	Slope (º)	Roughness	Orientation (º)	Catchment area (m2)	Environment description	UTM Coord.
APA	Asphalt	**Pedestrian area**	3º	Rough	35º NE	15.7	Urban environment (some trees nearby)	425234,0 E; 4595078,0 N
TPA	Precast concrete tile		6º	Smooth	130º SE	15.7	Urban environment (one side bounded by a building facade)	425954,0 E; 4594941,0 N
CPA	Concrete		5º	Rather rough	305º NW	19.8	Urban environment (no trees but a building nearby)	425200,0 E; 4595040,0 N
AR	Asphalt	**Road**	2º	Rough	12º N	40.2	Urban environment (small trees and some buildings nearby)	424818,0 E; 4594934,0 N
CR	Concrete		45º	Rather smooth	180º S	142.7	Urban environment (one side bounded by a building facade)	424657,0 E; 4594777,0 N
AP	Asphalt	**Parking**	3º	Rough	45º NE	21.2	Urban environment (small trees and a building nearby)	425235,0 E; 4594914,0 N
CP	Concrete		9º	Rather smooth	20º N	9.3	Urban environment (no trees but some buildings nearby)	425666,0 E; 4594751,0 N

5.2.2. Experimental design

A rainwater harvesting conveyance and storage system was installed in each study surface. All selected surfaces were located topographically higher than the storage tank in order to allow the storm water to flow by gravity to it, thereby avoiding major building constructions and road works. The experimental design consisted of delimiting the catchment area and installing the system components which consisted on a gutter and a downpipe that conducted water to one or two polypropylene storage tanks of 1 m3 as it is shown in Figure 1. A common membrane filter (0.28 mm pore diameter) was installed at the entrance of the storage tank to prevent leaves and other large objects from entering the tank. No first flush diversion was installed for any of the systems and there was no maintenance of the catchment surface along the experimental period. However, pipes and gutters were frequently cleaned out of sand, leaves and other pollutants while the storage tanks were rinsed with pressurized water twice a year.

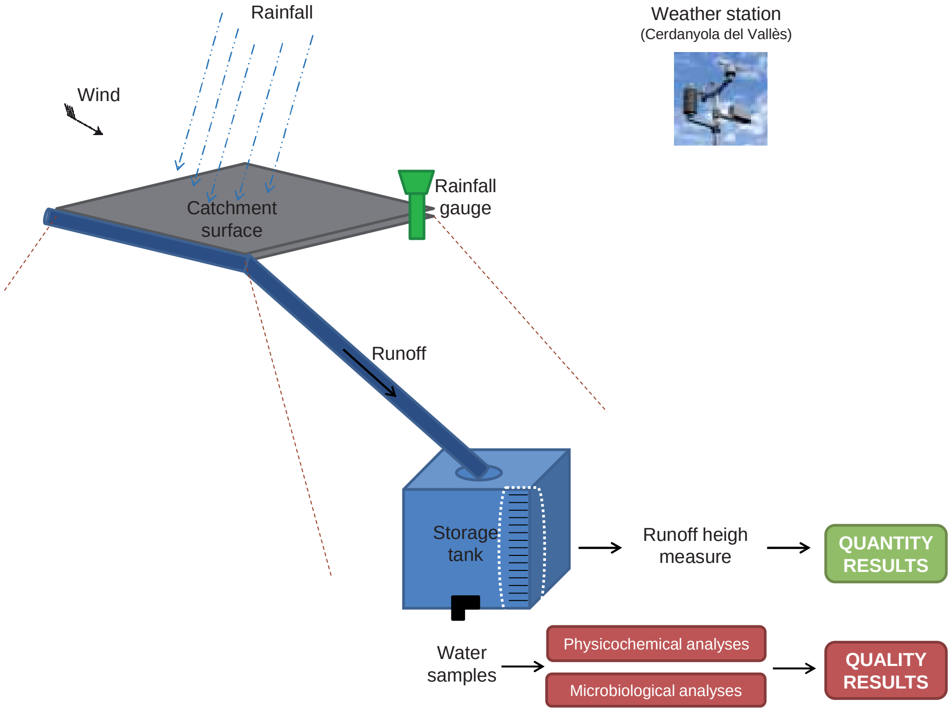

Figure 5.1. Rainwater harvesting system installation and experimental design diagram.

Along a period of 22 months of experimental campaign (June 2011 to April 2013) quality and quantity data from 25 different rain events were collected. Rainfall events of less than 2.4 mm were excluded because runoff was insufficient. Local rainfall was monitored with a rain gauge set nearby each catchment surface.

5.2.3. Quantity assessment

(i) Data collection

The variables recorded after each rainfall event needed to perform the quantity assessment were the following: the rainfall height (monitored locally with the rainfall gauges and contrasted with the weather station measures of Cerdanyola del Vallès) and amount of water collected; duration of the event; minimum and maximum temperatures; predominant wind orientation and speed; and antecedent dry weather period (ADWP). After the measures were taken the storage tank and rainfall gauge was emptied.

The selected number of valid events used for the quantity calculations (when runoff was generated but did not exceed the tank capacity) for each catchment surface together with the ADWP and the rainfall height range are presented in Table 2.

Table 5.2. Rain events considered in the determination of the RC for quantity analysis.

QUANTITY ASSESSMENT			
Roof	**# monitored events**	**ADWP range (days)**	**Rainfall range (mm)**
APA	16	3 - 45	2.4 - 66.8
TPA	15	3 - 45	2.4 - 66.8
CPA	12	3 - 30	2.4 - 24.6
AR	12	3 - 30	2.4 - 66.8
CR	16	3 - 29	2.4 - 38.2
AP	15	3 - 45	2.4 - 66.8
CP	15	3 - 45	2.4 - 66.8

(ii) Data analysis. Determination of runoff coefficient

The aim of the quantity assessment was to determine the initial abstraction of each type of catchment surface and the runoff coefficient (RC) of each surface.

First of all a correlation analysis was conducted by means of the statistical software PASW Statistics 20 (IBM Corp, 2011) taking into account the amount of runoff depending on rainfall height. In all cases the assumptions were verified.

Once verified, linear regression models were performed with the recorded dataset to estimate the initial abstraction of each surface. This concept refers to the amount of rainfall that is retained by the surface material or lost by infiltration and therefore is not present in the direct runoff, which is the amount of water actually collected by the tank (McCuen, 2004).

The calculation of the RC for each surface consists on estimating the real runoff of each rain event and dividing the total runoff per year by the annual rainfall (Farreny et al, 2011). Data regarding the local rainfall profile was provided by the weather station of Cerdanyola del Vallès (automatic station owned by the Meteorological Service of Catalonia) for the last 10-year period.

5.2.4. Quality assessment

(i) Sample collection, physicochemical and microbiological analysis.

After each monitored rain event two water samples (V=0.5 L each) were taken from the rainwater contained in the storage tanks. One sample was used to perform the physicochemical analysis and the other to determine the microbiological, hydrocarbons (HC) and metal content. After that, the tank was emptied and made ready for the next rainfall event. Samples were kept refrigerated until their delivery to the laboratory. The composition of the sample represents the Event Mean Concentration (EMC) of that event, which refers to the total amount of pollutant present on the site during the rain event divided by the amount of rainfall collected (Bertrand ‐ Krajewski et al, 1998).

The recorded number of rainfall events analysed together with the rainfall and ADWP range for each surface are presented in table 3.

Table 5.3. Rain events considered for sample collection for quality analysis.

QUALITY ASSESSMENT						
	Physicochemical			Microbiological, Hidrocarbons and metals		
Roof	# monitored events	Rainfall range (mm)	ADWP range (days)	# monitored events	Rainfall range (mm)	ADWP range (days)
APA	16	2.4 - 66.8	3 - 45	6	2.4 - 34.5	5 - 45
TPA	14	2.4 - 66.8	3 - 45	7	13.2 - 34.5	5 - 45
CPA	13	2.4 - 66.8	0 - 30	4	2.4 - 24.6	3 - 19
AR	13	2.4 - 66.8	0 - 30	4	2.4 - 24.6	3 - 19
CR	16	2.4 - 66.8	3 - 45	6	2.4 - 34.5	5 - 45
AP	13	2.4 - 66.8	3 - 45	6	13.2 - 34.5	5 - 45
CP	14	2.4 - 66.8	3 - 45	6	13.2 - 34.5	5 - 45

The physicochemical parameters analysed comprise the following: pH and electrical conductivity (EC) at 20° C measured with a pH meter ORION 701A and a conductivity meter ORION 101; alkalinity (HCO3-), ammonia (NH4+) and phosphate (PO43 ‐) analysed by segmented flow colorimetry (AutoAnalyzer3 Bran&Luebbe); chloride (Cl-) and sulphate (SO42 ‐) measured with a conductivity detector (Waters 431), nitrite (NO2-) and nitrate (NO3-) determined by a UV-Visible detector (Waters 2487) at a wavelength of 214 nm (anionic column IC-Pack Anion 4.6 x 50 mm Waters); Total Suspended Solids (TSS) measured by membrane filtration (Whatman filters of 47 mm diameter and 1.2 micron pore); Total Organic Carbon (TOC) and Chemical Oxigen Demand (COD) analysed by IR spectrometry (TOC Analyser) and colorymetry (Spectroquant NOVA 60 Merck), respectively.

