Modelling and sustainable management of rainwater harvesting in urban systems

By

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

Universitat Autònoma de Barcelona

Institut de Ciència i Tecnologia Ambientals · UAB

June 2012

This thesis was developed thanks to the Departamento Administrativo de Ciencia, Tecnología e Innovación (Colciencias - Colombia) and research projects with the Universidad Tecnológica de Pereira (Colombia) and the Ministerio de Ciencia e Innovación (Spain).

<< Bruscamente la tarde se ha aclarado
Porque ya cae la lluvia minuciosa.
Cae o cayó. La lluvia es una cosa
Que sin duda sucede en el pasado. >>
Extracto del poema
"La lluvia" de Jorge Luis Borges

The present thesis entitled *Modelling and sustainable management of rainwater harvesting in urban systems* 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, Dr. Xavier Gabarrell both from the ICTA and the Department of Chemical Engineering at the UAB and Dr. Carles Martínez Gasol from the Inèdit Innovació (INEDIT, spin-off of UAB research park).

Bellaterra (Cerdanyola del Vallès), June 2012

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Supervisors

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List of acronyms, abbreviations and notation

AB	Apartment buildings
AEAS	Asociación Española de Abastecimientos de Agua y Saneamiento
AEMET	Agencia Estatal de Meteorología (Spain)
AGA	Asociación Española de Empresas Gestoras de los Servicios de Agua a Poblaciones
BCR	Benefit-cost ratio
Camacol	Colombian Chamber of Construction
CEC	California Energy Commission
CML	Instititute of Environmental Sciences (Leiden university)
CNE	Comisión Nacional de Energía (Spain)
CO_2 eq.	Carbon dioxide equivalent emissions
CRA	Comisión de Regulación de Agua Potable y Saneamiento Básico (Colombia)
DANE	Departamento Nacional de Planeación, Colombia
DPC	Defensoría del Pueblo de Colombia
EEA	European Environmental Agency
EC	European Commission
EP	Eutrophication potential
EPRI	Electric Power Research Institute
ESH	Eight single-houses
FAO	Food and Agriculture Organization of the United Nations
FAO Aquastat	FAO's global information system on water and agriculture
FU	Functional unit
GAB	Groups of apartment buildings
GAT	Reseach group on Local Environmental Management
GH	Groups of houses
GWP	Global warming potential
HTP	Human toxicity potential
ICTA	Institute of Environmental Science and Technology
IDEAM	Instituto de Hidrología, Meteorología y Estudios Ambientales (Colombia)
ILCD	International Reference Life Cycle Data System
INE	Instituto Nacional de Estadística (Spain)
IRR	Internal rate of return
ISO	International Organization for Standardization
ITeC	Institut de Tecnologia de la Construcció de Catalunya
KS	Kolmogorov-Smirnov
kWh	kilowatt hour
LCA	Life cycle assessment
LCIA	Life Cycle Impact Assessment
LKS	Lilliefors modification of the Kolmogorov-Smirnov
MAETP	Marine aquatic ecotoxicity potential

MFA	Material flow analysis
NPV	Net present value
NPVC	Net present value cost
ODP	Ozone layer depletion potential
OWH	Organization World Healt
PBP	Payback period
PCI	Precipitation Concentration Index
PEI	Potential environmental impact
PO_4^{3-} eq.	Phosphate equivalent emissions
POCP	Photochemical ozone creation potential
ROI	Return of invest
RWH	Rainwater harvesting
Sb eq.	Antimony equivalent emissions
SD	System dynamics
SETAC	Society of Environmental Toxicology and Chemistry
SO_2 eq.	Sulphur dioxide equivalent emissions
Sostenipra	Research group on Sustainability and Environmental Prevention
TETP	Terrestric ecotoxicity potential
TRWR	Total renewable water resources
TSH	Two single-houses
UAB	Universitat Autònoma de Barcelona
UN	Unated Nations
UNEP	United Nations Environment Programme
UNFPA	United Nations Population Fund
UN-Habitat	United Nations Human Settlements Programme
UNICEF	United Nations Children's Fund
US	United States
UTP	Universidad Tecnológica de Pereira (Colombia)
UWOT	Urban Water Optioneering Tool
WHO	World Health Organization
WRI	World Resources Institute
WWAP	World Water Assessment Programme
YAS	Yield-after-spill
YBS	Yield-before-spill

Acknowledgments

The author wish to thank the projects “Modelado de la dinámica de oferta y demanda de recursos naturales bajo criterios de sostenibilidad” (Vicerrectoria de Investigaciones, Innovación y Extensión, Universidad Tecnológica de Pereira, Colombia) and “Análisis ambiental del aprovechamiento de las aguas pluviales” (Spanish Ministry for Science and Innovation, ref. CTM 2010-17365) for financing this study and express appreciation for the grant awarded to Tito Morales Pinzón by Colciencias (Departamento Administrativo de Ciencia, Tecnología e Innovación de Colombia). Additionally, the authors would like to thank the "ECOTECH SUDOE SOE2/P1/E377, LCA and Ecodesign International network for environmental innovation" project.

Durante mi estancia en la bella ciudad de Barcelona he tenido la gran oportunidad de realizar esta investigación. Son muchas personas las que han contribuido de diferentes maneras a este logro en mi vida profesional y personal.

Agradezco a mis directores Dr. Joan Rieradevall, Dr. Xavier Gabarrell y Dr. Carles M. Gasol, quienes han transmitido sus valiosos saberes de forma siempre oportuna.

A los compañeros de la sala de Ecología Industrial y de Sostenipra (los que han terminado y los que están en camino), que gran compañerismo, los llevaré en mis pensamientos. Recuerdos especiales de Alfredo, Esther, Eva, Farah, Ileana, Jesús, Joan Manuel, Jordi, Julia, Katherine, Mohammad, Montse, Neus, Ramon, Raul, Roberto, Rodrigo, Sara, Violeta.

A mi gran familia por ser pacientes y esperar mi regreso y por su confianza y alegría compartida en todos los momentos. En especial a mi padre Rubén y mi madre Olga, he cumplido nuestro sueño. A mi esposa Claudia y mi hijo Camilo, como si nunca hubiera partido.

A los Hermanos que siempre me han apoyado y mostrado el camino y al Maestro Diego que siempre me enseña, gracias por acoger mi familia.

Al Padre que todo lo provee, porque siempre sentí Tu presencia. Ya puedo cumplir Tus designios.

Summary

This dissertation developed a model to evaluate technical, economic and environmental aspetcs of rainwater harvesting systems for domestic urban use. Different types of housing (semi-detached house and apartment house) and different systems (one single-house, apartment building and neighborhood) were analyzed. Then, scenarios of economic and environmental viability were found and specific sub-models were developed for use in direct evaluation of a wide range of climatic conditions, prices and quality of mains water in different urban scales.

The methodologies used to develop the research were very effective and showed their wide applicability to study systems of rainwater harvesting. System dynamics is a methodology easily adaptable to use in technical, economic and environmental evaluations. The life cycle analysis involved specifying the environmental potential impact of the entire system using indicators widely used such as the global warming potential (GWP).

Rainwater harvesting is an alternative viable in urban areas of both developed and developing countries. The best conditions are on neighborhood scale systems and when the rainwater can be used as a substitute for hard water for use in hot water consuming appliances.

In summary, the potential environmental impact found per cubic meter (m^3) of rainwater consumed by the system is less than 1.47 kg CO_2 eq. and the economic benefits could reach values of 0.4 Euros. The implementation of these systems could bring savings of up to 42 kWh/household/year in urban areas with a water supply network with high hardness. It was always possible to find a system configuration to provide a lower environmental impact than mains water. Environmental impacts can be avoided in 0.25 kg CO_2 eq./m^3 for urban scenarios and low hardness of mains water, and in 8.0 kg CO_2 eq./m^3 for scenarios of hard mains water.

These results lay the groundwork for the future development of urban projects (new neighborhoods) given the tools and the decision criteria that will enable urban planners and environmental managers to incorporate rainwater harvesting as a strategy of adaptation to climate change and a response to future increase in water demand for domestic and other urban uses.

Resumen

En esta dissertación se desarrolló un modelo para evaluar técnica, económica y ambientalmente sistemas de recogida de agua de lluvia para aprovechamiento doméstico urbano. Se analizaron diferentes tipologías de vivienda (vivienda tipo casa y vivienda tipo apartamento) y diferentes sistemas (vivienda unifamiliar, edificio de apartamentos y barrio). Se encontraron los escenarios de viabilidad económica y ambiental y se desarrollaron submodelos específicos para la evaluación directa en un amplio rango de condiciones climáticas, precios y calidad del agua para sistemas de diferentes escalas urbanas.

Las metodologías empleadas en el desarrollo de la investigación fueron muy efectivas y mostraron su gran capacidad de aplicación al estudio de los sistemas de recogida de agua de lluvia. La dinámica de sistemas es una metodología que se adpató con facilidad al análisis técnico, económico y ambiental de este recurso. El análisis de ciclo de vida permitió detallar el impacto potencial ambiental de todo el sistema con indicadores ampliamente utilizados como el impacto potencial al calentamiento global (GWP).

La recogida de agua de lluvia es una alternativa viable en áreas urbanas tanto de paises desarrollados como en desarrollo. La mejores condiciones se presentan en sistemas de escala barrio y cuando el agua de lluvia puede ser utilizada como sustituto de agua dura para uso en electrodomésticos que consuman agua caliente.

En resumen el potencial impacto ambiental encontrado por cada metro cúbico (m^3) el agua de lluvia consumida por el sistema es inferior a 1.47 kg CO_2 eq., y los beneficios económicos podrían alcanzar valores de 0.4 Euros/m^3. La implementación de estos sistemas podría traer un ahorro de hasta 42 kWh/vivienda/año en areas urbanas con suministro de agua de red con dureza alta. Siempre fue posible encontrar una configuración del sistema que presentara un menor impacto ambiental que el del agua de red. Los impactos ambientales evitados pueden ser de hasta 0.25 kg CO_2 eq./m^3 en escenarios urbanos de agua de red con dureza baja y hasta 8.0 kg CO_2 eq./m^3 es escenarios con dureza alta.

De esta forma se han sentado las bases para que en el desarrollo de proyectos urbanísticos futuros (nuevos barrios), se disponga de las herramientas y los criterios de decisión adecuados, que les permita a los planificadores urbanos y gestores ambientales incorporar la cosecha del agua de lluvia, como una estrategia de adpatación al cambio climático y como una respuesta a la demanda creciente de agua para uso doméstico y otros usos urbanos.

Preface

The thesis "Modelling and sustainable management of rainwater in urban systems" was developed under supervision of Dr. Joan Rieradevall Pons, Dr. Xavier Gabarrell Durany and Dr. Carles Martínez Gasol. This work was carried out within the Sustainability and Environmental Prevention research group (Sostenipra) at the Institute of Environmental Science and Technology of Universitat Autònoma de Barcelona, Catalonia, from October 2009 to June 2012.

The dissertation is part of the "Environmental Analysis of the Use of Urban Rainwater" research project (Pluvisost) financed by the Spanish Ministry for Science and Innovation, ref. CTM 2010-17365 and the project "Modelling the dynamics of supply and demand for natural resources with sustainability criteria" financed by Universidad Tecnológica de Pereira, Colombia.

The thesis is based on published papers and other papers submitted to international peer-reviewed journals using some of the chapters developed:

Chapter three has been used to present the following paper:

Morales-Pinzón, T., Rieradevall, J., M. Gasol, C., Gabarrell, X. Plugrisost: A Model for Design and Environmental Analysis of Integrated RWH Systems. Submited in April 2012 to Environmental Modelling and Software.

Next paper was published and has served as the basis for chapter four:

Morales-Pinzón, T., Rieradevall, J., M. Gasol, C., Gabarrell, X., (2012). Potential of rainwater resources based on urban and social aspects in Colombia. Water Environment Journal. doi: 10.1111/j.1747-6593.2012.00316.x

A second paper was published and has served as the basis for chapter five:

Morales-Pinzón, T., Angrill, S., Rieradevall, J., Gabarrell, X., M. Gasol, C., Josa, A., (2011). LCM of Rainwater Harvesting Systems in Emerging Neighborhoods in Colombia. In: M. Finkbeiner, M. Finkbeiner (ed), Towards Life Cycle Sustainability Management, Springer, Berlin, pp 277-288, doi: 10.1007/978-94-007-1899-9_27.

Chapter six has been used to present the next paper:

Morales-Pinzón, T., Lurueña, R., Rieradevall, J., M. Gasol, C., Gabarrell, X. Financial Feasibility and Environmental Analysis of Potential RWH Systems in Spain. Submited in April 2012 to Resources, Conservation and Recycling.

Chapter seven has been used to present the following paper:

Morales-Pinzón, T., Lurueña, R., Rieradevall, J., M. Gasol, C., Gabarrell, X. The consideration of water hardness as an important factor for the environmental and economic analyses of rainwater use in domestic appliances. Submited in May 2012 to Water Research.

Structure of the dissertation

The dissertation is prepared into five main parts and eight chapters. The structure of the doctoral thesis is shown in Figure A. This flow chart can be used throughout the reading of this document as a *dissertation map*.

Part I. INTRODUCTION and METHODOLOGICAL FRAMEWORK APPLIED

Part I is divided into two chapters. **Chapter 1** introduces the general work presenting a comprehensive framework of water resources and their importance in the cities. This includes both the supply and renewability and water resources in some countries of the world and the urban water demands and trends of future urban growth. Also it is shown a relationship of domestic consumption of mains water and the relationship between water and energy. Finally, the motivations and the objectives that led to this dissertation are presented. **Chapter 2** presents the general methodology that was developed, presenting a special emphasis on system modelling, economic analysis and environmental assessment. In addition, this chapter includes the systems and case studies included in the research and validation carried on the main model developed.

Part II. MODELLING RAINWATER HARVESTING SYSTEMS

Part II includes the **Chapter 3**. This chapter presents in detail the development of a simulation model of RWH systems, and its benchmarking against other existing softwares. This software is called Plugrisost as an acronym for pluvials, grey and sustainability. In addition, the chapter describes the determinants factors that led to its creation and the new features included to facilitate the comprehensive assessment of rainwater harvesting.

Part III. SOCIAL ASPECTS, POTENTIAL SUPPLY AND ENVIRONMENTAL BENEFITS OF RAINWATER IN URBAN AREAS

Part III is composed of two chapters. **Chapter 4** presents a study of the potential of rainwater harvesting in countries in process of development taking as a case study in Colombia. Additionally, this study shows that some socioeconomic aspects may influence the potential to capture rainwater. **Chapter 5** discusses the potential environmental impacts in the context of new neighborhoods in developing countries, taking as a case study in Colombia. This chapter presents models that can be applied in rapid environmental assessments in these scenarios.

Part IV. MAIN FACTORS IN THE ECONOMIC AND ENVIRONMENTAL ANALYSIS

Part IV is composed of two chapters. **Chapter 6** analyzes the economic and financial viability and environmental impact of RWH systems taking as a case study in Spain. Models to asses economically and environmentally these systems are developed. Also, the determinants that affect these assessments are exposed. **Chapter 7** is focused on analyzing the potential effect of water network quality in the economic and environmental analysis of RWH systems. Hardness of the water is the parameter analyzed over a broad range of urban conditions and different systems.