Microbiological analyses were conducted by common seed and count in culture mediums for colonies at 22 and 37°C, total and faecal coliforms, Pseudomonas aeruginosa, Clostridium perfringens, Enterococcus, which correspond with the most common indicators in water analysis. The Total Petroleum Hydrocarbon (TPH) of the samples was determined by gravimetry (petroleum ether extraction with Soxhlet equipment, vacuum pump and filtration funnel). The metal content was measured with plasma emission spectrometry (ICP-OES) for chrome (Cr), nickel (Ni), copper (Cu), zinc (Zn), mercury (Hg), cadmium (Cd), lead (Pb), iron (Fe) and arsenic (As). Data results below the European legislation thresholds for drinking water purposes (EC, 2010) were not further obtained.

(ii) Data analysis

The data analysis was also conducted with the aid of the software PASW Statistics 20. Descriptive statistics were obtained for each parameter and type of surface expressed as maximum and minimum values, the mean (with standard deviation) and the median.

Then, the dataset was subjected to a variance and correlation analysis. The variance analysis detects if differences in the mean or median concentration of compounds in the studied surfaces were statistically significant. Since data did not satisfy the one-way ANOVA test conditions (data distribution did not follow a normal distribution) the test of Kruskall-Wallis, suitable for k-independent samples, was performed.

Finally, a correlation analysis was conducted to determine the degree of association between water quality parameters among themselves and its association with the storm characteristics (total rainfall height and ADWP). This analysis was performed for the whole set of surfaces by means of the Spearman Rho correlation coefficient.

5.3. Results and discussion

5.3.1. Quantity assessment

Results show that the correlation between rainfall height (P) and surface runoff (R) is high (Pearson coefficient >0.9) for four out of seven studied surfaces: APA, CR, TPA and CP. These results can be seen in Figure 2 where the regression models ($R=mP+n$) are shown for each catchment surface (R = runoff; P = rainfall height). All the regression models have proved to be statistically significant ($p<0.05$). However, in any of them the constants values for the y-intercept (n), which are related with the initial abstraction estimations, are significant in statistical terms. Therefore, conclusions and extrapolations of these results should be addressed carefully.

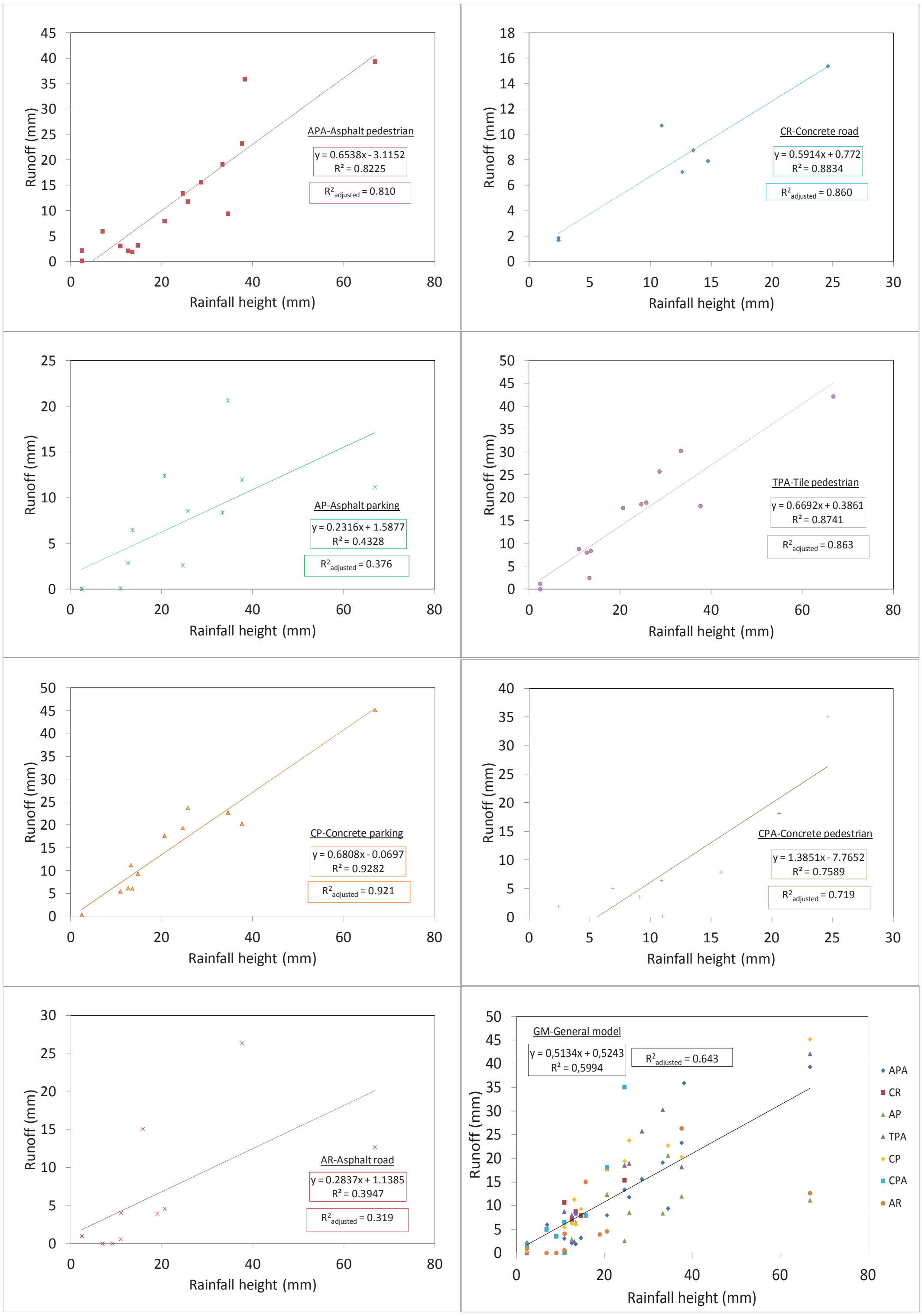

Fig 5.2. Regression models for surface runoff and rainfall height presented for each catchment surface. Regression equations and corrected R2 are also shown. Each point represents a monitored rain event.

(i) Initial abstraction

It was expected that different surface materials would present different values for the initial abstraction. This is due to the initial water retention and runoff behaviour that occurs in the surface during the first rainfall volume (Göbel et al, 2007). The initial abstraction includes water losses before runoff begins that are due to water retention in surface depressions, evaporation and infiltration processes (Corbitt, 1998). Therefore, this phenomena is also influenced by the surface slope and texture. The initial abstraction was estimated by means of the linear regression formulae for each surface from where it was extracted to the point where the regression line intercepts the x axis (-n/m). Although the obtained data is correct, the statistical evidence suggests that more samples are needed in order to obtain a statistically significant estimation of the initial abstraction of the studied catchment surfaces. The values obtained are 4.8 mm and 5.6 mm of initial abstraction for APA and CPA, respectively. APA is made of asphalt, material that has been proved to have a high retention potential when combined with a low slope (3°). However, the results obtained for CPA (concrete surface) are even higher and this can be due to the roughness of the surface. The CP (concrete) surface initial abstraction resulted to be close to 0. This result value differs significantly from the CPA, which is also concrete-made. The finish of the surface when it was first built, diminishing its roughness, could be a reason for those differences. It might be argued that a certain amount of initial abstraction must be related to this surface but results show that it is so close to zero that it was not possible to determine it with the collected data available.

In addition, it should be taken into account the effect of wind intensity and direction (Villarreal and Dixon, 2005) as well as the nearby infrastructures that delimitate the surface (buildings, trees,…) since both factors directly influence the effective collection area of each surface. The authors suggest that this might be a possible reason for the lack of significance of the y-intercept estimation for any of the selected catchment surfaces.

(ii) Global runoff coefficient

The following equation was used to calculate the RC of those surfaces that have proved to be significant according to the Pearson correlation test:

$$\mathbf{RC = R / P}$$

RC is affected by the local climatic characteristics of the area, specifically by the rainfall profile. Therefore, it should be kept in mind that the study was performed in a semi-wet Mediterranean area and results will differ in other climatic regions.

Regression models were used to calculate the runoff for those rain events that exceed the initial abstraction. The RC values obtained according to the gathered experimental runoff data and the precipitation data obtained from the weather station of Cerdanyola del Vallès (Meteocat, 2013) during the period 1999-2009 for the studied urban surfaces are presented in Table 4.

Table 5.4. Runoff coefficient values (RC) and standard deviation (sd) for each atchment surface.

Urban surfaces	Acronym	RC ± sd
Asphalted pedestrian área	APA	0.43 ± 0.03
Concrete road	CR	0.82 ± 0.02
Asphalted parking	AP	0.61 ± 0.05
Tiled pedestrian área	TPA	0.82 ± 0.01
Concrete parking	CP	0.73 ± 0.00
Concrete pedestrian área	CPA	0.85 ± 0.08
Asphalted road	AR	0.56 ± 0.04
General model		0.76 ± 0.02

Results show higher RC values associated with concrete surfaces that range between 0.73 and 0.85. The precast concrete tile surface has been included in this classification since the surface material is also concrete. On the contrary, asphalted urban surfaces present values from 0.43 to 0.61 which could also be related with the texture of the pavement materials. APA shows a very low RC due to the roughness and degradation state of the surface's material, results that agree with the high initial abstraction estimation obtained before.

These results were contrasted with those found by Farreny et al (2011) in several roof surfaces of the UAB campus as well during the period 2008-2010 preceding with the same experimental design criteria than the ones presented in this study. In this research metal and plastic roof covers, that present a smooth surface, were given RC values over 0.9. Besides, ceramic tiles that consist of a more porous material with a higher interception capacity showed a lower RC (0.84). Finally, the flat gravel roof presented a RC of 0.62, much lower than the others due to the almost absence of slope and the high water retention capacity (greater interstitial pore space). Therefore, a special attention should be placed on the surface slope since exist significant differences exist between them as well as to the material's texture and conservation degree, which influence to a great extent the RC resulting value. However, no statistical evidence was found to prove the effect of variables such as the ADWP, the wind direction and the annual thermal variability on the tested models.

Looking the results from another perspective, porous surfaces with a high water retention capacity may become relevant for storm water management prevention in urban areas. Thus, selecting a paved surface with a low RC would increase runoff retention and therefore flood prevention (Farreny et al, 2011; Yu and Zhao, 2012).

5.3.2. Quality assessment

There are a wide variety of pollutant sources in urban environments that directly or indirectly affect runoff quality such as the atmospheric pollution, animal waste, road traffic, pavement weathering and erosion, drain gates corrosion, public works and debris and others related to the anthropogenic use of the surface (Simmons et al, 2001; Villarreal and Dixon, 2005; Sazakli et al, 2007; Skaryska et al, 2007; Llopart-Mascaró, 2010).

Table 5 presents the descriptive statistics extracted from the dataset results of the water samples taken along the experimental process. The minimum and maximum values, the mean and standard deviation together with the median are given for the whole set of urban surfaces. Also, the table compares the results obtained by Farreny et al (2011) from roof surfaces as well as the thresholds established by the European regulation Drinking Water Directive (DWG) 98/83/EC that set the water quality guidelines for human consumption (EC, 2010). In the end, the values extracted from regional surface and groundwater watercourses that are the current raw water sources in the region are also provided for an extended comparison. The quality values correspond to the location where water is extracted and transferred for water purification to the treatment plant (ACA, 2013).

(i) General assessment of the runoff quality for the whole set of roofs

The pH range of the samples varies from 6.9 to 8.6, with a slight alkalinity tendency that can be due to the predominance in the region of winds that come from the northern part of Africa and the related dry atmospheric deposition (Farreny et al, 2011; Göbel et al, 2007). Besides, the low presence of sulphates, nitrates and other ions found might have an influence as well in the alkalization of the collected rainwater. In this pH range undesired chemical reaction that occur along the storage period are generally avoided (Zhu et al, 2004).

EC is a leading indicator of the dissolved ion content and results show low values when compared to the DWG and to surface and underground water sources. This is a common characteristic found in rainwater (Göbel et al, 2007). A worst case result was included in the analysis and corresponds to a snowfall event. In this sample 27,150 μS/cm was found in the pedestrian surface CPA due to the anthropogenic addition of salt to help people falling and major injuries caused by the snow.

Most pollutants are mainly associated with sediments. In this research TSS median values are low (8 mg/L) when compared with similar studies (Kayhanian et al, 2007). Although nowadays there is nowadays no legislation for this parameter in the DWG a value under 25 mg/L is considered as an excellent water quality. As well, there is no threshold for TOC values in water for human consumption. Results show higher values than the ones found in the other natural water sources and even better than the results found in the roof surfaces study case. However, TOC concentration below 20 mg/L corresponds to a good water quality. The same tendency was shown in COD (median value 16 mg O2/L) which resulted 3 times higher than the DWG legislation and higher as well than surface and underground sources. The conveyance of rainwater from ground-level surfaces implies a higher concentration of organic matter and other pollutants accumulated on the floor which is later diluted into the collected water. Moreover, sulphates, NOx and other organic compounds can also be related to trafficked surfaces since they are commonly used as fuel additives or emitted during its combustion. TOC and COD results were compared with analogue case studies and have resulted to be of much better quality than these others (i.e. Kayhanian et al (2007), Göbel et al (2007) and Nolde (2007).

Table 5.5. Urban paved surfaces runoff quality results.

Parameter	Units	Case study urban paved surfaces					Case study roofs[a]					DGW[b]	Surface and groundwater sources[c]		
													1	2	3
Physical-chemical parameters		min	max	mean	sd	med	min	max	mean	sd	med	Limit	mean	mean	mean
pH	upH	6,90	8,60	7,79	0,34	7,80	6,64	8,85	7,59	0,07	7,61	6,5-9,5	8,17	7,92	7,52
Conductivity	µS/cm	38	27150	455,09	2717,70	123,00	15,35	456	85,03	9,98	59,25	2500	1402,6	419,6	3175,5
SST	mg/L	2	171	16,26	22,96	8,00	0	38,5	5,98	0,95	3,63	-	87,00	2,34	n.a.
TOC	mg C/L	1,00	39,00	6,87	6,06	5,40	0,65	53,60	11,56	1,72	6,40	-	4,04	1,76	0,50
COD	mg O2/L	10	144	25,08	24,36	16,00	n.a.	n.a.	n.a.	n.a.	n.a.	5,00	15,24	15,00	n.a.
HCO_3^-	mg/L	34,0	222,0	66,02	26,87	56,00	n.a.	n.a.	n.a.	n.a.	n.a.	-	259,23	160,86	209,05
Cl^-	mg/L	2,0	355,9	19,67	54,66	5,00	0,15	119	8,86	2,38	3,38	250	275,7	33,2	978,2
SO_4^{2-}	mg/L	5,00	101,00	12,65	14,33	8,00	0	11,5	3,54	0,39	2,59	250	173,5	54,7	218,4
NO_2^-	mg/L	0,05	6,60	0,36	0,93	0,13	0,00	3,45	0,13	0,05	0,00	0,1	0,61	0,16	0,05
NO_3^-	mg/L	0,57	41,81	4,20	6,21	2,41	0,01	9,34	1,75	0,26	1,16	50	10,15	8,82	4,89
PO_4^{3-}	mg/L	0,31	1,50	0,38	0,20	0,31	0,00	6,60	0,32	0,14	0,00	-	0,47	0,08	n.a.
NH_4^+	mg/L	0,10	10,00	0,50	1,10	0,19	0,04	2,42	0,5	0,07	0,42	0,50	0,86	0,09	0,18
Microbiological parameters															
Colonies at 22ºC	ufc/mL	2450	6120000	318308	1037444	26500						100/ml	n.a.	n.a.	n.a.
Colonies at 37ºC	ufc/100mL	1670	1150000	98100	228934	18800						20/ml	n.a.	n.a.	n.a.
Total coliforms	ufc/100mL	30	616000	34786	109159	2500						0	34628	44	n.a.
Fecal coliforms	ufc/100mL	4	143000	7630	26832	128						0/250ml	9128	16	n.a.
Pseudomonas aeruginosa	ufc/100mL	0	168000	7725	29419	46						0/250ml	n.a.	n.a.	n.a.
Clostridium perfringens	ufc/100mL	0	140	18	28	6						0	n.a.	n.a.	n.a.
Enterococcus	ufc/100mL	1	41000	3114	8047	355						0/250ml	n.a.	n.a.	n.a.
Hidrocarbons															
TPH	mg/L	2,0	9,8	3,66	2,82	2,00					PAH (µg/l)	0,10	7,69	6,75	n.a.
Metals															
Cr	µg/L	4	13	4,51	1,80	4,00						50,00	0,00	0,00	1,00
Ni	µg/L	7	7	7,00	0,00	7,00						20,00	0,01	0,01	5,72
Cu	µg/L	10	41,2	12,37	8,35	10,00						2,00	0,00	0,00	19,99
Zn	µg/L	7	191	31,74	38,73	11,00						-	1,76	0,03	83,28
Hg	µg/L	1	1	1,00	0,00	1,00						1,00	0,00	0,00	n.a.
Cd	µg/L	2	2	2,00	0,00	2,00						5,00	0,00	0,00	n.a.
Pb	µg/L	25	25	25,00	0,00	25,00						25,00	0,01	0,01	2,50
Fe	µg/L	15	440	72,10	93,73	37,00						200,00	0,04	0,02	n.a.
As	µg/L	5	8	5,08	0,48	5,00						10,00	0,00	0,00	n.a.

n.a. = not available . a) Results from Farreny et al, 2011; b) Drinking Water guidelines; c) Source 1, 2 and 3 correspond to quality data from Llobregat river, Ter river and Llobregat delta aquifer, respectively

Inorganic nitrogen was found mainly as nitrates (median value 2.4 mg/L) although this concentration is far below the DWG threshold and the amounts found on the other water sources. Their origin could be very diverse. In this case it might come from animal faeces, fuel combustion, soil and dry deposition of molecules of this compound. Ammonia and nitrites are also low according to the legislation. Ammonia results differ from the ones found by Farreny et al (2011) which were 2.2 times higher. This fact can be explained by the greater presence of bird faeces on roofs which are more common than at ground-floor level. Parallel to these results, sulphate concentrations are low as well, which implies low interferences with pollution originated by industrial facilities and traffic emissions.