Part V. CONCLUSIONS AND NEXT STEPS

Part IV is composed of one chapter. **Chapter 8** presents the overall findings of the dissertation in accordance with the stated objectives. It is also included future researches that may continue to be developed in RWH systems.

[*Note:* Each chapter (from 3 to 7) presents an article –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].

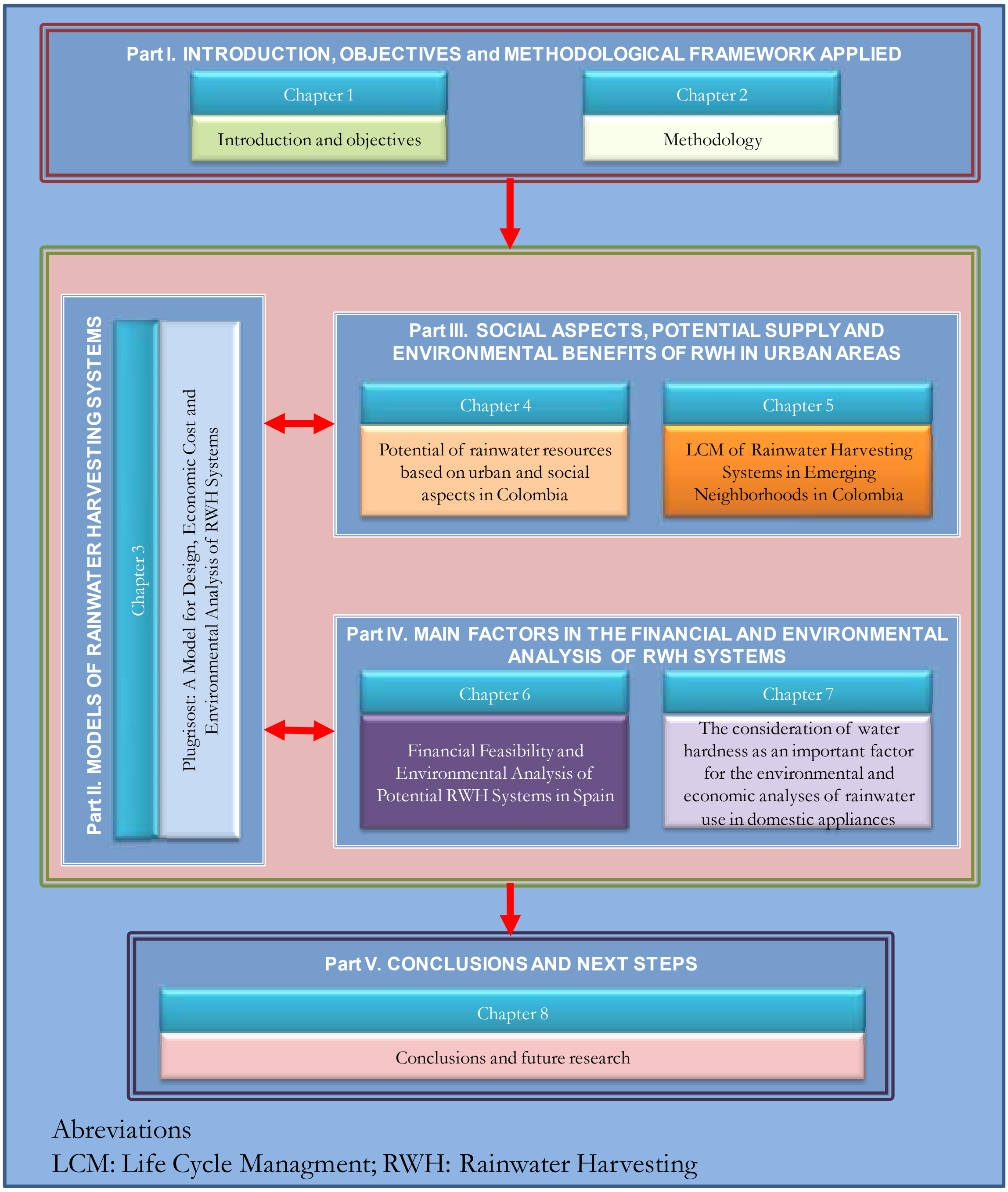


Figure A. Structure map of the dissertation.

PART I

INTRODUCTION, OBJECTIVES AND METHODOLOGICAL FRAMEWORK APPLIED

Chapter 1

Introduction and objectives

Chapter 2

Methodology

Urban area of Pereira (Colombia). Photography by Tito Morales

Chapter 1
Introduction and objectives

Chapter 1 presents the rainwater harvesting (RWH) as an alternative of water supply in urban areas join to the general context of supply and demand for water that motivate this dissertation. Then the justifications and objectives of this work are exposed.

This chapter is structured as follows:

- Renewable water supply
- RWH as urban resource in a scenario of water dependency and sustainability in cities
- Water demand and domestic rainwater uses
- Justification to the dissertation
- Objectives of the dissertation

1 Introduction and objectives

Water is essential for urban sustainability. However, water is a finite resource that will limit future economic growth and development worldwide (WWAP, 2012). Renewable water resources are becoming less adequate for meeting the growing demands of the world population. This trend is particularly true in urban areas because there is a tendency toward an urban dominated world (WWAP, 2009).

Thus, water can be considered the most limiting natural resource for the future growth and development of urban areas, particularly in underdeveloped countries or developed countries with a limited water supply. In addition, water is a threatened resource. Nearly 2 million tons of waste (industrial, urban and agricultural) is dumped into receiving waters. Because rainwater is the main source of fresh water for various uses and for ecosystems, this threat is greatest when rainwater is considered waste (United Nations/World Water Assessment Programme, 2003).

In the context of sustainability, one of the main challenges facing today's society is the water supply. Water is increasingly recognised as a valuable resource as the available quantity and quality decreases. The United Nations (2007) have highlighted the growing evidence for water scarcity worldwide and the need for cooperation and integration to ensure sustainable, efficient and equitable water resources locally and internationally.

This research analysed the feasibility of using rainwater as a valuable resource that should be incorporated into the management of urban systems. This research was developed to contribute to the sustainability assessment of rainwater harvesting and to be considered a supplement to centralised tap water. Thus, this study focused on the analysis of the technical, social, economic and environmental aspects that are essential when recommending the inclusion of this resource in urban planning.

Different urban contexts and climates were studied to provide a broad framework that would allow the consolidation of a tool for modelling these systems with specialised software.

The objective of this research is to promote rainwater harvesting (RWH) and to provide information, discussion, results and analysis tools to urban planners and stakeholders in the design stage of rainwater harvesting systems. In addition, these tools should provide support for decision makers to implement policies that encourage the use of unconventional sources (rainwater and greywater) and help reduce pressure on conventional water sources. These tools would allow the generation of alternative responses for the sustainable management of water resources with respect to the current urban growth and the management of the global climate change effects (which are manifested in rainfall variation in the near future) (IPCC, 2012).

To achieve this objective, adequate knowledge and tools must be obtained to integrate the technical, economic and environmental impact of the RWH and greywater systems. In addition, the most relevant information about the different water supply alternatives for domestic use must be considered to ensure that current and future development projects are properly planned.

To counteract urban growth and increased water demand, rainwater should no longer be considered an untapped resource or (in many cases) waste. RWH should be considered a complementary alternative for water supply in urban areas with different uses.

The Plugrisost software (Morales-Pinzón et al., 2012) that resulted from the integration of different methodological tools was used in this research. This software is used for technical analysis, economic feasibility studies and environmental assessments of systems that capture and use rainwater and greywater. The software is operated within an integrated framework for urban water management for domestic use. This modelling tool aims to contribute to water urban planning and, in particular, to make the future development of urban projects more sustainable.

1.1 Renewable water supply

The amount of renewable water (maximum theoretical amount of water annually available for each country) is not synonymous with its availability to the population. However, the amount of renewable water is a reference for considering the state of a countries potential water supply. Some countries have a plentiful supply of water as a result of rainfall (areas of Brazil, the USA and China). However, other countries have lower water supplies (South Africa, Spain and the United Kingdom) (see Table 1.1). If the impact of the number of inhabitants is included, the amount of total renewable water resources (TRWR per capita) gives the maximum amount of water theoretically available annually on a per person basis in cubic meters (World Resources Institute, 2008). This calculation reveals that, for example, South American countries such as Brazil and

Colombia have more TRWR than countries such as South Africa and India (see Table 1.1).

Table 1-1. Water resources in some countries

Water resource	Brazil	United States of America	China	Australia	India	Colombia	South Africa	Spain	United Kingdom
INTERNAL RENEWABLE WATER RESOURCES (IRWR)									
Precipitation (mm/year)	**1,782**	**715**	**645**	**534**	**1,083**	**2,612**	**495**	**636**	**1,220**
Area of the country (1000 ha)	851,488	983,151	960,000	774,122	328,726	114,175	121,909	50,537	24,361
Precipitation (km^3/year)	**15,174**	**7,030**	**6,192**	**4,134**	**3,560**	**2,982**	**603**	**321**	**297**
Surface water: produced internally (km^3/year)	5,418	2,662	2,172	440	1,404	2,112	43	110	144
Groundwater: produced internally (km^3/year)	1,874	1,383	829	72	432	510	5	30	10
Overlap between surface water and groundwater (km^3/year)	1,874	1,227	728	20	390	510	3	28	9
Total internal renewable water resources (km^3/year)	5,418	2,818	2,813	492	1,446	2,112	45	111	145
TOTAL RENEWABLE WATER RESOURCES (TRWR)									
Surface water (km^3/year)	8,233	2,913	2,739	440	2,039	2,132	48	110	146
Overlap between surface water and groundwater (km^3/year)	1,874	1,383	829	72	432	510	5	30	10
Groundwater (km^3/year)	1,874	1,227	728	20	390	510	3	28	9
Total renewable water resources (km^3/year)	8,233	3,069	2,840	492	2,081	2,132	50	112	147
Population (2011) (million inhabitants)	197	313	1,348	23	1,242	47	51	47	62
Urban population (%) (2010)	87	82	47	89	30	75	62	77	80
TRWR (m^3/inhabitant/year)	**41,856**	**9,802**	**2,107**	**21,770**	**1,676**	**45,458**	**990**	**2,398**	**2,356**

Sources: Data and estimations from the FAO Aquastat (2012) and the UNFPA (2011).

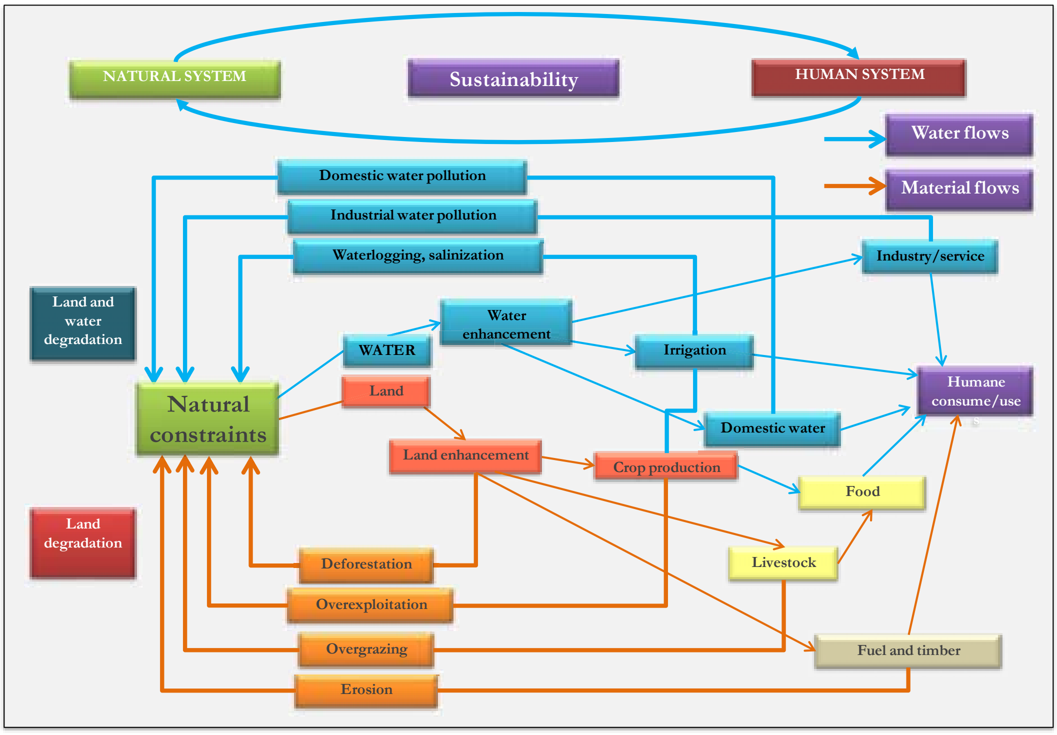
The potential water supply varies from country to country. Rain is the main factor that contributes to the supply of renewable water resources. Urban water supplies are traditionally based on limited freshwater resources that are located outside of the cities. However, cities are currently turning to new technologies and strategies to increase their self-sufficiency by using internally located water sources (Rygaard et al., 2011) such as rainwater.

Centralised water supply systems are the most common alternative for providing water to populations and are an indicator of development. For example, 54% of the world population had a tap water connection for their homes in 2006; however, only 33% used other improved drinking water sources (WWAP, 2009). This progress was greatest in East Asia, in which drinking water coverage improved from 68% in 1990 to 88% in 2006 (WWAP, 2009).

1.2 RWH as an urban resource in a water dependency and sustainability scenario in cities

Urban areas can consume more water than is available within their own territory and often depend on water imported from neighbouring areas. However, some cities have reduced their dependency on imported water by more than 15% by harvesting rainwater (Rygaard et al., 2011).

Water is one of the five demands that are typical of human society in settlements. These water demands include water for drinking and water for household use (cooking, cleaning, hygiene and sanitation) (WWAP, 2012). Water is part of a complex web of relationships that exists between the natural system and the human system (a limiting factor for sustainability) (see Figure 1-1).



Source: Modified from Falkenmark (1986).

Figure 1-1. Complex interactions and feedback between the natural and human systems

The dynamics of water demand are directly related to growth and urban development. Urban areas are expanding across the globe; the percentage of the urban population is already 70% in Europe, America and Oceania and up to 50% globally (United Nations, 2006). Furthermore, the urban population is expected to continue to grow during this century (Bai, 2007).

As a concentrated centre of economic and social activity, cities are formed by constructed buildings and service networks (such as water), which sustain their social and economic activities. In the world, three major urbanisation trends can be identified. Large cities or "Metacities" with populations greater than 20 million are located in Asia, Latin America and Africa. However, more than half of the world's population are living in cities with less than 500,000 inhabitants. Furthermore, nearly 20 per cent live in cities of between 1 and 5 million inhabitants, which will account for 95% of the urban growth in the next two decades (2030) (UN-Habitat, 2006).

According to WHO/UNICEF (2010), 87% of the world population and 84% of the population in developing regions obtain their drinking water from improved sources. In urban areas, 94% of the population obtains their water from improved drinking sources, and only 76% of the rural populations have access to improved water sources. Therefore, population growth is becoming an urban phenomenon that is concentrated in the developing world (UN-Habitat, 2006). The world population is expected to increase by 33.8% (6.8 to 9.1 billion) between 2009 and 2050 (UN Department of Economic and Social Affairs, 2007).