Microbial results are found to be less positive since legislation does not allow faecal bacteria to be present at any concentration in human consumed water. In all collected samples microbial and pathogen registers associated with the analysed categories were found (> 1 CFU/100 mL). Besides, total coliforms in water may come from a faecal but also from other origins such as soil and vegetation and thus, its presence in urban open areas was expected due to the presence of dust and plant material and may not indicate just a faecal contamination source (Ahmed et al, 2011). The results are in concordance with those obtained by Kwaadsteniet et al (2013) where a review of international studies that assess the microbial quality of roof-collected rainwater was performed. Besides, a great number of individual studies have agreed with the poor microbiological quality of urban spaces runoff due to high levels of bacterial contamination (Sazakli et al, 2007; Nolde 2007; Zhu et al, 2004), although the amount found vary greatly depending on the environment and the maintenance of the surface. Therefore, the effort should focus on the installation of a water treatment (or combination of them) to clean rainwater from pathogens. A membrane or granular-activated carbon filter together with chemical disinfection with chlorine is highly recommended and the most spread practice (Sazakli et al, 2007). In addition, solar UV water treatment, slow sand filtration and finally heat treatment (if water is intended for hot water uses) could improve significantly microbiological water quality (Kwaadsteniet et al, 2013).

TPH include a big family of compounds with origin in the crude oil and some derivatives, while PAH (Polycyclic Aromatic Hydrocarbons) corresponds to a group of polycyclic HC included in the TPH aggregation. PAH compounds are created by the inefficiencies in engine combustion and stand out for their effects on human and animal health and therefore its concentration in water is expected to be more restrictive than TPH. In general, hydrocarbons have shown not to be a problem in our samples since they were found at very low doses (median value 2 mg/L). In most samples, no further information was given by the laboratory further than <2mg/L, which is the lowest detection limit of the equipment used in the measurements. Therefore, results shown in this table present the worst case scenario recorded. The same analytical limitation was found for Cu, with a lowest detection limit of 10 μg/L and therefore above the DWG thresholds. Zn values, which together with Pb are the more related with road trafficked surfaces (Nolde, 2007) due to tyre wear, motor and lubricating oil, grease and bearing wear (Ball et al, 1998; Helmreich et al, 2010), appeared to be also high though no legislation was found for this metal. Despite this, the other analysed metal concentrations found are consistent with the DWG directive.

It should be taken into account for a more complete and precise interpretation of these results that factors such as the storage time until the sample was taken together with the ADWP and the seasonal fluctuation may have a significant influence in microbiological (as well as in physicochemical) results, since most microbial present an logarithmical growth in a convenient environment (Zhu et al, 2004; Kayhanian et al, 2007).

Moreover, the overall runoff quality obtained is directly influenced by the first flush phenomena. As a result of not diverting the first few millilitres that contain the main concentration of pollutants the whole water quality is affected. In practice, a simple first flush diverter would increase runoff quality significantly (Villarreal and Dixon, 2005).

(ii) The effect of rainfall height and ADWP on runoff quality

The correlation between rainfall height and the EMCs of the analysed compounds was run to evaluate to which extent the dilution process of pollutants had a dependency on the amount of incident rainfall on the catchment surface (Kim et al, 2007). Table 6 present the results from the Spearman Rho correlation analysis for all analysed water quality parameters).

Significant and negative correlations ($p<0.05$) were found between rainfall height and the following parameters: EC and Fe (Spearman Rho correlation coefficient $0.5< |r| <0.8$), COD, HCO3-, Cl-, NO2-, NO3-, SO42- and NH4+ (Spearman coefficient $|r| <0.5$).

Furthermore, the ADWP parameter was correlated as well with the others to determine the existence of a significant statistical correlation between the pollution load of the samples and the antecedent period without precipitations. Results found were positively significant for TOC, COD, NO2-, NO3-, SO42-, PO43- and NH4+. The Spearman coefficient ranged from 0.280 to 0.557). At the same time, an inverse correlation was found between ADWP and pH (Spearmen coefficient $|r| = 0.311$) which can be related with an acidification processes that occur due to the accumulation of compounds such as sulphates and nitrates in the atmosphere and surface during the dry period.

Other significant direct correlations were found between EC and TOC, COD, HCO3-, Cl- and SO42- ($0.5< |r| <0.8$) as well as with NO2-, NO3-, PO43- and NH4+ ($|r| <0.5$). This dependency is due to the relationship between EC and ionic compounds. Significant correlations were also obtained between ammonia and HC ($|r| = 0.754$) since ammonia can be used as antistatic additive in polymers, between pH and Cu ($|r| = - 0.530$), between any combination of the parameters TOC, COD, HCO3-, SO42 ($0.5< |r| <0.8$) and between NO2- and NO3- ($|r| = 0.669$) as it was expected. Obviously, total and faecal coliforms are also positively correlated as well as faecal coliforms and enterococcus and colonies at 22 and 37°C. Unexpected inverse correlations were found between enterococcus and HC for which no explanation was possible.

Table 5.6. Spearman Rho correlation coefficients between the water quality parameters for all catchment surfaces.

p<0.05;p<0.01. The colour-shaded cells indicate the degree of correlation (green: |r|<0.5, blue:0.5<|r|<0.8, red |r|>0.8)*

		Physical-chemical parameters												
		Rainfall	pH	EC	TOC	COD	HCO_3^-	Cl^-	NO_2^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	NH_4^+	SST
Physical-chemical	ADWP	,121	-,311**	,166	,557**	,280**	,144	,046	,366**	,489**	,306**	,305**	,369**	,159
	Rainfall		,085	-,502**	-,029	-,446**	-,358**	-,266**	-,404**	-,286**	-,387**	-,209*	-,323**	-,118
	pH			-,060	-,311	-,302**	-,181	,124	-,314**	-,244*	-,200*	-,145	-,341**	,320**
	EC				,547**	,678**	,716**	,724**	,339**	,377**	,793**	,381**	,202*	,255*
	TOC					,752**	,600**	,426**	,399*	,409**	,605**	,465**	,387*	,137
	COD						,575**	,464**	,310**	,392**	,665**	,410**	,333**	,089
	HCO_3^-							,254*	,432**	,465**	,614**	,417**	,344**	,034
	Cl^-								,020	,038	,519**	,203*	-,100	,276**
	NO_2^-									,669**	,416**	,240*	,502**	-,056
	NO_3^-										,492**	,409**	,452**	,040
	SO_4^{2-}											,422**	,313**	,164
	PO_4^{3-}												,358**	,144
	NH_4^+													-,020

		Microbiological parameters							HC	Metals				
		Colonies 22ºC	Total coliforms	Fecal coliforms	Pseudomonas aeruginosa	Clostridium perfringens	Enteroc.	Colonies 37ºC	TPH	Cr	Cu	Zn	Fe	As
	ADWP	,213	,118	-,166	-,023	-,032	-,258	,232	,359	-,256	-,184	,126	-,365*	,000
Physical-chemical	Rainfall	,018	,007	,065	-,151	,026	-,068	,003	-,088	-,166	-,239	-,090	-,569**	,000
	pH	-,418**	-,305	-,306	,159	,404*	-,031	-,332*	-,254	,294	-,530**	-,315	,221	,188
	EC	,227	,161	-,037	,166	,022	,114	,142	,188	,024	,193	,329*	,233	,202
	TOC	,104	,069	-,164	,223	-,241	-,150	,115	,349	-,101	,231	,067	-,099	,245
	COD	,241	-,098	-,135	-,003	,009	-,131	,076	,352	-,059	-,123	-,003	-,026	,267
	HCO_3^-	,106	,180	,005	,060	-,239	,074	,099	,177	,117	,121	,379*	,033	,245
	Cl^-	,156	,152	-,097	,227	,246	,089	,152	,097	,052	,142	,162	,480**	,130
	NO_2^-	,112	,145	-,036	-,008	-,236	-,067	,143	,325	,060	,078	,404*	,009	,202
	NO_3^-	,108	-,036	-,211	-,227	-,188	-,202	,087	,468*	-,020	-,072	,206	-,251	,232
	SO_4^{2-}	,195	,101	-,094	,064	-,108	-,062	,056	,479*	,113	,155	,324*	,111	,261
	PO_4^{3-}	-,006	,111	-,006	,161	-,361*	,174	,139		,102	,177	-,035	-,146	,390*
	NH_4^+	,208	-,143	-,226	-,261	-,267	-,349*	,150	,754**	,024	,000	,214	-,066	,130
	SST	,178	,144	,134	,230	,105	,202	,267	,071	,027	-,146	,131	,398*	,261
Microbiological	Colonies 22ºC		,187	,284	-,070	,177	,195	,749**	,096	-,153	,082	,117	,124	-,216
	Total colif.			,546**	,348*	-,233	,506**	,462**	-,287	-,083	,342*	,235	,016	-,202
	Fecal colif.				,478**	-,137	,818**	,300	-,437	,034	,248	,133	,030	-,156
	P. aeruginosa					,156	,478**	,163	-,481*	-,123	,258	,003	,068	-,087
	C. perfringens						-,122	,116	-,311	-,041	-,308	,015	,278	-,218
	Enterococcus							,405*	-,728**	,126	,155	,054	,199	,029
	Colonies 37ºC								-,151	-,112	,188	,252	,048	-,234
HC	TPH									,084	,017	,112	-,042	,000
Metals	Cr										-,218	,071	,292	,493**
	Cu											,372*	-,068	-,224
	Zn												,163	-,178
	Fe													,117

(iii) Differences in water quality between urban surfaces

Figure 5.3 presents in box diagrams the water quality results obtained during the experimental period from the runoff collected for each urban surface studied.

After executing the Kruskall-Wallis test for independent samples significant differences were found between catchment surfaces and the following analysed parameters: pH, EC, COD, NO3-, Cl-, NO2-, HCO3-, SO42-, SST, Zn and Fe (Figure 3).

The precast concrete tile pedestrian area (TPA) presents the highest quality runoff water. Two reasons may support this outcome. On one hand, the pedestrian area is not located on a busy area of the university campus and therefore is not much transited. This probably helped in keeping it cleaner than the other urban surfaces studied. On the other hand, the tile's surface is quite smooth and that might avoid the accumulation of particles and retention of pollutants. According to the previous results initial abstraction was found to be around 0, which supports this explanation as well.

On the contrary, asphalted surfaces have shown the worst water quality results. In particular the asphalted pedestrian area (APA) presents the highest values for COD, NO3-, HCO3- and SO42-. This surface belongs to a campus square build at the same time that the UAB university, which has existed more than 40 years. It is very crowded because of its location and those factors probably accelerated the material weathering. The surface shows deposition of particulates, associated flora on them, sand, seeds and other anthropogenic waste that together with the roughness of the material would have favored this outcome. Besides this, the lack of slope aids the development of these processes. The asphalted parking (AP) also shows the worst results for NO2- parameter probably related with the traffic emissions and particles deposition.

Finally, concrete-built urban areas present a good runoff water quality for most analysed physicochemical indicators. However, CPA (concrete pedestrian area) shows extremely high chlorine records due to a punctual snowfall event and its anthropogenic counteraction (salt addition) to avoid falls and injuries. High values were found as well for SST on this surface that can be due to its frequency of use because it is located near the entrance of a university faculty. Moreover CPA presents the worst Fe mean value that can be related with the corrosion of the metal drain gate installed for the runoff collection. This was assumed as the origin of higher metal records for Fe in this catchment surface.

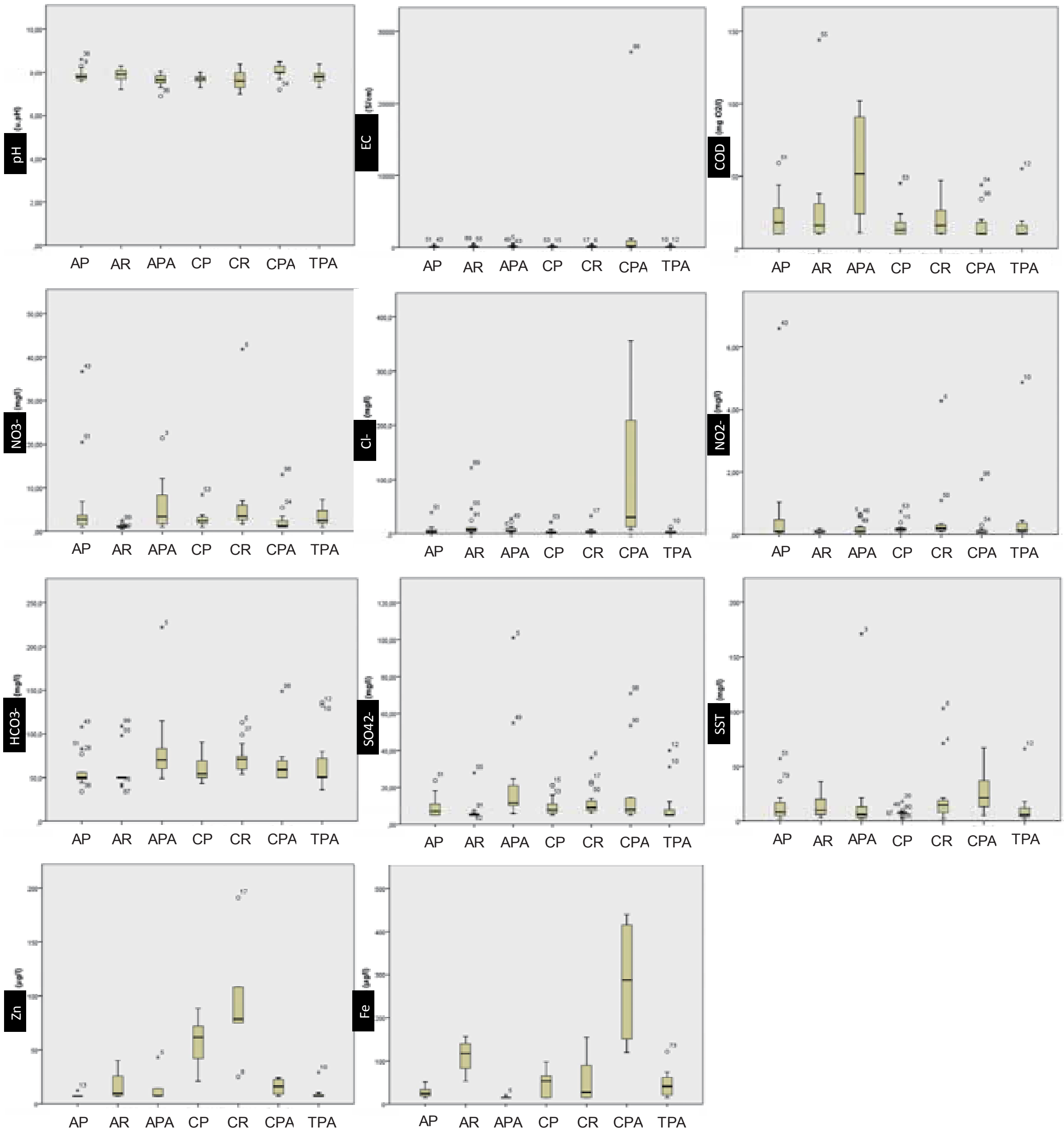

Figure 5.3. Box plot diagram of catchment runoff water quality for each urban surface.
Abbreviations: AP = asphalted parking; AR = asphalted road; APA = ashpalted pedestrian area; CP = concrete parking; CR = concrete road; CPA = concrete pedestrian area; TPA = tiled pedestrian area.

The only correlation associated with the surface use was found for CR, CP and AR which all correspond with trafficked surfaces and present as well high concentrations of Zn. This metal is one of the most common in roads as an organometallic compound derived mainly from tyre wear (Ball et al, 1997; Davis et al, 2001; Helmreich et al, 2010). For this reason other studies propose porous pavements as a solution to runoff pollutants derived from vehicles (Shutes et al, 1999; Yu and Zhao, 2012)

From these results, one can affirm that runoff water quality is highly determined by the catchment surface material (and its conservation state). The type of activity developed in the surface resulted only relevant for highly-pollutant surface uses such as traffic areas. Further studies should extend both materials as well as surface uses in order to validate with a wider margin these results. In particular, the microbiological content of runoff is a matter that should be addressed since it is of major concern for public administrators and sanitary institutions.

5.4. Conclusions and recommendations

In the light of the results obtained it can be stated that physicochemical runoff quality is outstanding when compared to surface and underground water sources. Proof of this is that for most parameters except COD runoff collection from urban spaces accomplishes the DWG directive thresholds for human water consumption. Metal and HC concentrations have appeared to be not significant. However, the treatment effort should be focused on microbial disinfection since all samples have traces of them and are considered a risk for most water applications and uses.

First flush diverters together with simple disinfection techniques applied during the conveyance and storage stages would improve runoff quality significantly.