This urban growth along with the effects of global climate change will create water supply problems in cities. Thus, new water sources and supply alternatives should be studied. Megacities (and other growing cities) could have a serious shortage of water and energy as a result of rapid urbanisation (Chiu et al., 2009). Rainwater harvesting (RWH) is recommended as one specific strategy for adapting to future climate change (Pandey et al., 2003; Mukheibir, 2008; Salas et al., 2009; Kahinda et al., 2010).

Rainwater is a resource that can be exploited in urban areas. For example, rainwater harvesting has been used in large cities such as Singapore and could be valuable in densely populated areas (UN-Habitat, 2010). In addition, pilot projects exist in which rainwater harvesting is used in residential areas (Villarreal and Dixon, 2005) and in commercial buildings (Chilton et al., 1999).

1.3 Water demand and domestic rainwater uses

Domestic water use can be classified as internal or external. Drinking water for human consumption is an internal use of domestic water. Drinking water is required to meet certain quality parameters, and the quantity of water must be carefully controlled in the water treatment process. Other internal water uses such as flushing toilets and washing laundry and external water uses such as car washing, pool use and irrigation can be supplied by RWH systems. All of these are uses for non-potable water. However, using a final water demand quality approach makes it possible to further differentiate between domestic water uses. For example, washing machines can be supplied by the RWH systems, while other water applications that allow for the use of lower quality water (for example, the toilet) can be satisfied with greywater systems.

According to Roebuck et al. (2010), the most widely accepted non-potable applications for harvested rainwater are WC (Water Closet) flushing, garden irrigation and washing machine use.

Ratnayaka et al. (2009) and Domene et al. (2004) showed that approximately 45% of domestic demand for water can be supplied by RWH systems (see Table 1-2). Mukhopadhyay et al. (2001), Lazarova et al. (2003) and Campisano and Modica (2010) have shown that up to 30% of water in houses is typically used for flushing toilets. This water demand would be satisfied by greywater systems. Furthermore, this use requires only basic water treatment (i.e., filtration and chlorination) (Campisano and Modica, 2012). Villarreal and Dixon (2005) revealed that 30% of the main water supply can be saved (toilet and washing machine use only).

Table 1-2. Internal water demands in some countries

Country	Internal water demand (Lcd)	Water closet	Laundry	Kitchen uses	Personal hygiene
Australia/Sidney (1)	184	45 (24.5)	49 (26.6)	24 (13)	66 (35.9)
Singapore (1)	162	26 (16.0)	31 (19.1)	36 (22.2)	64 (39.5)
UK/Thames (1)	153	46 (30.1)	21 (13.7)	11 (7.2)	77 (50.3)
USA/Seattle (1)	240	71 (29.6)	56 (23.3)	65 (27.1)	48 (20.0)
Spain/Barcelona (2)	141	30 (21.3)	16 (11.3)	13 (9.2)	82 (58.2)

Percentages are shown in parentheses. Sources: (1) Ratnayaka et al. (2009) and (2) Domene et al., (2004).

1.3.1 Relationships between energy and water

The relationships between water and energy are important to consider for rainwater research and use. The different production processes that require water extraction of materials, cleaning materials and biofuel crops and the production (see Table 1-3) and distribution of water are important. Approximately 40% of the energy used in water networks (including waste water treatment) is for production systems (22%) and distribution (17%) (Cheng, 2002). Thus, saving potable water should result in energy savings.

Additionally, all of the different energy sources (including electricity) use water for diverse productive processes. These processes include raw material extraction, cooling (in thermal processes), cleaning materials, cultivation of crops for biofuels and powering turbines (WWAP, 2012)

Table 1-3. Relationships between energy use and water production

	Source/treatment type	Energy use (kWh/m³) (1)
Water	Surface water	0.06
	Groundwater	0.16
	Brackish groundwater	1.0 to 2.6
	Seawater	2.6 to 4.4
Wastewater	Trickling filter	0.25
	Activated sludge	0.34
	Advanced treatment without nitrification	0.4
	Advanced treatment with nitrification	0.5

(1) Average US data do not include the energy used for distribution. Reported by the WWAP (2012) from the following sources: CEC (2005), EPRI (2002), Stillweell (2010) and Stillwell et al. (2010, 2011).

In other studies, the life cycle energy associated with water supply systems was from 2.86 to 3 kWh/m^3, where the indirect energy (energy associated with material use and administrative services) of the water supply was comparable to or greater than the direct energy (energy used on site for constructing, operating, and maintaining water supply systems) (Mo et al., 2010).

1.4 Justification

The growing demand for water in urban areas of developing countries has added to the reduced supply of conventional water sources (either by pollution or by the effects of global climate change). This growing demand is also occurring in developed countries. Water management in urban environments is a central subject for researchers and stakeholders in water resource management. Modelling rainwater harvesting in an integrated management framework of water resources will help to assess and compare the different water supply alternatives in present and future urban development scenarios (e.g., regarding the climate, urbanisation, water consumption, building design and management sources that are integral for the urban domestic use of water).

Modelling of the RWH systems uses a wider range of variables and is a **technical necessity** because existing models (used for sizing RWH systems) are focused on meeting rainwater demands. Thus, the main purpose of these models was to define the optimum size for rainwater storage tanks. However, some variables that may affect the results were not considered.

- Thus, there is a need to improve the existing models by integrating the behavioural rainwater harvesting system indicators that are based on the local precipitation and existing or simulated (for example, using parametric models) data. These systems include the potential catchment surface (depending on the type of roof), the water demand and the required quality criteria (depending on final domestic use). This integration will be used to correctly estimate the supply of rainwater and the most favourable range of rainwater tank volumes.
- In addition, RWH system models should be easily integrated into the analysis of other sources, such as greywater (reuse) and tap water.

Along with the technical barrier, the implementation of a rainwater harvesting system is limited by **economic evaluation,** which would help to decide if it is feasible to use this natural resource.

- Existing models for economic evaluation of a rainwater harvesting system do not allow a rapid assessment because they require too much effort or information that is not readily available.
- Because efficient spending and strategic management of financial resources is mandatory (in certain scenarios), it is necessary to develop models for the effective economic evaluation of RWH systems that use less resources.

None of the existing software includes an **environmental impact assessment** from **the** life cycle perspective of the RWH systems.

- These analyses that are used to determine the environmental feasibility of rainwater harvesting systems are complex. Thus, it is necessary to develop models that integrate the technical and economic aspects with a range of environmental indicators. This integration would enable a comprehensive assessment and facilitate the selection of the best alternatives.
- The life cycle assessment is a powerful tool for quantitative environmental analysis. Its integration with economic and social aspects is feasible for assessing the sustainability of RWH systems.

Furthermore, the implementation of a RWH system is controlled by **social factors** that should be investigated.

- In particular, there is interest in understanding the potential of rainwater harvesting in different rainfall scenarios of social level and water consumption patterns. This knowledge is important for establishing a framework to develop urban rainwater management strategies in developing countries.

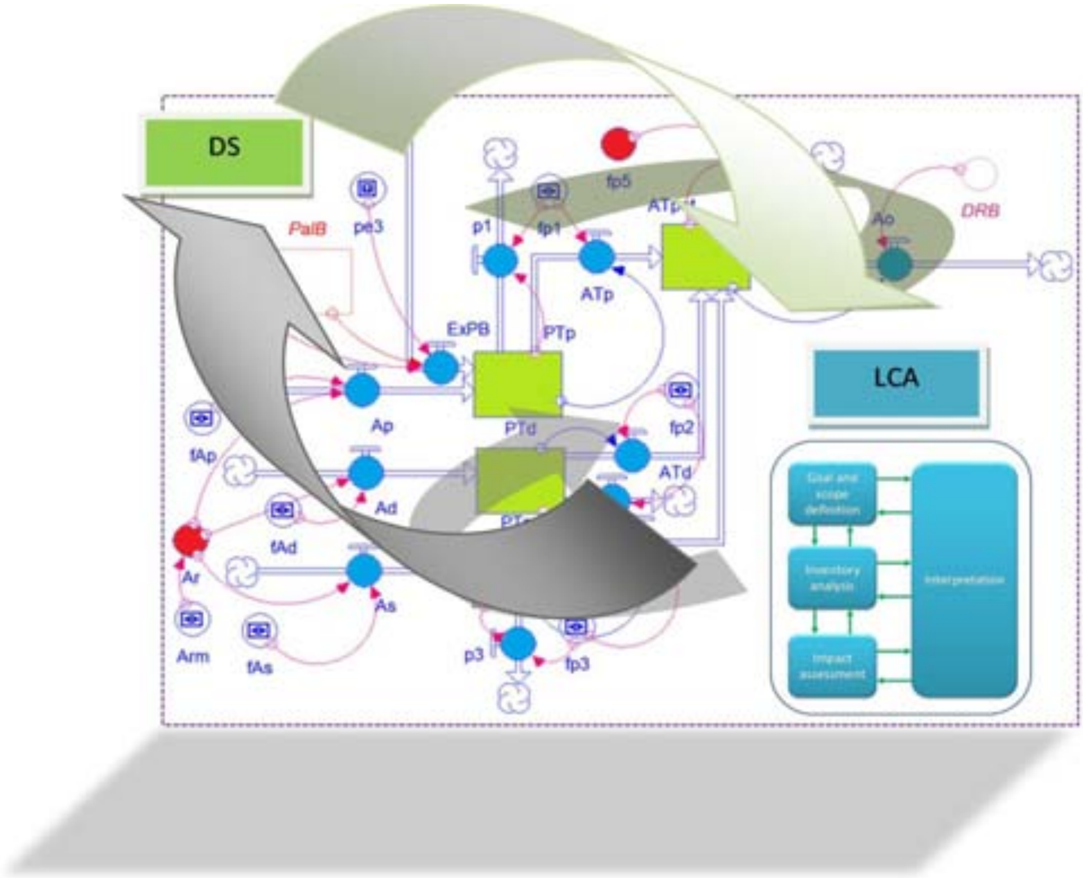
The expected benefits of RWH system modelling depend on the sustainable management of this resource. Sustainable use of rainwater involves the need to build a **comprehensive approach for water management**. This approach should include different uses based on the particular conditions of the analysed urban areas.

- This dissertation is motivated by the need to provide researchers, urban planners and environmental managers with tools and models that facilitate the technical, economic and environmental analysis of RWH systems from an integral view of the water resource management in urban areas.

1.5 Objectives of this dissertation

The central objective of this dissertation is **to model the potential water supply, the economic feasibility and the environmental impact of urban rainwater harvesting systems in developed and developing countries**. To achieve this objective, the following specific objectives were addressed:

1. To generate simulation software that assesses the potential rainwater supply, the economic feasibility and the environmental potential impact of urban RWH systems.
    a. To develop models to evaluate the potential of urban RWH systems.
    b. To develop models to evaluate the economic feasibility of RWH systems.
    c. To develop models to assess the potential environmental impacts of RWH systems.
    d. To propose models for RWH system selection that have low environmental impacts.
2. To apply models to estimate the potential RWH in urban systems with different urban density and social levels.
3. To evaluate and avoid potential environmental impacts of urban RWH systems in developing and developed countries.
4. To quantify the economic cost and the financial benefits of RWH systems at different urban scales.
5. To analyse the potential environmental impacts of RWH systems in different infrastructures.
6. To determine the main financial viability and the environmental impact factors for RWH systems in different rainfall, tap water quality, cost and infrastructure scenarios.
7. To calculate the potentially avoidable environmental impacts of RWH systems for domestic use in home appliances.
8. To expose the most sustainable conditions for RWH systems in urban areas.



Chapter 2
Methodology

Chapter 2 presents an overview of the general methodological aspects of this dissertation. First, the modelling methodology applied to the technical component is presented. Second, the economic aspects that were considered are described. Third, the methodology of environmental impact assessment used and its integration with other models developed are exposed. Finally, the general process of verification and validation of the model is explained.

This chapter is structured as follows:

- Modelling using system dynamics
- Economic and financial analyses of RWH systems
- Life cycle assessment of rainwater harvesting systems
- Integration of LCIA - midpoint indicators and a technical model
- Verification and validation procedures

2 Methodology

The studied systems ranged from a single house (the simpler system should be studied) to a residential neighbourhood. On the basis of this analysis, different RWH system scales were defined that should be modelled with a high level of detail. These models formed a sample for the generalised model definitions that were incorporated into the simulation software.

The research was conducted in two parallel tracks. First, possible case studies for the development and the adaptation of the theoretical models were selected.

The second track followed a general model building process to simulate the integration of specific models for each of the components studied (technical, economic and environmental aspects). In addition, the impacts of socioeconomic variables on the viability of RWH systems were studied.

2.1 Modelling using system dynamics

System dynamics (SD) is a methodology for modelling complex systems. The definition of system boundaries must agree with the questions that need to be solved. A system is a set of two or more interrelated elements (of any kind) (Ackoff, 1971). These systems have the following three properties (Ackoff, 1974):

- The properties or behaviours of each element in the set affect the properties or behaviours of the entire set.
- The properties and behaviours of each part and how they affect the whole depend on the properties and the behaviours of at least one other element in the set.
- Every possible subgroup of elements in the set has the first two properties. Thus, each element has an effect (and none has an independent effect) on the entire set.

These elements or components are interrelated and interact with each other to fulfil a purpose. A general diagram of this system is shown in Figure 2-1.

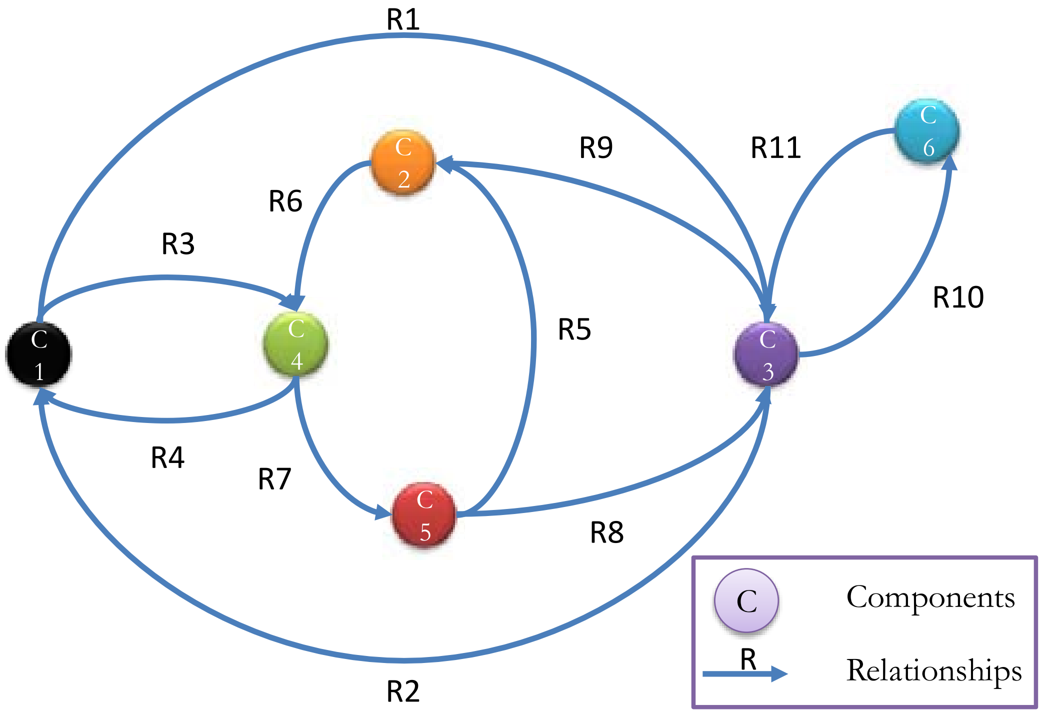


Figure 2-1. Graph representing a system.