Significant and inverse correlations ($p<0.05$) were found between the rainfall height and the pollution load of the samples. The ADWP parameter also had a significant direct correlation with the EMCs of most of the compounds found in the stored rainwater. Therefore, there is dependency between the amount of runoff and the dilution of the deposited pollutants as well as with the antecedent dry weather period and pollutant load diluted in the runoff.

Finally, results indicated that asphalted urban spaces due to its roughness are more likely for particulate deposition and accumulation which may become diluted in the runoff and are responsible for the decrease of the rainwater quality collected. On the contrary, precast tiles present a smoother surface that allows all deposited particles to be washed away with water leaving a cleaner surface behind and therefore a better quality runoff event by event. It should be taken into account that in practice first flush diverters should be installed in order to increase the collected water quality and a periodical maintenance of the public urban surfaces should be provided. Besides, the runoff from concrete urban surfaces presents an in - between quality.

In conclusion, it can be stated that although activities performed on the catchment surface affect to a great extent rainwater quality, in special traffic surfaces due to the highly pollutant nature of the activity, the surface material and its maintenance play a crucial role in conferring runoff water a higher or lower quality.

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Part IV

General conclusions and future research

Chapter 6. Conclusions

This dissertation presents and develops on one side which are the environmentally friendlier rainwater harvesting strategies to be applied in urban areas of water-stressed regions such as the Mediterranean area. On the other, it asseses the quantity and quality of runoff water to maximize its use as a non-potable valuable and remewable resource. **Chapter 6** addresses the main research findings based on the conclusions presented in Chapters 3 to 5.

Conclusions are structured as follows:

- Environmental assessment or rainwater harvesting strategies in Mediterranean regions
- Rainwater harvesting quantity and quality assessments

6.1. Environmental assessment of rainwater harvesting strategies in Mediterranean regions

The main conclusions from the theoretical case studies formulated in Part II are presented below.

Diffuse and compact urban density models

- In the context of drought-stress environments such as the Mediterranean region the use of endogenous local resources such as rainwater becomes a real possible solution to increase water supply. Besides, RWH is nowadays recognized as an available strategy to mitigate climate change repercussions.
- The estimation of potential 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 was performed. The outcomes of the LCA point out that the environmentally optimal infrastructure, regardless of urban density, is to locate the storage tank on the roof, which were considered flat as it is a common practice in Mediterranean areas, distributing all its weight on the building structure. By doing so, a considerable reduction of structural components was found. In addition, the absence of catchment components, since water is supplied by gravity to domestic laundry machines, and the adjustability of the tank to the shape of the roof are also advantages of this proposed scenario.
- The most environmentally critical stages associated with the life cycle or RWH infrastructures analysed was the extraction and processing of the tank materials and the structural reinforcement components. All these components were found to be very significant in the diffuse-density model, especially in the scenario with the tank placed on the roof, centred over a pillar, for which results show a relative contribution of more than the 95% of the total impact in all categories analysed.
- In general terms RWH systems applied to compact urban density models present lower environmental impacts than in diffuse urban models. However, this does not follow a linear trend and is highly dependent on the building reinforcement type as well as the pumping requirements. In compact urban densities the distribution stage becomes the most relevant, particularly in underground tank scenarios at building scale, which is related to the power consumption during the use stage of the infrastructure. This contribution is 78% of the total impact of these scenarios for the GWP category. Therefore, the distribution strategy chosen plays a decisive role when water is to be supplied to important heights.
- Significant CO_2 emissions savings can be achieved by the incorporation of the most beneficial RWH installation option during the planning and design stage of a new residential area. The possibility of integrating a tank distributed over the roof, rather than constructing an underground one in an existing building (the most practice option in retrofit actions), can reduce the environmental impacts up to 4.7 and 1.5 times in compact and diffuse urban models respectively.

- Additionally, the implementation of RWH in diffuse urban city models allows for almost total self sufficiency in water for laundry demand, although showing the greater total impact loads when compared to compact densities, as it was stated before due to economies of scale. Compact density models have shown lower unitary environmental impacts and higher water efficiency levels although they are characterized by a greater water deficit of around 47% of the demand met.

Distribution strategies at building scale

- The results of the previous research focused the analysis to extend other variables that directly affect the environmental load of RWH infrastructures. The building height and the distribution strategy within the building were combined with the tank location (roof or underground) to assess the environmental impact of RWH systems in compact neighborhoods. Results agree with conclusions from the previous study, since a roof storage tank was found to be in all examined cases, the least environmentally dretimental tank location. For instance, for a 15-story building with harvested water distribution to all the apartments, the reductions in impacts due to tank location range from 61% to 89%, depending on the impact category. Therefore, the installation of a roof tank enhances material and energy savings and very probably contributes to a more energy-efficient building due to its performance as thermal insulation (further studies should address this issue).
- The most relevant variable in the determination of the environmental impacts of RWH systems in buildings of different height was found to be the distribution strategy chosen. Therefore, considering a roof tank scenario and a distribution strategy that concentrates demand on the ground floor, enabling water to flow by gravity to the washing machines, was the environmentally optimal option, resulting in impact reductions from 25% to 54% depending on the building height. However, this is currently not a common laundry practice in residential buildings of the Mediterranean region since access to drinking water is extremely easy. For this reason a behavioural change should be proported in southern Europe towards a more sustainable and energy conscious society that optimizes resources and reduces its footprint.
- From these results it can be concluded that the implementation of one particular RWH scenario over another is significient. Selecting the most favorable scenario in the development of newly constructed residential areas provides significant savings in CO2 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.

6.2. Rainwater harvesting quantity and quality assessments

The main conclusions drawn from the experimental case study addressed in Part III are summarized in this section.

- A experimental design was conducted between June 2011 and April 2013 in the UAB university campus with the aim to assess quantitatively and qualitatively the runoff of open and public urban areas transited by vehicles and pedestrians. There are a great variety of pollutant sources that directly or indirectly affect RWH quantity as well as quality. Therefore, when analysing the results, it should be kept in mind the local climatic characteristics of the study area as well as the surrounding environment (presence of industries, highways with dense traffic…).
- As a result of the quantitative assessment of runoff in urban spaces RC values were estimated for all catchment surfaces and were found statistically significant. Results show higher RC values associated with concrete surfaces that range between 0.73 and 0.85 while on the contrary, asphalted urban surfaces present lower RC estimations (<0.61) which are mainly determined by the texture of the pavement materials and the degradation state of the surface. These results can be useful in order to maximize surfaces runoff conveyance to rainwater tanks (by means of selecting smooth pavements). Therefore, streets and roads are no longer just about providing connections between people and places but also about rainwater collection towards a more sustainable water cycle in urban areas.
- In the light of the qualitative results obtained it can be stated that physicochemical rainwater harvested from open urban areas such as roads, streets and parking lots is outstanding when compared to surface and underground water sources. All analysed parameters except COD accomplish the DWG directive thresholds for human water consumption. Metals and hydrocarbons have resulted not to be significant in the studied urban area. However, the treatment effort should be focused on microbial disinfection since all samples have traces of them and are considered a risk for many water applications and uses. First flush diverters together with simple disinfection techniques applied during the conveyance and storage stages would improve runoff quality significantly.
- Significant inverse correlations ($p<0.05$) were found between the rainfall height and the pollution load of the samples. Also, the ADWP parameter was found to have a direct significant correlation with the EMCs of most of the compounds found on the stored rainwater. Therefore, there is dependency between the amount of runoff and the dilution of the deposited pollutants, as well as with the antecedent dry weather period and pollutant load diluted in the runoff.
- Results indicated significant differences in runoff water quality between asphalted urban spaces and concrete-made ones. Due to its roughness, asphalted surfaces are more likely for particulate deposition and therefore greater interactions between rain and the accumulated particles take place, as they are diluted into the runoff and are responsible for the decrease of the

rainwater quality collected. On the contrary, precast tiles present a smoother surface that allows all deposited particles to be washed away with water, leaving a cleaner surface behind and a runoff of better quality, event by event. It should be taken into account that in practice first flush diverters should be installed in order to increase the collected water quality and a periodical maintenance of the public urban surfaces should be provided. Besides, the runoff from concrete urban surfaces presents an in - between quality.

- In conclusion, it can be stated that although activities performed on the catchment surface affect to a great extent rainwater quality, in particular traffic surfaces due to the highly pollutant nature of the activity, the surface material and its maintenance play a crucial role in conferring runoff water a higher or lower quality. These results provide criteria for the design and planning of cities, and are also relevant to answer one of the main concerns in taking the decision of implementing RWH systems, which is of storm water runoff quality. Moreover, they may be helpful for reducing water dependence in water scarce areas by maximizing runoff availability.

Chapter 7. Future research and strategies

Chapter 7 highlights some future lines of research that may be followed after this dissertation towards a sustainable management of rainwater harvesting in urban settlements. Some of them relate to one specific chapter of the dissertation, and others present general lines of action or research.

This chapter is structured as follows:

- Towards a sustainable rainwater harvesting management in urban areas

7.1. Towards a sustainable rainwater harvesting management in urban areas

In this dissertation there is a series of ecodesign proposals related to the implementation of RWH infrastructures in urban areas. The proposals aim to promote a change in the environmental sustainability of cities in regards to water self-sufficiency. However, a lot of effort should still be taken, mainly to complement these results, with social and economic vectors in order to have a holistic view of the subject.

Rainwater harvesting strategies applied to urban areas

- Conducting sensitivity analysis of the materials used in the tank, structural reinforcement, the use of pipes and pump would be useful in evaluating the representativeness of the results obtained in this dissertation and for the comparison of these outcomes with other alternatives.
- The possibility of offering a potential water surplus to nearby neighbourhood 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 buildings, with those for existing buildings.
- Field and laboratory work should be extended to a wider variety of surface commonly-used materials and linked to local environmental and climatic conditions in order to expand the quantitative and qualitative assessment of rainwater.
- Deeper investigation on low-impact technology for rainwater treatment and disinfection should be of major concern in the light of the microbiological results found in this dissertation.
- Further research should include an energy 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 holistically the most sustainable option, taking into account the cost-efficient of these infrastructures as well as the social perception and their repercussions on users. The integration of environmental, social and economic vectors in case studies of urban areas is a very relevant issue to be addressed, which due to a lack of time could not be further assessed in this dissertation. These results should come up with new water management model proposals that will lead to a more sustainable urban planning and the redesign of the cities of the future in a climate change context.
- 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.

- ❖ Regarding the comparison between RWH systems, conventional networks and alternative technologies it can be concluded that a priority 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 macro scale of the same order of magnitude and to include additional adjustments in order to make a consistent comparison.

Sustainable water management of urban areas

- ❖ There is a need in the design of new neighbourhoods and urban areas to include environmental criteria through new approaches and tools for the design and planning of sustainable water management urban systems. The most convenient scale of action should be determined in each case. However, working at smaller scales eases the detection of the critical variables as well as simplifying the decision-making process to local governments and planners. This process should include a life cycle approach in order to consider all stages of the water management infrastructures, from their construction to their removal.
- ❖ Informed action at an early stage (planning and design) of the urban area development avoids future retrofit costs, however this issue should be addressed more in detail through the entire life cycle of the infrastructures. On the other hand, retrofit actions regarding water management infrastructures are a necessary task in urban settlements around Europe due to the limited lifespan of the materials and components. Therefore, a huge effort should be proposed to study in depth how to redesign the urban environment with an urban sustainability perspective.
- ❖ To assess RWH management from a sustainable context the economic analysis performed should include not only direct costs but also the externalities caused by RWH. Some examples are flood prevention in urban areas, extra water reliability and reduction of water supply and treatment infrastructures). From the perspective of social issues such as general acceptance and maintenance of RWH systems, these should be addressed together with the periodic revision of the local and regional water management legislation on the topic.
- ❖ The potential of RWH systems to be used in touristic (diffuse or compact) urban is a topic of main interest due to the high water requirements of those urban environments. These studies should combine both climatic and demand seasonality and fluctuations from a holistic perspective.
- ❖ Moreover, the environmental results found should be complemented with other social and territorial tools such as Geographical Information Systems (GIS) and Data Envelopment Analysis (DEA), for instance.

Annexes

Annex I. Supplementary information for Chapter 4

The Annex I corresponds to the Supplementary information of the Chapter 4 that is based on the following paper:

- Angrill, S., Segura, L., Rieradevall, J., Gabarrell, X., & Josa, A. (2013) Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate. Water Resources Management (Submitted September 2013).

This first annex is divided in the following sections

- Initial hypothesis taken into account during the calculation of the building structure and the foundations
- Tank performance according to water demand and rainwater offer
- Detailed Life Cycle Inventory data concerning materials and processes for each scenario

Annex I.I. Initial hypothesis taken into account during the calculation of the building structure and the foundations

Structural calculations were performed using building calculation software that fulfills constructive and statutory minimum values and, therefore, were not intended to optimize the reinforcing results. Nevertheless, it was important to choose for the calculation the most real values in practice rather than the most adjusted ones.

The main considerations taken into account during the calculation of the upper structure and the foundations were the following:

Geometry of the upper structure: The geometry of the upper structure was predefined by adopting a unique geometry to each height. All apartments had the same distribution and geometry of beams and slabs.

- Pillars: Two geometry types, internal and external (all square in shape).

- Framework: The same reticular slabs for all floor cases were used.

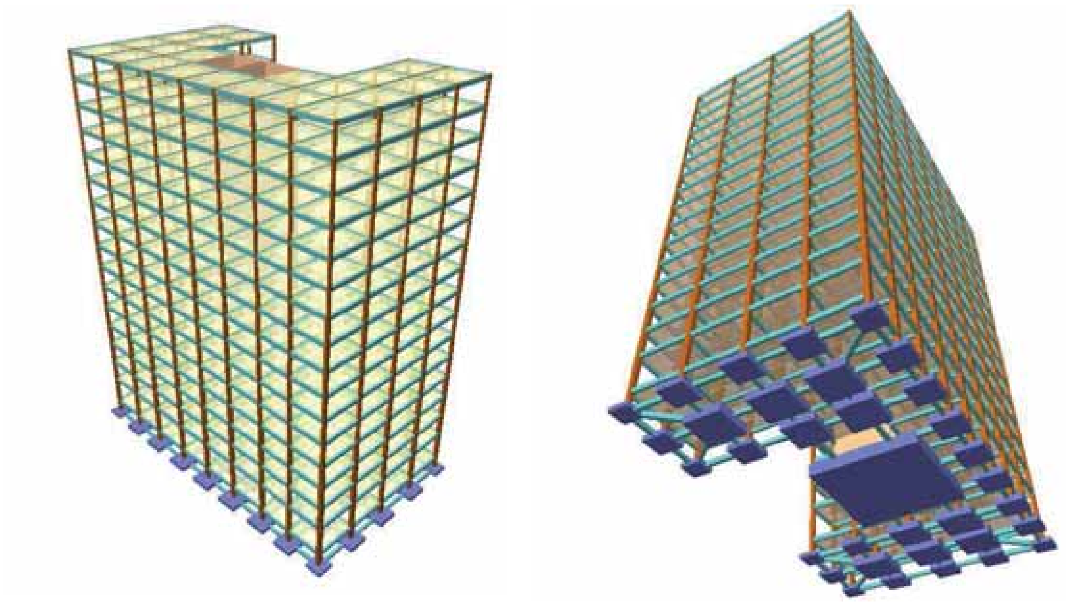

Fig1 Three-dimensional sketch of the structure and foundations of the fifteen-story building. *Source: CYPE v2011*

Geometry of the foundations: The geometry of the foundations was calculated by the program, according to an iterative process, which determines the required area so as not to exceed the soil strength. All footings were centered so that the foundation beams became mainly tie beams.

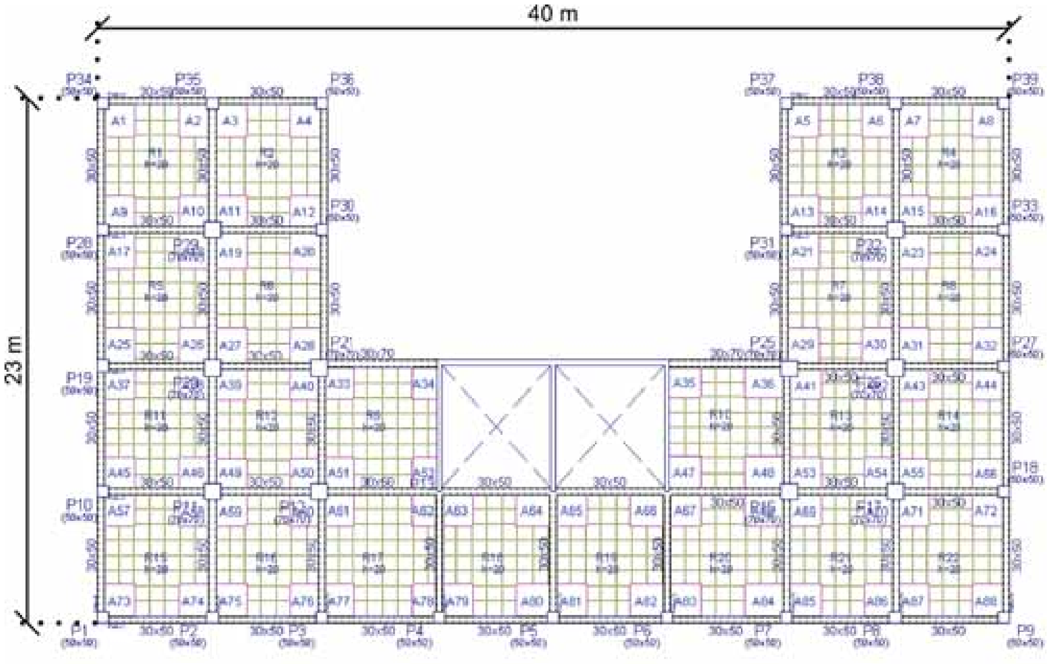

Fig2 Floor plan of the foundations of the fifteen-storey-building. Source: CYPE software

Structural loads (Table 1):

- Foundation level.