The system dynamics methodology developed by Forrester (1961) was selected as the RWH system analysis method. This methodology defines a system from two basic structures, Level and Flow, using a four-tiered structural hierarchy (Richardson, 2011).

- *Closed boundary around the system*
  - *Feedback loops as the basic structural elements within the boundary*
- *Level (state) variables representing accumulations within the feedback loops*
- *Rate (flow) variables representing activity within the feedback loops*
  - *Goal*
  - *Observed condition*
  - *Detection of discrepancy*
  - *Action based on discrepancy*

A key aspect of modelling a complex system is to generalise the system. It is possible to model any system using diagrams, rates (flows) and levels (stocks). The levels are variables that accumulate or integrate the net difference between the inflow and the outflow rates. The auxiliary variables are found in the information channels between the levels and flows as part of the rate equations (Forrester, 1968) (see Figure 2-2). When the source of a flow does not influence the system, it is represented as an "infinite" source, which cannot be exhausted. Similarly, the sinks represent the flows once they exceed the limits of the system (Forrester, 1968) (see Figure 2-2).

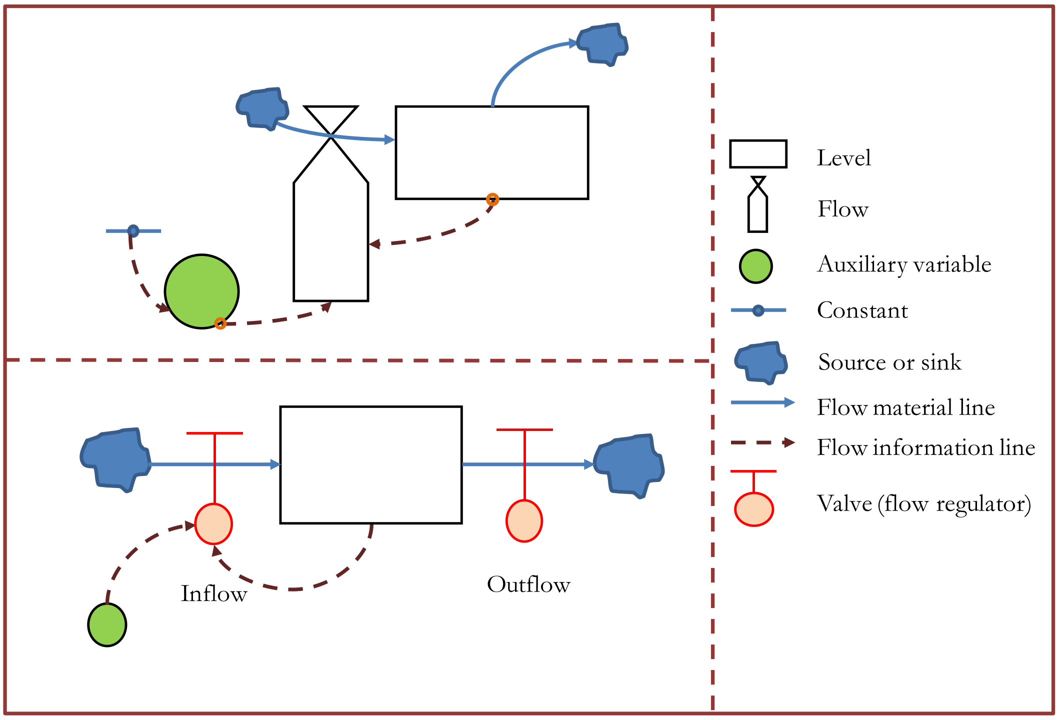


Figure 2-2. Graph representing a Forrester diagram.

The system behaviour over time is defined by the level dynamics. The level increases or decreases in a system as a result of flow. When the inflow is greater than the outflow, accumulation occurs. When inflow is less than the outflow, the level decreases. When inflow is equal to outflow, the level does not change. Equations 2-1(Eq. **3-4** and 2-2 mathematically represent the system.

$$Level_{(t)} = Level_{(t_0)} + \int_{t_0}^{t} (Inflow - Outflow) \cdot ds \qquad \text{(Eq. 2-1)}$$

$$\frac{d(Level)}{dt} = (Inflow - Outflow) \qquad \text{(Eq. 2-2)}$$

2.1.1 Technical analysis of RWH systems

The rainwater volumes from the RWH system tanks were defined as levels for the application of SD in the technical component modelling. Two flows always affect every level, including the supply of rainwater and the domestic consumption of stormwater. A causal model was proposed as a guide for subsequent mathematical modelling. The general model represents the variables that influence the rainwater harvesting and storage process, the consumption dynamics and the relationship with other systems within an integrated concept of domestic water management (see Figure 2-3).

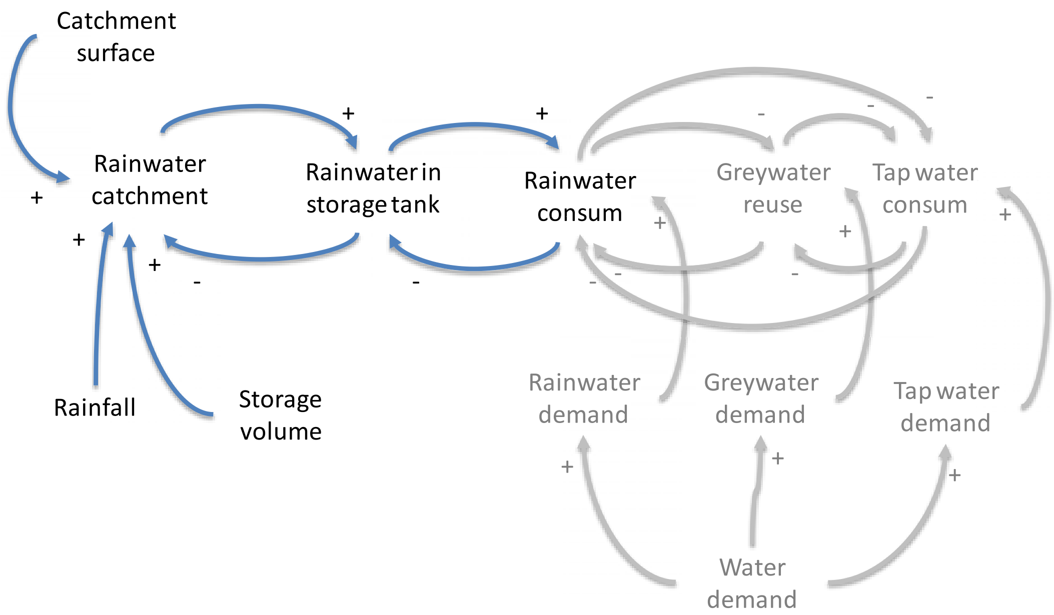


Figure 2-3. Causal model for the technical analysis of RWH systems.

Similarly, a conceptual model for the domestic use of greywater was developed (see Figure 2-4).

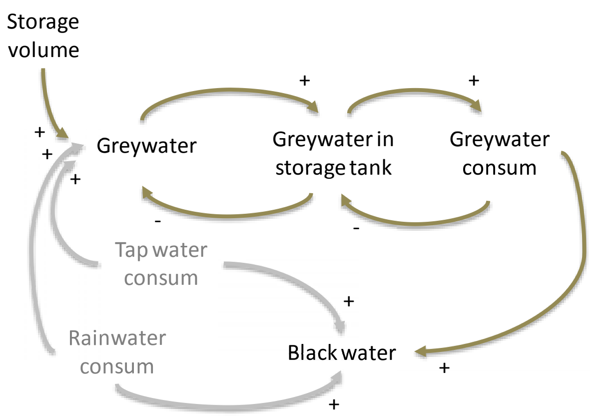


Figure 2-4. Causal model for the technical analysis of Greywater systems.

Based on the causal diagram, a flow chart of the RWH system was developed that incorporated three components, including water supply, water demand and production of wastewater. In this model, mathematical equations were written that shaped the technical components of the Plugrisost software (Morales-Pinzón et al., 2012) (see Figure 2-5).

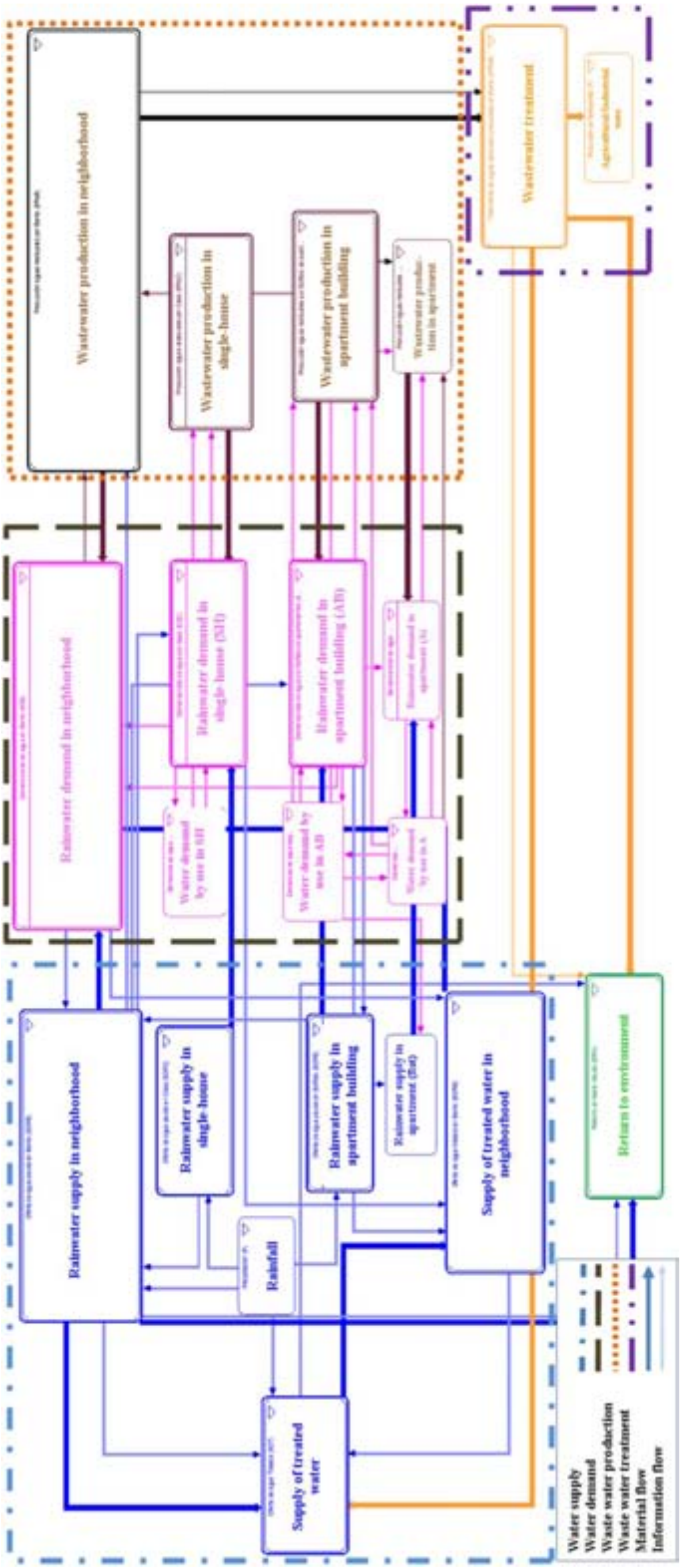


Figure 2-5. Flow model for technical analysis of Rainwater systems.

The behaviour of demand satisfied the rainwater and stormwater storage capacity and was selected as a response variable for the technical analysis. Using these analyses, an optimum volume was found and was used in the environmental and economic analyses. The environmental analysis used (in Plugrisost) linear and quadratic models to estimate the amount of material (kg) and the processes that were required based on the deposit size and the RWH system scale.

2.2 Economic and financial analyses of RWH systems

For the economic study, a general list of materials required for the RWH construction was developed. The labour required to install a RWH system was estimated by a construction database (ITeC, 2011). In addition, a maintenance factor was included for the RWH system.

Four types of prefabricated tank materials (steel, concrete, fibreglass polyester and polyethylene) with storage capacities from 3 to 125 m^3 (according to the most frequent values) were selected based on the materials available. In each RWH system, an adequate storage capacity was used.

A steady increase in water prices and energy (used in pumping the RWH system) was assumed. Transport of the materials was estimated for a distance of 30 km.

A sample of companies that specialise in providing the required water tanks, pumps and pipelines were selected. Prices of similar products were calculated to obtain an average.

The financial feasibility of the RWH systems was assessed by using the following indicators: the net present value (NPV), the internal rate of return (IRR), the return of invest (ROI), the benefit-cost ratio (BCR) and the payback period (PBP).

2.3 Life cycle assessment of rainwater harvesting systems

The environmental assessment was performed based on the environmental impact estimations using the life cycle assessment methodology (LCA). The amount and type of material required to build a RWH system was estimated from a technical analysis that depended on the optimum tank volume estimate and the scale analysed (single house, apartment building and neighbourhood). The LCA methodology was selected because it has a life cycle perspective (for example, cradle to grave) and is an ISO standard. In addition, the LCA method is able to express quantitative values for environmental impacts.

SETAC (1991) defined LCA 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 to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to 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*".

According to the EEA (1998), life cycle assessment (LCA) (also called "life cycle analysis", "life cycle approach" or "cradle to grave analysis") involves the evaluation of some aspects (often the environmental aspects) of a product system through all of its life cycle stages.

LCA is a technique for understanding and addressing the environmental impacts associated with products and services. The LCA technique is carried out in the following four phases that are normally interdependent (ISO 14040, 2006) (see Figure 2-6).

a) the goal and scope definition phase
b) the inventory analysis phase
c) the impact assessment phase
d) the interpretation phase

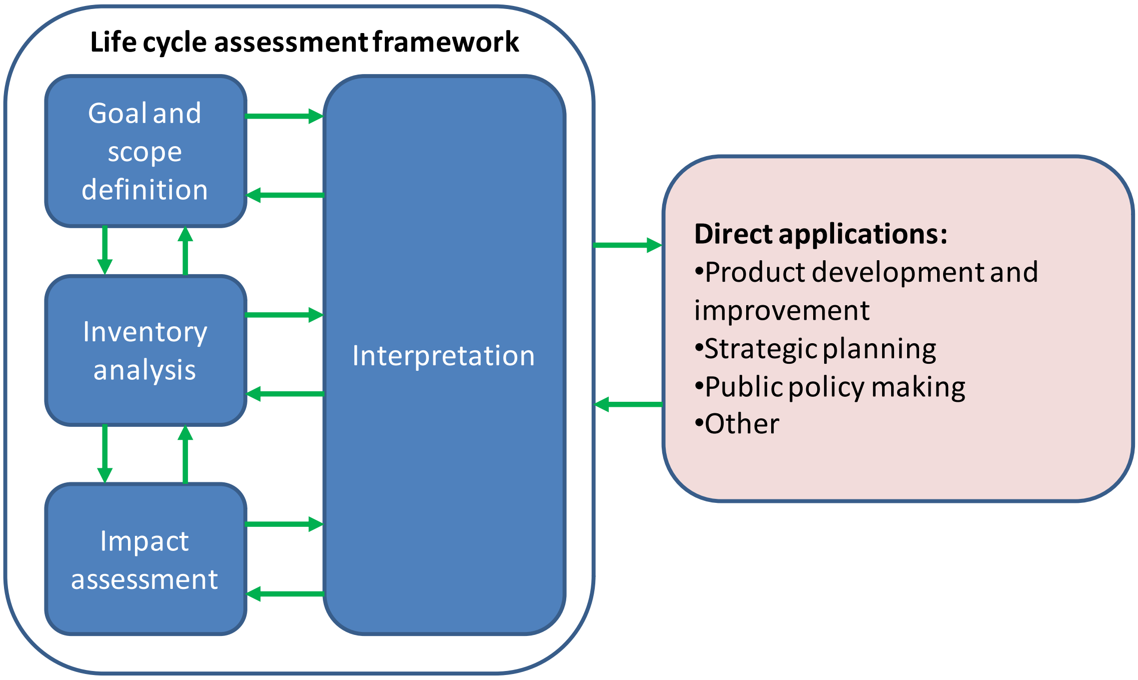


Figure 2-6. Stages of LCA (ISO 14040, 2006).

The goal and scope definition phase provides the context for the assessment and explains to whom and how the results are to be communicated. This phase includes technical information that details the functional unit, the system boundaries, and the assumptions and the limitations of the study, the impact categories and the methods.

The inventory analysis phase includes all emissions released into the environment and the resources extracted from the environment. This phase includes the entire life cycle of a product. The life cycle inventory results are associated with the midpoint categories, which are associated with the damage categories (see Figure 2-7).

The impact assessment phase translates the environmental intervention results or indicators into environmental impacts with an impact assessment method.

Finally, the interpretation phase (according to ISO 14040, 2006) should offer consistent results (according to the defined goal and scope), clarify the limitations and provide recommendations.

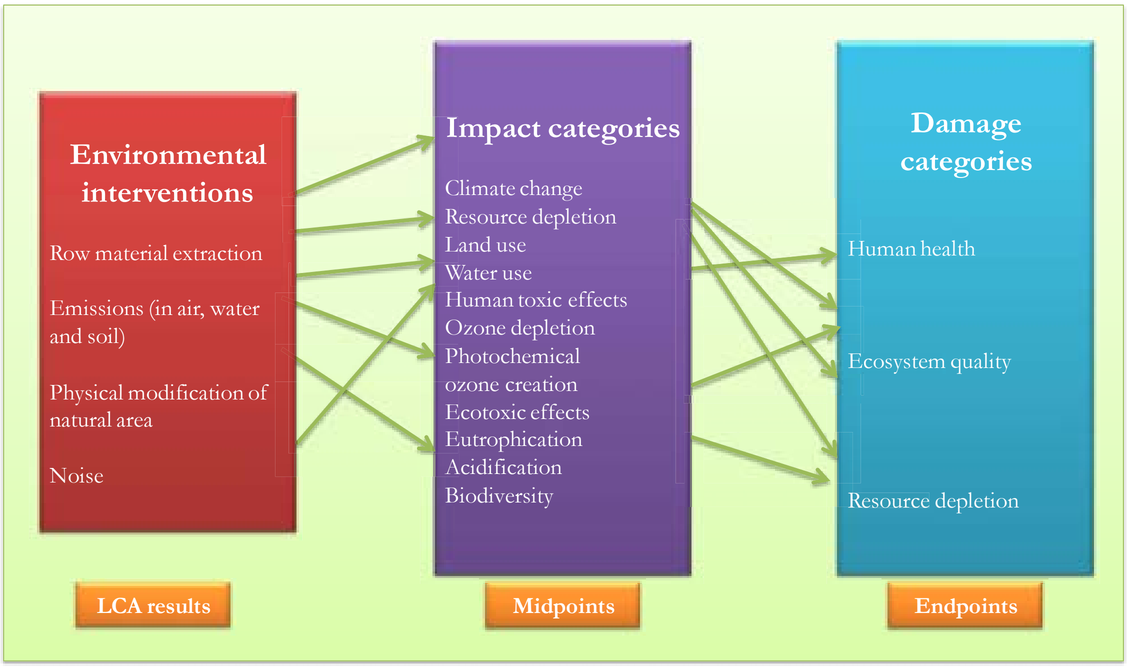


Figure 2-7. Overall UNEP/SETAC scheme of the environmental Life Cycle Impact Assessment (LCIA) framework from Ciroth et al. (2011).

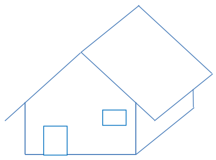
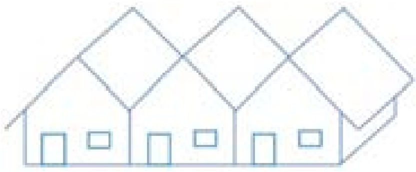
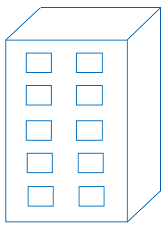
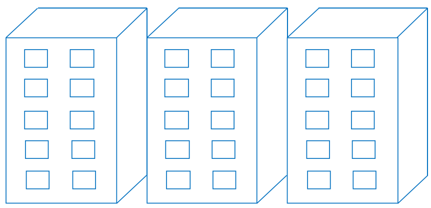
2.3.1 Functional unit

According to the ILCD (2010), the LCA is always linked in a precise and quantitative manner to the description of the function offered by the studied system. This linking is generally accomplished with a functional unit. The functional unit quantifies the performance of a product system for use as a reference unit (ISO 14040, 2006).

2.3.2 System and case studies

Three general systems were defined according to the urban scale analysis. These systems were a single house, apartment building and neighbourhood (see Table 2-1). According to ISO14040 (2006), the Functional Unit was defined as the collection, storage and supply of 1 m^3 of rainwater provided per person per year for use as non-potable water for laundry.

Table 2-1. Housing types defined as the RWH systems object of study

Housing type		Catchment surface (range in m^2)	Rainwater demand (range in L /day)
Single house		60 to 100	33.8 to 67.5
Neighbourhood of low urban density or group of single houses		3,960 to 4,800	2,700 to 3,240
Apartment building		220 to 700	1,013 to 1,586
Neighbourhood of high urban density or group of apartment buildings		2,880 to 7,000	10,126 to 18,226

Urban area case studies were selected to meet conditions that were representative of developed and developing countries that had a wide range of uncontrollable variables (rainfall, tap water aspects and social scenarios) (see Table 2-2).

Table 2-2. Definition of case studies as scenarios of variability

Scenario	Variable	Range	Study
Colombian urban areas	Rainfall	800 to 2,300 L/m²/year (1)	Technical, environmental and social aspects
	Social scenarios	Different socioeconomic stratums	
Spain urban areas	Rainfall	300-1,800 L/m²/year (2)	Technical, economic, environmental and effect of tap water quality
	Water price	<3 Euros/m³ (3)	
	Water quality	Different values of tap water hardness	

(1) Average for main urban areas of Colombia (IDEAM, 2005)
(2) Average for main urban areas of Spain (AEMET, 2011)
(3) Average tap water price in Spain (AGA-AEAS, 2010)

2.4 Integration of LCIA - midpoint indicators and a technical model

From the technical definition of the optimal deposit volume in each of the RWH systems (single house, apartment building and neighbourhood), it was performed a detailed inventory of the materials and processes required for construction. These components were categorised as collection, storage or distribution (see Figure 2-8). This procedure was performed by using three scenarios for the studied systems. A series of rainfall records from the past 20 years was used. The optimistic scenario was defined as the optimum deposit volume obtained by the annual rainfall. The pessimistic scenario for the lower supply was obtained from the rainwater tank volume that was optimal for an average rainwater catchment potential.

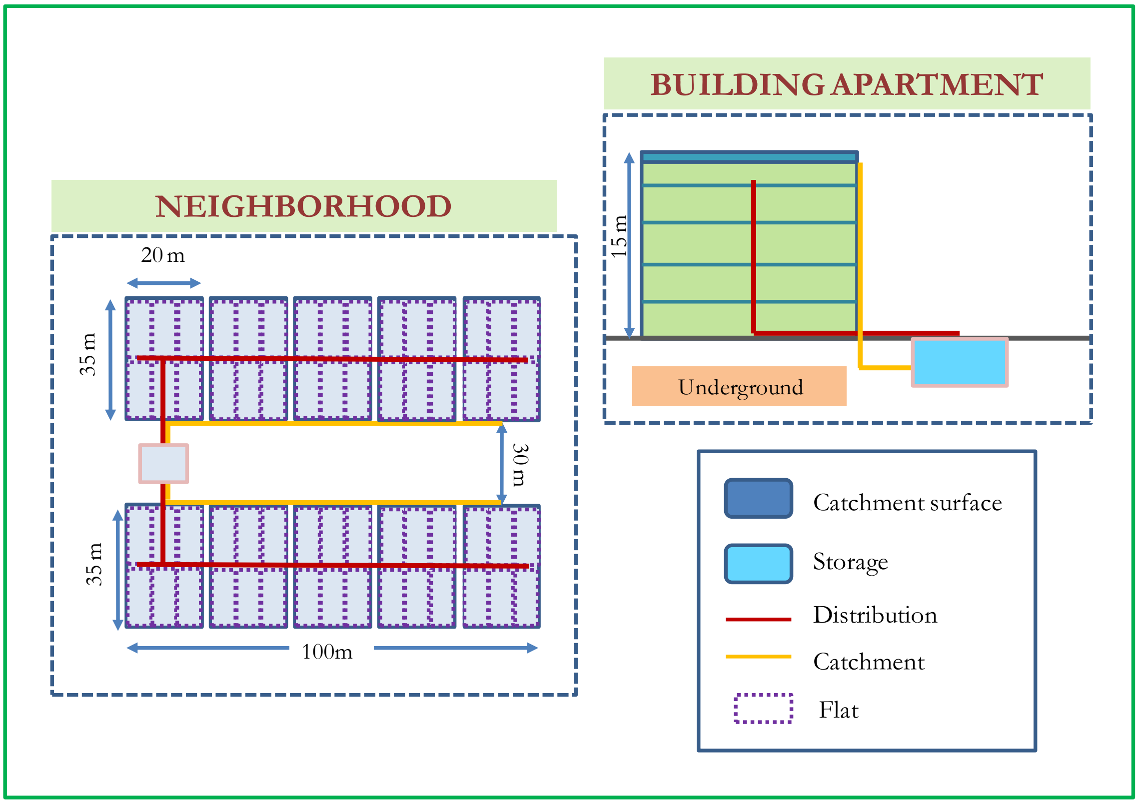


Figure 2-8. RWH system at a neighbourhood scale.

As a method of analysis for potential impacts, the CML Baseline was used (Guinée et al., 2001). The selected impact categories are showed in Table 2-3. The energy use potential of the system (EUP in terms of kWh) was also calculated.

For each material, the potential environmental impact per unit of measurement was calculated with the ecoinvent database (Swiss Centre for Life Cycle Inventories, 2009) with the SimaPro software (PRé Consultants, 2010). These results were exported to the Plugrisost software (Morales-Pinzón et al., 2012). Next, the quantities of material were input and the required processes were estimated by the software to obtain the potential environmental impact of the RWH systems.

The potential environmental impact of a RWH system was compared with the water mains by incorporating it into the Plugrisost software (Morales-Pinzón et al., 2012). A detailed inventory of chemicals, materials and required energy for the conventional water treatment were used. Two alternative tap waters were used for surface water and for the desalination process as referenced by Muñoz et al. (2010).

Table 2-3. Selected environmental impact categories from the CML method

Impact category	Reference substance
Global Warming Potential	GWP in terms of kg CO_2 eq. (Carbon dioxide)
Abiotic Depletion Potential	ADP in terms of kg Sb eq. (Antimony)
Acidification Potential	AP in terms of kg SO_2 eq. (Sulphur dioxide)
Eutrophication Potential	EP in terms of kg PO_4^{3-} eq. (Phosphate)
Human Toxicity Potential	HTP in terms of kg 1,4-DCB eq. (1,4-dichlorobenzene)
Ozone Depletion Potential	ODP in terms of kg. CFC-11 eq. (Trichloromonofluoromethane)
Fresh Water Aquatic Ecotoxicity	FAETP in terms of kg DCB eq. (1,4-dichlorobenzene)
Terrestrial Ecotoxicity	TETP in terms of kg DCB eq. (1,4-dichlorobenzene)
Photochemical Ozone Creation Potential	POCP in terms of kg C_2H_4 eq. (Ethylene)

2.5 Verification and validation procedures

Model verification was performed in the Plugrisost software (Morales-Pinzón et al., 2012) by evaluating the logical consistency from the expected behaviour of the variables. "Verification of intermediate simulation output" was used as one of the four verification techniques presented by Kleijnen (1995). This technique is only reviewed if the computer code contains any programming errors. Each of the subsystems (technical, economic and environmental) was evaluated for their consistency. Next, a general verification was performed for the model.

After the verification process, validation of the model was continued to assess the validity of the conceptual simulation model compared with the correct representative studied system. This validation assessed the validity of the conceptual simulation model compared with the correct representative studied system with a simple test. This test compared the simulated and real data using a graph, tables and a t-test (see Table 2-4) (as is suggested by Kleijnen, 1995).

Table 2-4. Statistic t-test used to validate the RWH model

Null hypothesis	Alternative hypothesis	Statistical test	Rejection region
$\mu_D = \Delta_0$	$\mu_D > \Delta_0$	$T = \frac{\bar{D} - \Delta_0}{S_D / \sqrt{n}}$	$T \geq t_{\alpha,n-1}$
	$\mu_D < \Delta_0$		$T \leq -t_{\alpha,n-1}$
	$\mu_D = \Delta_0$		$\lvert T \rvert \geq t_{\alpha/2,n-1}$

Assumptions: This t-test is applied assuming normality for n sample pairs. $\bar{D}$ represents the difference between the simulated and the real average rainwater supplies. μ_D is the expected value of D and Δ_0 is the value of the null-hypothesis. T is the t statistic and $\bar{D}$ is the average of the n differences between the simulated average n and the real rainwater supply average n in cubic meters per day. n is the number of observations and S_D represents the estimated standard deviation of D. $t_{\alpha/2,n-1}$ is the critical value in the t-distribution.