- Floor and upper slab structure: The floor corresponds to the slab structure in the ground level. Then, slabs are grouped into sets of 3, which is the difference between the number of slab structures in the buildings of different heights.

- Terrace: The top slab structure.

Table 1 Structural loads from the terrace, the floor and upper slab structure, and the foundation level

	Usage overload (kN/m^2)	Dead load (kN/m^2)
Terrace	1.7	2.0
Floor and upper slab structure	2.0	2.9
Foundation level	0.0	0.0

Soil strength: Soil strength was considered to be 0.363 MPa (corresponding to a coarse sand or gravel). This high soil strength value was chosen for all building heights with the same type of foundation.

Measurement: Blinding concrete was not taken into account within the foundations measurements.

Calculation and Sizing:

- Structural sizing and foundation reinforcement were calculated using the iterative method within Cype software. Because Cype optimizes the solution when the calculation is repeated, it was repeated 9 times to reach a stable solution.

- No calculation was made for wind; it was believed that it would have secondary influence on the reinforcing. However, central shear walls were set out to provide buildings with sufficient rigidity to resist this action. The geometry of the pillars was chosen so that the structural reinforcement was carried out with less than 25 mm of thickness. (A sufficient margin is left in the pillars as well to resist this action.)

-The increase of volume in the foundations added to the upper structure allowed the calculation of the necessary reinforcement to support the roof tank. However, the foundation volume increase does not imply an increase in the reinforcement steel.

- The data used in the environmental assessment was calculated as the reinforcement difference between the structure with and without a roof tank.

Annex I.II. Tank performance according to water demand and rainwater offer

Figure 1 illustrates the rainwater tank behavior taking into account the water demand (number of apartments per building) and the rainwater offer (rainwater supplied per year and building) for a constant tank volume (25 m3), rainfall (90-year-rainfall series) and catchment area (690 m2).

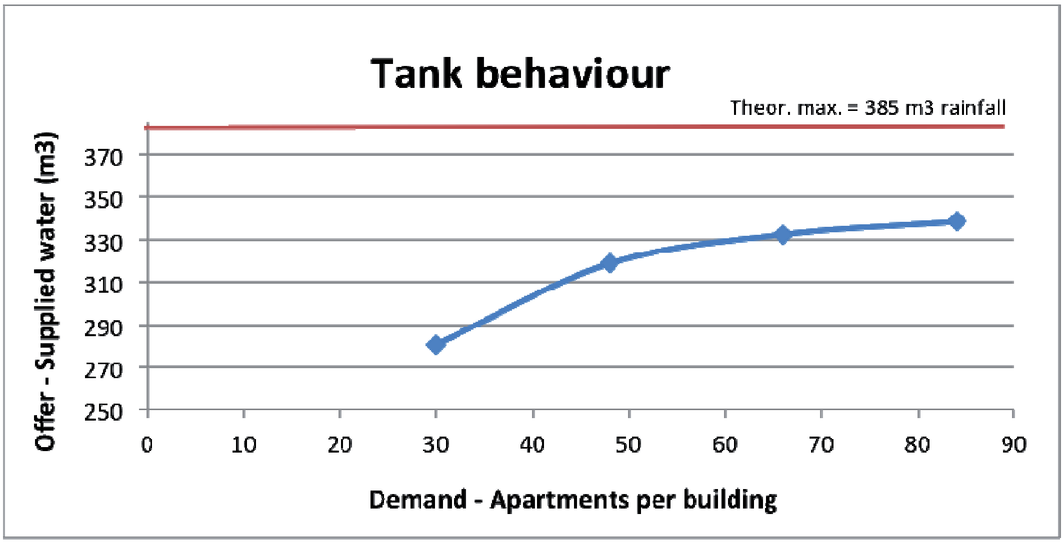

Fig3 Rainwater tank performance taking into account water demand and offer for a constant tank volume and catchment area

Water demand increases with the number of floors in the building (demand distribution strategies A –laundry room- and C –all the building-). This promotes a more efficient performance of the water storage tank by collecting more rainwater during rain peaks, which are very typical in Mediterranean climates due to the seasonality of the climate and the frequency and intensity of the rainfalls. Therefore, the more the water demand rises, the more the rainwater offer will increase as well. Figure 1 illustrates this tank behavior where a change in the slope of the curve indicates proximity to the maximum value (potential rainwater harvested per year and building), which is also determined by the tank size.

Annex I.III. Detailed Life Cycle Inventory data concerning materials and processes for each scenario

Table 1 Life Cycle Inventory of materials and processes for each scenario over the lifespan of the infrastructure

					ROOF TANK (R)				UNDERGROUND TANK (U)			
	Life cyle stages	**Components**			**6 floors**	**9 floors**	**12 floors**	**15 floors**	**6 floors**	**9 floors**	**12 floors**	**15 floors**
CATCHMENT	**Materials**	Pipe material	Galvanized steel (kg)		0	0	0	0	126.0	126.0	126.0	126.0
			PP (kg)		0	0	0	0	46.4	62.6	78.8	95.0
	Construction	Power consumption	Diesel (MJ)		0	0	0	0	648.6	648.6	648.6	648.6
	Transportation	Transport materials to site	Van <3.5t (tkm):30km		0	0	0	0	5.2	5.7	6.1	6.6
		Transport waste to manager	Van <3.5t (tkm):50km		0	0	0	0	9.1	9.9	10.8	11.6
	Deconstruction	Demolition energy	Diesel (MJ)		0	0	0	0	648.6	648.6	648.6	648.6
STORAGE	**Materials**	Tank material	Concrete 20MPa (m^3)		0	0	0	0	9.5	9.5	9.5	9.5
			Reinforcing steel frame (kg)		0	0	0	0	602.7	602.7	602.7	602.7
			Waterproof sheet(m^2)		632.5	632.5	632.5	632.5	0	0	0	0
			Brick wall (kg)		1398.5	1398.5	1398.5	1398.5	0	0	0	0
			Lining mortar (kg)		168.3	168.3	168.3	168.3	0	0	0	0
		Structural reinforcement	Reinforcing steel frame (kg)		142.3	250.0	258.2	165.2	0	0	0	0
			Concrete 20MPa (m^3)		0.5	0.9	1.2	0.6	0	0	0	0
	Construction	Power consumption	Diesel (MJ)		0	0	0	0	433.8	433.8	433.8	433.8
	Transportation	Transport materials to site	Lorry 16-32t; 30km (tkm)		118.0	151.6	176.0	129.7	672.2	672.2	672.2	672.2
		Transport waste to manager	Lorry 16-32t; 50km (tkm)		206.5	265.3	308.0	227.0	1176.4	1176.4	1176.4	1176.4
	Deconstruction	Demolition energy	Diesel (MJ)		43.5	43.5	43.5	43.5	1305.8	1305.8	1305.8	1305.8
DISTRIBUTION	**Materials**	Pipe material	PP-copolymer (kg)	**A**	52.4	68.6	84.8	101.0	36.0	36.0	36.0	36.0
				B	421.6	421.6	421.6	421.6	443.0	443.0	443.0	443.0
				C	527.0	843.2	1159.4	1475.6	548.4	864.6	1180.8	1497.0
		Pump material	Stainless steel (kg)	**A**	0	0	0	0	20.8	20.8	33.2	33.2
				B	0	0	0	0	36.8	36.8	36.8	36.8
				C	0	0	0	0	41.2	58.4	84.8	101.2
	Construction	Power consumption	Diesel (MJ)		0	0	0	0	648.6	648.6	648.6	648.6
	Transportation	Transport materials to site	Van <3.5t; 30km (tkm)	**A**	1.6	2.1	2.5	3.0	1.7	1.7	2.1	2.1
		Transport waste to	Van <3.5t;		2.8	3.6	4.5	5.3	3.0	3.0	3.6	3.6

		manager	50km (tkm)									
		Transport materials to site	Van <3.5t; 30km (tkm)	B	12.6	12.6	12.6	12.6	13.9	13.9	14.3	14.3
		Transport waste to manager	Van <3.5t; 50km (tkm)		22.1	22.1	22.1	22.1	24.3	24.3	25.0	25.0
		Transport materials to site	Van <3.5t; 30km (tkm)	C	15.8	25.3	34.8	44.3	17.1	26.6	36.4	45.9
		Transport waste to manager	Van <3.5t; 50km (tkm)		27.7	44.3	60.9	77.5	29.9	46.5	63.7	80.3
	Use	Pumping energy consumtion	Electricity (kWh/ 50years)	**A**	0	0	0	0	395.4	1385.9	1758.1	2107.8
				B	0	0	0	0	4187.8	4187.8	4187.8	4187.8
				C	0	0	0	0	5564.8	13422.2	23777.4	36550.5
	Deconstruction	Demolition energy	Diesel (MJ)		0	0	0	0	648.6	648.6	648.6	648.6