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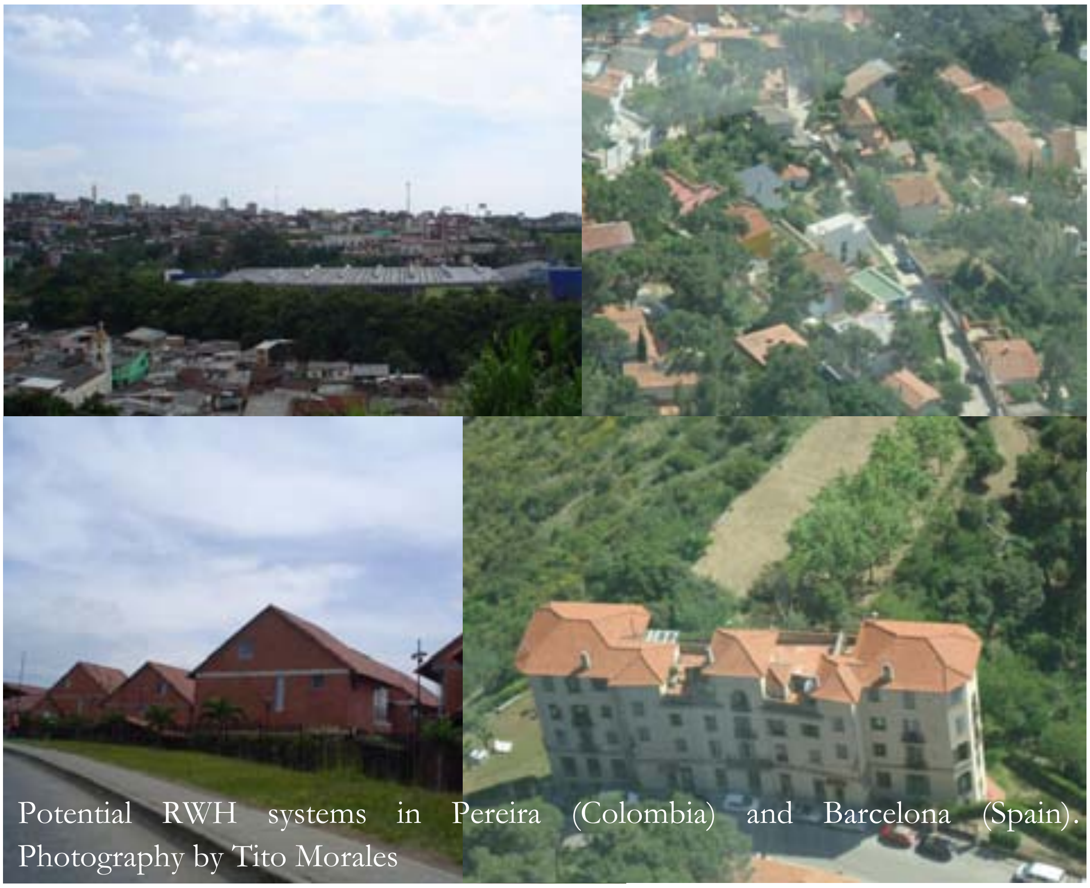
PART II

MODELLING RAINWATER HARVESTING SYSTEMS

Chapter 3

Plugrisost: A Model for Design and Environmental Analysis of Integrated RWH Systems



Potential RWH systems in Pereira (Colombia) and Barcelona (Spain). Photography by Tito Morales

Chapter 3

Plugrisost: A Model for Design and Environmental Analysis of Integrated RWH Systems

3 Plugrisost: A Model for Design, Economic Cost and Environmental Analysis of RWH

This chapter has been used to present the following paper:

Morales-Pinzón T., Rieradevall, J., M. Gasol, C., Gabarrell, X. Plugrisost: A Model for Design, Economic Cost and Environmental Analysis of RWH Systems. Submitted in April 2012 to Environmental, Modelling and Software.

Annexe 1 includes a CD with the file of the Plugrisost software and its user manual.

Abstract
As a result of the integration of different methodological tools and studies to evaluate the economic cost and the potential environmental impact of alternative water supplies (rainwater and greywater) for urban use, the software program Plugrisost (pluvials, greys and sustainability) has been developed. This modelling tool aims to contribute to urban water planning for smart city development. Plugrisost is a simulation model that facilitates the evaluation of rainwater harvesting (RWH) and greywater systems at different scales of urban planning. It is the only tool known thus far to integrate structural elements such as the sizing of storage tanks, estimated cost and quantitative environmental analysis. Plugrisost can be an adequate tool in the design stage because it provides environmental and economic information related to rainwater tank sizing and its estimates are more conservative than those of other tools. Plugrisost contributes to the design of urban infrastructure of low environmental impact, such as infrastructure that incorporates the use of rainwater, and the self-sufficiency analysis of water in cities. Using Plugrisost, we have found that on the single-house scale, the economic viability of a RWH system would be possible if the price of water is greater than 4 Euros/m^3; and the environmental analysis would be favourable to tanks with less than 5 m^3 of storage capacity. On the apartment-building scale, the results are 1.4 Euros/m^3 and 33 m^3, respectively.

Keywords
housing, rainwater harvesting, greywater, LCA, system dynamics.

3.1 Introduction

It is a fact that urban areas are expanding across the globe. The urban population already comprises 70% of the total population in Europe, America and Oceania and up to 50% of the global population (United Nations, 2006), and this value is expected to continue to grow during this century (Bai, 2007). Rainwater is an alternative water supply that can be utilised for domestic use in urban environments; such use would constitute an anticipated response (UN-Water, 2011) to the high demand for a water network due to urban growth and would help mitigate the effects of climate change (Kahinda et al., 2010) in both developed and developing countries. As a complement to rainwater, greywater would contribute to a reduction in tap water consumption (Dixon et al., 1999), especially for uses that do not require high water quality. Rainwater harvesting and greywater would help to increase the self-sufficiency of cities in terms of water demand.

Furthermore, there is a tendency in urban planning to consider sustainability as a criterion for planning and life style in cities (Inayatullah, 2011). This tendency is reflected in the certification systems of buildings and neighbourhoods (e.g., LEED) that promote buildings that are environmentally responsible (e.g., water efficient). A necessary condition for developing "smart cities" is the wise management of natural resources to contribute to sustainable urban development (Caragliu et al., 2009). The goal of sustainability in these areas could be defined as reducing the use of natural resources and waste production while simultaneously improving liveability and quality of life, which may be best handled within the capabilities of local, rather than regional or global, ecosystems (Newman, 1999), within a context of social equity and welfare.

In this context and keeping in mind the challenges presented by self-sufficiency and smart-city planning, water would be considered a limited natural resource for future growth and the development of urban areas. Water is an endangered resource, with nearly two million tons of waste (industrial, urban and agricultural) discarded into receiving waters. This threat is greater when rainwater (and greywater) is considered as waste. Rainwater is the main source of fresh water for various uses and ecosystems (United Nations/World Water Assessment Programme, 2003).

According to the Summit of Sustainable Development held in Johannesburg in 2002, the use of rainwater has been incorporated with greater force into the political agendas of many countries (India, Nepal, Australia, Germany, United

States) as a strategy to promote sustainability (World Water Assessment Programme, 2012).

To enable the sustainability of urban water, the management of domestic rainwater and greywater is a main factor. Growing evidence of worldwide water scarcity and the need for cooperation and integration to ensure sustainable, efficient and equitable water resources, both locally and internationally, have been highlighted by the United Nations (2007). The main purpose of rainwater harvesting is to supplement the water supply of urban systems and reduce the pressure on tap water use. Additionally, it is possible to reduce the environmental impact of urban water, making the management of water resources more efficient. Rainwater harvesting (RWH) and reusing and recycling (grey) water reduces negative downstream and upstream effects on water quality and quantity (UN-Water, 2011).

RWH systems have three objectives: first, on the macro scale, to offer water as a strategic response to urban growth; second, on the design scale, to meet the highest percentage of the demand for rainwater from a building or neighbourhood; and third, to obtain economic, environmental and social results justifying a decentralised system of water.

In this regard, one of the most urgent issues is the need for the appropriate tools to provide as much detail as possible regarding the technical, economic and environmental feasibility of implementing RWH systems. These demands include the analysis of different alternative water supplies for domestic use (rainwater and greywater) as support for the proper planning of current and future urban development projects.

There is a significant number of models and specialised computer software to analyse alternatives water supplies for urban and other uses. The detailed review by Zoppou (2001) focuses on models used to simulate stormwater quantity and quality in an urban environment, and Elliott and Trowsdale (2007) analysed models for low-impact urban stormwater drainage systems. Ward, Memon and Butler (2010) discuss ten models used to analyse RWH systems. Some of these software, e.g., UWOT (Makropoulos et al., 2008), allow for a qualitative assessment of sustainability.

These models feature different levels of detail and are focused on sizing tanks, supply and rainwater harvesting (using historical records) and domestic water demand.

Although the software incorporate great environmental awareness and some are very robust, none of the models integrate a lifecycle assessment perspective. The decision to implement RWH systems is usually based on the results of financial and economic analyses. This occurs due to the lack of tools that can evaluate these systems according to environmental and social criteria.

Consequently, the objective of this research was to develop a software program called Plugrisost (acronym for pluvials, greys and sustainability) to facilitate the planning and management of rainwater harvesting and greywater systems. The specific objectives of this paper are as follows:

- To discuss the issues that contributed to the conceptualisation of the Plugrisost software.
- To present a general algorithm for the analysis of integrated RWH systems in terms of rainwater use, greywater reuse and potential environmental impacts.
- To demonstrate the performance of some quantitative indicators of RWH systems used for environmental analysis and to optimise the storage volume.

3.2 Method

The following describes the methodology considered when developing the Plugrisost software program.

3.2.1 Urban water system design

As a model for urban water systems, Plugrisost analyses the optimal design variables, cost and environmental performance of RWH and Greywater systems, using tap water production as a reference system for comparison.

Tap water production includes water catchment, treatment and distribution. Rainwater harvesting includes the storage, processing and distribution of rainfall. Greywater includes catchment, processing and reuse.

Domestic water use includes using water in domestic activities for internal or external applications (cleaning, toilet and garden) and potential greywater recycling. Wastewater treatment includes the transportation and treatment of wastewater and sludge produced. Urban processing comprises urban use and water treatment, and urban management includes connections with other systems (Figure 3-1).

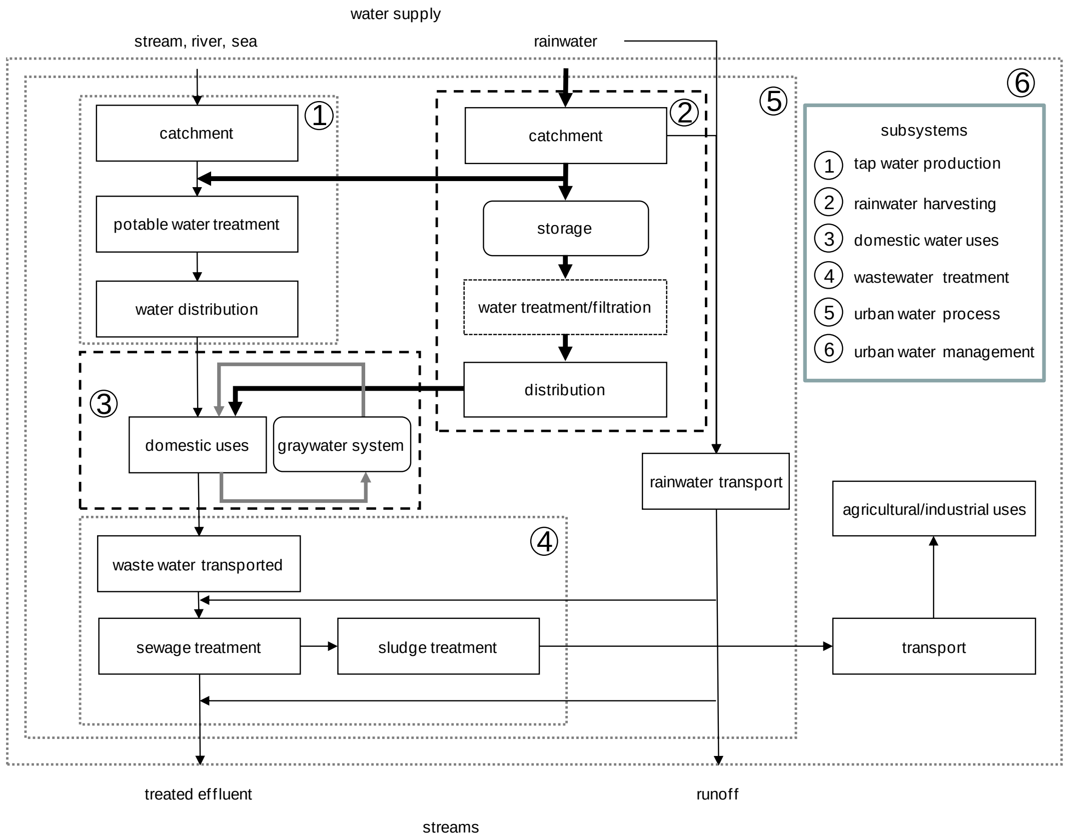


Figure 3-1. Urban water system considered in Plugrisost

Current supply plans are focused on subsystems 1 to 3, where our efforts were focused (Figure 3-1). Subsystem 1 models potable water treatment in terms of the inputs required to treat two alternative water sources: surface water and salt water. Subsystem 2 models only filtration, excluding the treatment of rainwater. Subsystem 3 models all flows according to specific internal and external demands, including the potential use of greywater.

3.2.2 Simulation algorithms applied in Plugrisost

There are different algorithms that can be used to model the flows and volume in store of RWH and Greywater systems. For RWH systems, Fewkes (1999) uses two algorithms, YAS (yield-after-spill) and YBS (yield-before-spill), based on an original concept devised by Jenkins et al. (1978). In their general form, both algorithms are represented by equations 3-1 to 3-3 (Latham, 1983). YAS and YAB are based on a water mass balance (Eq. 3-1), water consumption from a rainwater tank (Eq. 3-2) and the volume remaining in the cistern (Eq. 3-3).

$$V_t = V_{t-1} + Q_t - D_t \qquad \text{(Eq. 3-1)}$$

$$Y_t = min\begin{cases} D_t \\ V_{t-1} + \theta Q_t \end{cases} \quad \text{(Eq. 3-2)}$$

$$V_t = min\begin{cases} (V_{t-1} + Q_t - \theta D_t) - (1-\theta)Y_t \\ S - (1-\theta)Y_t \end{cases} \quad \text{(Eq. 3-3)}$$

where:

V_t volume in store during time interval (t)

Q_t rainwater runoff during time interval (t)

Y_t yield from store during time interval (t)

D_t rainwater demand during time interval (t)

S store capacity

θ a parameter between 0 and 1. If θ=0, then the algorithm is YAS, and if θ=1, the algorithm is YAB.

In Plugrisost, the algorithm used to model these systems is based on system dynamics. System dynamics is a methodology proposed by Forrester (1961) to model complex systems. By identifying only two components (levels/stocks and rates/flows), it is possible to describe any system (Figure 3-2). The level (L) is the increase or decrease in system volume due to flows (Eq. 3-4). When the inflow (I_f) and the outflow (O_f) are known at each time step, equation 3-5 defines the system. Then, the level (L) at time t corresponds to the initial level $L(t_0)$ and the integral of its net flow (I_f - O_f) over time (Eq. 3-6).

$$\frac{dL}{dt} = (I_f - O_f) \quad \text{(Eq. 3-4)}$$

$$L_{(t)} = L_{(t-dt)} + (I_f - O_f) \cdot dt \quad \text{(Eq. 3-5)}$$

$$L_{(t)} = L_{(t_0)} + \int_{t_0}^{t} (I_f - O_f) \cdot ds \quad \text{(Eq. 3-6)}$$

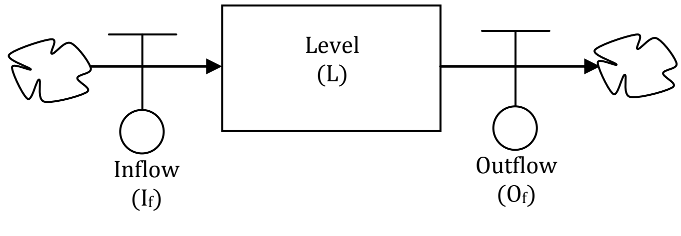


Figure 3-2. Essential blocks in a system dynamics model

A behavioural model of a RWH system will be fully defined if we know the initial conditions of the system variables that compose the general equation of mass balance (Eq. 3-5). Following the methodology selected, the model was constructed in Stella, a software program that is widely used to model dynamic systems. This program, like many others, solves equation 3-6 using Runge–Kutta methods (Euler's approximation, 2^{nd}-order and 4^{th}-order Runge-Kutta) (High Performance Systems, 2004).

To apply these methods, equation 3-5 is used. Due to the use of integer variables in the model, we applied the Euler method. Additionally, changes in the system are assumed to occur over an interval of one day; thus, a dt equal to 1 is used, which, compared to a lower value of dt, does not generate significant changes in the system indicators. A dt value equal to one requires less computational time than a smaller dt.

3.2.3 Determining factors in the design of RWH systems

As determining factors in building the model, we considered two central aspects: tank size and scale of analysis.

Storage tank sizing has been the central component of most published studies on the design of RWH systems. Following this approach and according to Guisi (2010), the sizing of rainwater tanks in houses (or buildings) is a function of rainwater catchment and rainwater demand. Rainwater catchment is a function of roof area and rainfall. Domestic rainwater demand is determined by the number of residents and water demand for uses that do not require tap water quality.

Another factor to consider is the scale of analysis because this can significantly affect the design parameters and, according to Angrill et al. (2011a), the potential environmental impacts in particular. To include this factor, the scale of analysis in Plugrisost (house, building, and large surface area) is considered as the building or buildings that meet the basic definition of roofed construction with walls used as a dwelling or for production activity (European Commission, 2009) (see Table 3-1).

Plugrisost focuses on residential buildings such as semi-detached houses and apartment houses. These include different urban scales as individual buildings, single-residential and neighbourhood or multi-residential buildings (see Table 3-1).

Table 3-1. Scale of analysis in RWH model

Residential building	Semi-detached house	Single-house or single-residential
		Group of houses or multi-residential houses (*)
	Apartment house	Apartment building
		Group of apartment buildings or apartment blocks (*)
Non-residential building	Large surface	Commercial
		Public
		Service

(*) Can be considered as being on the neighbourhood scale.

3.2.4 General model assumptions

We defined the minimum conditions of homogeneity that would be obtained for the analysis and a comparison with a reference system.

The scale of analysis used in the model was that of a single-family house. A neighbourhood is modelled using single-family houses and apartment buildings.

All dwellings are homogeneous with respect to rainwater roof area, and similarly, buildings are homogeneous with respect to catchment surface as well as the number of floors and apartments per floor. When modelling a large area, it is assumed that the whole catchment area is connected and that rainwater can be captured in the same tank.

Each home is inhabited by the same number of people, making it possible to assume average values for the variables of water demand for internal and external applications. Water demand can be modelled as either a constant or variable depending on the day or month of the year; however, in the absence of data, the daily average value is used unless indicated otherwise.

Precipitation is the same for the entire system and is assumed to be homogeneous throughout the day it rained. The model does not take into account the number of episodes of rain or their duration. The value captured is the daily rainfall recorded by weather stations or estimated by stochastic models.

Because the model is developed using a day-time interval, the behaviours of supply and demand are held constant for each simulated day.

There is no waste of water in distribution, and all deposits incorporated into the model are initially empty.

When water demand can make use of both rainwater and greywater, the hierarchy of use is as follows: greywater, rainwater, tap water.

3.3 Comparison of Plugrisost with others RWH models

To compare the performance of Plugrisost, we selected two software programs (Aquacycle and RainCycle) suggested by Ward, Memon and Butler (2010) that use a generic algorithm. Aquacycle is a general tool that models a continuous water balance using a YBS algorithm (Mitchell, 2005). RainCycle is a modelling tool built specifically for RWH systems; it uses a YAS algorithm to construct a continuous mass-balance simulation (Roebuck and Ashley, 2006).

A single-family house and apartment building were used as two scales for comparison; their input values are presented in Table 3-2.

Volume of rainwater used and the percentage of demand satisfaction were used as variables for comparison. Both indicators can be calculated using any of the three programs indicated. Additionally, in Plugrisost, Global Warming Potential (GWP, kg CO_2 eq.) and Energy Use (kWh/m^3) were selected as environmental indicators associated with life cycle assessment (LCA), and cost of rainwater used in the system (Euros/m^3) was selected as an economic indicator. These indicators are only available in Plugrisost.

Three scenarios were developed for each analysis: optimistic (more favourable), pessimistic (less favourable) and average (using all rainfall data).

Table 3-2. Inputs to RWH models

Variable	**Year**	**Single-house**	**Apartment building**	**Input required by... (3)**
Rainfall (L/m²/year) (1)	2002	954.4		P, R, A
	2003	601.3		
	2004	577.4		
	2005	558.6		
	2006	474.6		
	2007	493.3		
	2008	600.1		
	2009	524.3		
Domestic water demand (L/day) (2)	2002 to 2009	773	18552	P, A
kitchen water use (L/day)		74	1776	P, A
bathroom water use (L/day)		258	6192	P, A
toilet water use (L/day)		237	5688	P, A
laundry water use (L/day)		204	4896	P, A
Domestic rainwater demand (L/day)		441	10584	P, R, A
Domestic greywater demand (L/day)		0	0	P, A
Catchment area (m²)		100	700	P, R, A
Runoff coefficient (0-1)		1	1	P, R
First-flush volume (mm)		0	0	P, R, A
Filter Coefficients (0-1)		1	1	P, R

(1) Daily data from weather station of Barcelona-Fabra (Agencia Estatal de Meteorología, 2011). (2) Daily data from a water-use profile (Mitchell, 2005). (3) Abbreviation for software programs applied in the analysis (P: Plugrisost, R: RainCycle, A: Aquacycle)

3.3.1 Environmental analysis in Plugrisost

The environmental impact model included a simplified LCA in which, according to ISO14040 (2006), the functional unit was defined as the collection, storage and supply of 1 m³ of rainwater to be used as non-potable water for a household washing machine and a toilet with a constant combined demand of 441 L/day on the single-house scale and 10584 L/day on the apartment-building scale.

The environmental impact assessment is based on CML Baseline v2.04 (Guinée et al. (2001), and the selected impact categories were the Global Warming Potential (GWP, kg CO_2 eq.) and the energy use potential of the system (EUP, kWh). The ecoinvent v2.2 database (Swiss Centre for Life Cycle Inventories, 2009) was used in combination with the software program SimaPro7.2.0 (PRé Consultants, 2010) for these assessments.

To compare the environmental performance of the RWH systems, the impact associated with the consumption of tap water was estimated from the average consumption of the inputs of potable-water plants in Spain using data from previous studies (Muñoz et al., 2010). The life spans of rainwater storage tanks, pipes and pumps are 50, 25 and 15 years, respectively (Roebuck et al., 2011).

According to Morales-Pinzón et al. (2011), the centralised system was defined as the standard treatment processes of water of surface origin, which include the average consumption of chemical inputs and the average energy required to purify and distribute water.

3.3.2 Variability analysis in Plugrisost

After obtaining an adequate volume for the rainwater tank, using the Plugrisost program, the average scenario was used to perform a statistical analysis of the system using simulated rainfall. This was performed by using one of the probabilistic models available in the software. Variability was observed in the variables percentage of demand met and GWP as a potential impact on the environment.

To estimate daily precipitation, the correct use of either probability distribution depends on the settings provided by the model. Two widely used tests of goodness of fit are the Lilliefors modification of the Kolmogorov-Smirnov (LKS) and the Kolmogorov-Smirnov (KS). However, it should be mentioned that it is essential to perform verification tests with different data than those used to generate the parameter estimates. Vlček and Huth (2009) demonstrated that the two tests yield considerably different results, with the LKS test being the preferred one. This test was used to select the best-fit model for rainwater.

3.4 General algorithm for flows and stocks of water in Plugrisost

Each analysis unit (house, building and large surface area) can be represented by the general scheme shown in Figure 3-3. Rainwater and greywater tanks were considered as distinct levels. The first level is affected by the inflow of rainwater

(R) and by the water outflow (Y) to meet the internal and external demand of rainwater (Dyi + Dye). The second level is affected by the potential inflow of wastewater (W) and the outflow of greywater reuse (Z) to meet the internal and external demand (Dzi + Dze). The flow of mains water (Ts) that supplies the unsatisfied amount of unconventional systems (Ti + Te) is considered as a supplementary variable.

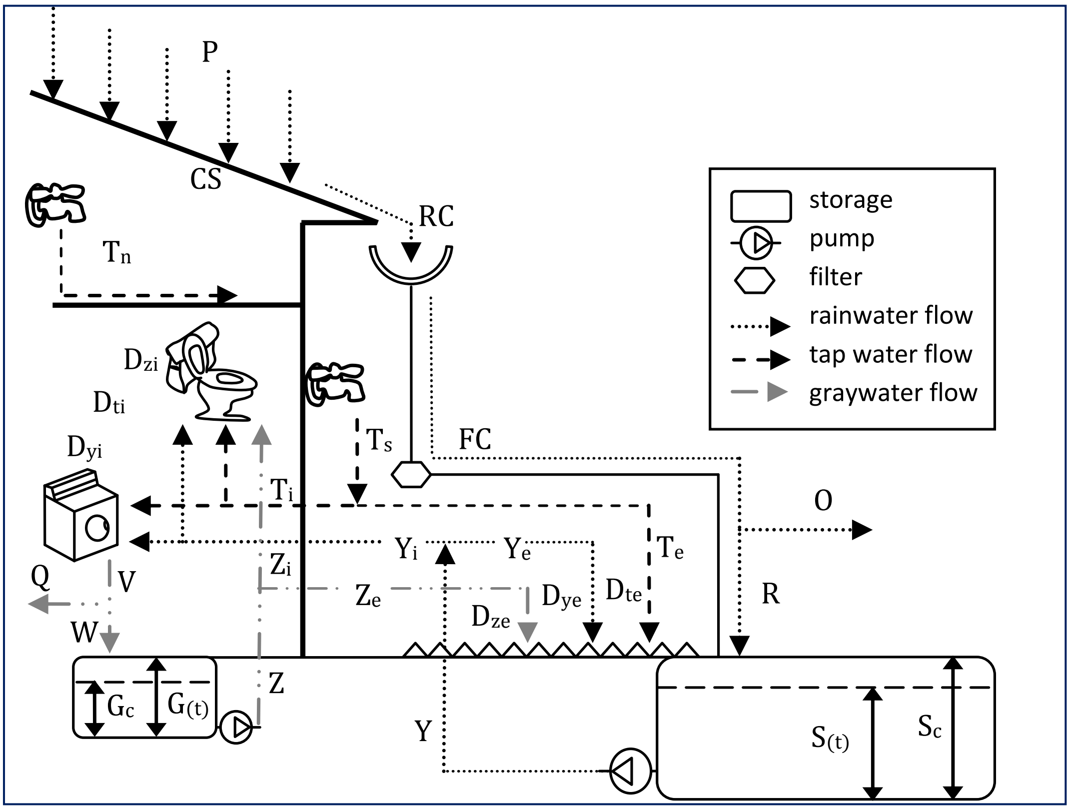


Figure 3-3. RWH system configuration

The general model can be described by three smaller models, which represent the rainwater, greywater and tap water flows and stocks.

3.4.1 Rainwater model

To model the potential of rainwater harvesting, it is common to directly use daily rainfall records of a given site or to use these data to estimate the parameters of random patterns that have been incorporated into software. Thus, rainfall is the first variable that will be modelled because it will affect the future yield of the system.

When modelling this variable, it is required that data be obtained from representative historical series. These data are usually available at institutions managing local weather stations. Historical rainfall records are inputs that reproduce past climate conditions and that under certain assumptions can be considered representative of local conditions to come.

In Plugrisost, the instantaneous variation in the volume of water in a rainwater tank is calculated using the following equation:

$$\frac{dS}{dt} = R - Y \qquad \text{(Eq. 3-7)}$$

where:

R useful runoff or inflow in rainwater store (m^3/d)

Y yield from rainwater tank (m^3/d)

Because not all of the rain can be harvested, the useful runoff is calculated as follows:

$$R = min\begin{cases} P \cdot CS \cdot RC \cdot FC, \\ S_c - S_{(t-dt)} \end{cases} \qquad \text{(Eq. 3-8)}$$

where:

P precipitation (m^3/d)

CS catchment surface (m^2)

RC runoff coefficient

FC filter coefficient

S_c storage capacity of rainwater tank (m^3)

$S_{(t-dt)}$ water volume of rainwater storage tank at time t-dt (m^3)

t moment in time (d)

dt interval of time between calculations

When the type of roof is a known variable, we recommend using the relationships described by Farreny et al. (2011), which have been incorporated into the model using equation 3-9.

$$R = min\begin{cases} (a_1 \cdot P + a_2 \cdot 10^{-3}) \cdot CS \cdot FC, \\ S_c - S_{(t-dt)} \end{cases} \qquad \text{(Eq. 3-9)}$$

where:

a_1 slope

a_2 independent term (L/m^2)

The values of "a_1" and "a_2" and the initial abstraction "$(-a_2/a_1)$" were estimated by Farreny et al. (2011) for clay tiles (0.95, -0.80), flat gravel (0.94, -3.55), metal (0.87, 0.32) and plastic (0.89, 0.48).

To estimate the yield from a rainwater tank, we need to know both the internal and external yield:

$$Y = Y_i + Y_e = min\begin{cases} D_y, \\ S_{(t)} \end{cases} \quad \text{(Eq. 3-10)}$$

where:

Y_i yield from rainwater tank for internal uses (m^3/d)

Y_e yield from rainwater tank for external uses (m^3/d)

D_y rainwater demand (m^3/d)

$S_{(t)}$ water volume of rainwater storage tank at time t (m^3)

For a residential building, the model makes a distinction between internal and external quality demands. This distinction helps model a larger number of scenarios and estimate the associated yield. A wide description and review of domestic water demand around the world is provided by Ratnayaka, Brandt, and Johnson (2009). In Plugrisost, the internal and external demand includes the most common house rainwater uses:

$$D_y = D_{yi} + D_{ye} \quad \text{(Eq. 3-11)}$$

$$D_{yi} = D_{wc} \cdot \varphi_1 + D_h \cdot \varphi_2 + D_k \cdot \varphi_3 + D_l \cdot \varphi_4 \quad \text{(Eq. 3-12)}$$

$$D_{ye} = D_p \cdot \varphi_5 + D_g \cdot \varphi_6 + D_o \cdot \varphi_7 \quad \text{(Eq. 3-13)}$$

$$\varphi_j = \begin{cases} 1, if\ \omega_j = 0 \wedge \tau_j = 0 \\ 0, if\ \omega_j = 1 \vee \tau_j = 1 \end{cases} \quad \text{(Eq. 3-14)}$$

where:

D_{yi} rainwater demand for internal uses (m^3/d)

D_{ye} rainwater demand for external uses (m^3/d)

D_{wc} water demand for WC (m^3/d)

D_h water demand for personal hygiene (m^3/d)

D_k water demand for kitchen uses (m^3/d)

D_l water demand for laundry (m^3/d)

D_p water demand for pool (m^3/d)

D_g water demand for garden (m^3/d)

D_o water demand for other uses (m^3/d)

φ_j rainwater quality indicator

ω_j greywater quality indicator

τ_j tap water quality indicator

In addition, the intermittent demand for water use in washing machines is obtained using the following equation:

$$D_l = \begin{cases} \dfrac{7 \cdot D_{lc}}{y}; \; if \; yt = t \\ 0; \; if \; yt \neq t \end{cases}$$ (Eq. 3-15)

where:

D_{lc} water demand equivalent per one day for laundry (m^3/d)

y number of days a week using washing machine (d)

t simulated day

The volume of water in a rainwater tank at any moment of time is calculated by integrating equation 3-7:

$$S_{(t)} = S_{(t-dt)} + (R - Y) \cdot dt$$ (Eq. 3-16)

For the excess flow of rainwater, the following expression is used:

$$O = P \cdot CS \cdot RC \cdot FC - R$$ (Eq. 3-17)

where:

O overflow of rainwater (m^3/d)

3.4.2 Simulation of rainfall data

It is not possible to know with certainty the behaviour of supply because if rainfall is considered a stochastic variable, then the ease of finding a suitable tank size for a particular site (or build) is conditional (Ngisi, 1999). However, the system can be studied to understand the expected behaviour.

Some RWH studies propose using stochastic and probabilistic models to evaluate the system, modelling rain (Basinger et al.l, 2010) or water deficit (Su et al., 2009).

According to Castellvi, Mormeneo and Perez (2004), with respect to the incidence of wet days, it has been shown that a first-order model performs well for a wide range of different climates. In most cases and climates, this model includes wet spells as well as higher-order models (Wilks, 1999). Markov chain models are widely used because of their simplicity and parsimony in modelling (Ng and Panu, 2010).

Daily precipitation can be modelled using parametric models of exponential (Cowden et al., 2008), mixed exponential [Wilks (1999), Schoof (2008)], log-normal (Shoji and Kitaura, 2006), Weibull (Castellví et al., 2004) and gamma distributions [Wilks (1999); Katz (1999); Groisman, et al. (1999); Semenov and Bengtsson (2002); Zolina et al. (2004); Husak et al., (2007)]. Nonparametric models can also be very efficient in representing daily rainfall (Basinger et al., 2010).

To generate data regarding daily precipitation that can be used in statistical analyses of a system, the incidence of rain and the amount of rain falling during the day were combined in Plugrisost. Wet days were generated using a first-order Markov chain, and a single-step transition was defined for each month of the year:

$$p_{(uv)m} = \begin{cases} Pr(w/w)_m \,; u = 1 \wedge v = 1 \\ Pr(w/d)_m; \; u = 1 \wedge v = 0 \\ Pr(d/w)_m; \; u = 0 \wedge v = 1 \\ Pr(d/d)_m; \; u = 0 \wedge v = 0 \end{cases} \qquad \text{(Eq. 3-18)}$$

where:

$p_{(uv)m}$ probability (Pr) of wet or dry day in time t given a wet or dry day at time t-1

u rain or dry state of the current day

v rain or dry state of the previous day

w wet day

d dry day

m month of year

Using the relative frequency of rainfall events in the local historical series as an estimator of probability:

$$p_{(11)m} \cong \frac{n(w/w)_m}{n_m} \qquad \text{(Eq. 3-19)}$$

$$p_{(01)m} \cong \frac{n(w/d)_m}{n_m} \qquad \text{(Eq. 3-20)}$$

where:

p_{11} Pr of rain in day t given rain at time t-1

p_{01} Pr of rain in day t given no rain at time t-1

$n(w/w)_m$ number of days with rain on day t given rain at time t-1 in month m

$n(w/d)_m$ number of days with rain on day t given no rain at time t-1 in month

n_m number of days in month m

To simulate rainfall, we opted to use log-normal, Weibull and gamma models. The density functions of the gamma, Weibull and log-normal precipitation distributions are:

$$f(x,\alpha,\beta) = \frac{x^{\alpha-1}e^{-x/\beta}}{\beta^{\alpha}\Gamma(\alpha)};\ \alpha > 0, \beta > 0 \qquad \text{(Eq. 3-21)}$$

$$f(x,\gamma,\kappa) = \frac{\kappa}{\gamma}\left(\frac{x}{\gamma}\right)^{\kappa-1} e^{-(x/\gamma)^{\kappa}};\ \ \gamma > 0, \kappa > 0 \qquad \text{(Eq. 3-22)}$$

$$f(x;\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-[lnx-\mu]^2/2\sigma^2} \qquad \text{(Eq. 3-23)}$$

where:

x daily amount of precipitation

β scale parameter

α shape parameter

Γ gamma function

γ scale parameter

κ shape parameter

μ mean of natural log of x

σ standard deviation of natural log of x

The distribution parameters were estimated for each month of the year. For the gamma distribution, the estimators for β and α were calculated using Thom's (1958) approximation:

$$\hat{\alpha} = \frac{1+\sqrt{1+\frac{4A}{3}}}{4A} \qquad \text{(Eq. 3-24)}$$

$$A = \ln(\bar{y}) - \frac{1}{n}\sum_{i=1}^{n} \ln(y_i) \qquad \text{(Eq. 3-25)}$$

$$\hat{\beta} = \frac{\bar{y}}{\alpha} \qquad \text{(Eq. 3-26)}$$

where:

A difference between the natural log of the sample mean and the mean of the natural logs of the data

$\bar{y}$ sample mean

y_i precipitation data for wet day i

n amount data

$\hat{\alpha}$ shape gamma estimator

$\hat{\beta}$ scale gamma estimator

For the Weibull distribution, the estimators for κ and γ were calculated using the Maximum Likelihood Estimator and the Excel Solver tool as follows:

$$\sum_{i=1}^{n} y_i^{\hat{\kappa}} ln(y_i) \Big/ \sum_{i=1}^{n} y_i^{\hat{\kappa}} - \frac{1}{\hat{\kappa}} - \frac{1}{n} \sum_{i=1}^{n} ln(y_i) = 0 \quad \text{(Eq. 3-27)}$$

$$\hat{\gamma} = \sum_{i=1}^{n} y_i^{\hat{\kappa}} / n \quad \text{(Eq. 3-28)}$$

where:

$\hat{\kappa}$ shape Weibull estimator

$\hat{\gamma}$ scale Weibull estimator

For the log-normal distribution, the estimators for μ and σ were calculated using the following:

$$\hat{\mu} = \sum_{i=1}^{n} ln(y_i) / n \quad \text{(Eq. 3-29)}$$

$$\hat{\sigma}^2 = \sum_{i=1}^{n} [ln(y_i) - \hat{\mu}]^2 / n \quad \text{(Eq. 3-30)}$$

where:

$\hat{\mu}$ estimator of mean of natural log of x

$\hat{\sigma}^2$ estimator of variance of natural log of x

3.4.3 Greywater model

Similar to the rainwater model, the instantaneous variation in the volume of water in the tank for greywater is computed using the following relationship:

$$\frac{dG}{dt} = (W - Z) \qquad \text{(Eq. 3-31)}$$

where:

W inflow in greywater system (m^3/d)

Z yield from greywater tank (m^3/d)

The amount of water entering the greywater system is:

$$W = min\begin{cases} V, \\ G_c - G_{(t-dt)} \end{cases} \qquad \text{(Eq. 3-32)}$$

where:

V greywater produced by system (m^3/d)

G_c storage capacity of greywater tank (m^3)

$G_{(t\text{-}dt)}$ water volume of greywater storage tank at time t-dt (m^3)

To estimate the yield from a greywater system, the following equation is used:

$$Z = Z_i + Z_e = min\begin{cases} D_y, \\ S_{(t)} \end{cases} \qquad \text{(Eq. 3-33)}$$

where:

Z_i internal use and yield from greywater tank (m^3/d)

Z_e external use and yield from greywater tank (m^3/d)

D_z greywater demand (m^3/d)

$G_{(t)}$ water volume of greywater tank at time point t (m^3)

Quality demands include the most common household uses of greywater:

$$D_z = D_{zi} + D_{ze} = D_{wcz} \cdot \omega_1 + D_{gz} \cdot \omega_2 + D_{oz} \cdot \omega_3 \qquad \text{(Eq. 3-34)}$$

$$D_{zi} = D_{wc} \cdot \omega_1 \qquad \text{(Eq. 3-35)}$$

$$D_{ze} = D_g \cdot \omega_2 + D_o \cdot \omega_3 \qquad \text{(Eq. 3-36)}$$

$$\omega_j = \begin{cases} 1, if\ \tau_j = 0\ \land\ \varphi_j = 0 \\ 0, if\ \tau_j = 1 \lor \varphi_j = 1 \end{cases} \qquad \text{(Eq. 3-37)}$$

where:

D_{zi} greywater demand for internal uses (m^3/d)

D_{ze} greywater demand for use external uses (m^3/d)

The volume of water in a greywater tank at any moment is calculated using the following equation:

$$G_{(t)} = G_{(t-dt)} + (W - Z) \cdot dt \qquad \text{(Eq. 3-38)}$$

For excess greywater flow, the following expression is used:

$$Q = V - W \qquad \text{(Eq. 3-39)}$$

where:

Q overflow of greywater (m^3/d)

3.4.4 Tap water model

This model describes the tap water consumption estimated from shared uses of rainwater and greywater. The tap water used in a system is calculated using the following equations:

$$T = T_n + T_s \qquad \text{(Eq. 3-40)}$$

$$T_s = T_i + T_e \qquad \text{(Eq. 3-41)}$$

where:

T_n tap water in non-shared uses (m^3/d)

T_s tap water in shared uses (m^3/d)

T_i tap water in internal uses (m^3/d)

T_e tap water in external uses (m^3/d)

Demand includes the most common household uses of tap water:

$$D_t = D_{ti} + D_{te} \qquad \text{(Eq. 3-42)}$$

$$D_{ti} = D_{wc} \cdot \tau_1 + D_h \cdot \tau_2 + D_k \cdot \tau_3 + D_l \cdot \tau_4 \qquad \text{(Eq. 3-43)}$$

$$D_{te} = D_p \cdot \tau_5 + D_g \cdot \tau_6 + D_o \cdot \tau_7 \qquad \text{(Eq. 3-44)}$$

$$\tau_j = \begin{cases} 1, if\ \varphi_j = 0 \wedge \omega_j = 0 \\ 0, if\ \varphi_j = 1 \vee \omega_j = 1 \end{cases} \qquad \text{(Eq. 3-45)}$$

where:

D_t tap water demand (m^3/d)

D_{ti} tap water demand for internal uses (m^3/d)

D_{te} tap water demand for external uses (m^3/d)

3.4.5 Economic cost in Plugrisost

To estimate the economic cost of the infrastructure, Plugrisost uses the costs of tanks, pumps and accessories of installation and renovation of the system using data obtained from 8, 2 and 2 suppliers, respectively, as a reference. Using data from Morales et al. (n.d.), 12 RWH systems were studied in detail to estimate a potential function of the cost of infrastructure; the operating cost of energy used to pump water was also included. The resulting economic cost of the RWH system was converted to total cost by 1 m^3 of storage, allowing for the generation of a cost curve depending on the size of the deposit.

To estimate the cost of rainwater supplied, the following equations were used:

$$C_{Ys} = {C_Y}/{(LS \cdot Y)} + C_E \cdot E_Y \cdot Y \qquad \text{(Eq. 3-46)}$$

$$C_Y = C_{Yi} \cdot S_c \qquad \text{(Eq. 3-47)}$$

$$C_{Yi} = b_1 \cdot (S_c)^{-b_2} \qquad \text{(Eq. 3-48)}$$

where:

C_Y economic cost of rainwater infrastructure (Euros)

C_{Yi} economic cost equivalent by 1 m^3 of storage capacity (Euros/m^3)

C_E cost of energy (Euros/kWh)

b_1, b_2 parameters of potential model

LS life span of the system (days)

E_Y energy used in pumping rainwater (kWh/m^3)

The parameters used by Plugrisost in the potential model were 6395 and 0.61 for b_1 and b_2, respectively, with a coefficient of determination (R^2) of 0.99. Additionally, the cost of energy by default was 0.14 Euros/kWh, which is the referenced price in Spain (CNE, 2012).

3.4.6 General algorithm for potential environmental impacts in Plugrisost

To estimate the potential environmental impact (PEI), Morales-Pinzón et al. (2011) propose a general model using system dynamics methodology and LCA. In Plugrisost, the system was divided into two components. First, infrastructure included the PEIs of relevant materials and activities used to build the system. Second, system use included the PEIs of energy use and inputs required for the system to function. The added impacts were estimated using LCA methodology.

The total potential environmental impact was calculated using the following expression:

$$I_{(t)} = I_{(t-dt)} + (I_Y + I_Z + I_T + I_K) \cdot dt \qquad \text{(Eq. 3-49)}$$

where:

I_Y PEI of rainwater

I_z PEI of greywater

I_T PEI of tap water

I_K PEI of waste water

Plugrisost includes detailed models for rainwater and tap water. For the PEI of rainwater, the following expression is used:

$$\frac{d(I_Y)}{dt} = I_{Yi} + I_{Yc} \qquad \text{(Eq. 3-50)}$$

where:

I_{Yi} PEI for infrastructure of rainwater

I_{Yc} PEI for pumping of rainwater

For comparison between different alternatives, the potential environmental impacts of rainwater infrastructure are allocated proportionally to the time of system operation. This will assign an impact proportional to flows under the hypothesis that the full impacts can be allocated proportionally.

The PEI of the infrastructure is calculated from the impact generated by the materials used in constructing the system (including replacement during the life span):

$$I_{Yi} = \sum [q_i \cdot (e_i + p_i) + w_i \cdot t_i]/LS \qquad \text{(Eq. 3-51)}$$

where:

q_i amount of material (kg or m^3)

e_i PEI per unit of material (PEI/kg or PEI/m^3)

p_i PEI of process associated with the materials (PEI/kg or PEI/m^3)

w_i weight of transported material

t_i PEI of transported material (PEI/tkm)

The PEI of the energy used to pump rainwater is estimated using the following equation:

$$I_{Yc} = Y \cdot E_Y \cdot e_{E1} \quad \text{(Eq. 3-52)}$$

where:

e_{E1} PEI of low-voltage electricity (PEI/kWh)

Additionally and for comparison purposes, Plugrisost includes a model to estimate the impacts of tap water treatment:

$$I_{Tc} = T \cdot \left[E_T \cdot e_{E2} + \sum r_i \cdot q_i\right] \quad \text{(Eq. 3-53)}$$

where:

E_T energy used to pump tap water (kWh/m^3)

e_{E2} PEI of medium-voltage electricity (PEI/kWh)

r_i amount of chemicals used in water treatment (kg/m^3)

q_i PEI per unit of chemical used in water treatment (PEI/kg)

3.4.6.1 System inventory in Plugrisost

For each of the systems, the water sources that could meet the domestic demand were analysed. For each water type, an inventory of materials and processes that produce the greatest potential environmental impact on system lifecycle was made. As a first approximation of the potential environmental impact of the system, the model considered the effects of water treatment processes and a wastewater network. For rainwater tanks, there are scenarios that include in situ fabricated and prefabricated tanks. For greywater reuse, Plugrisost only considers a direct-use system with filtration and a tank fabricated in situ (Table 3-3).

Table 3-3. Inputs and process inventories for LCA

Units	Inputs Materials and transport (1)	Process (1)	Data source and observations (2)
Rainwater			
kg	Steel, low-alloyed, at plant/RER S	Hot impact extrusion, steel, 1 stroke/RER S	Base inventory of Angrill et al. (2011a) for storage tank. This inventory includes materials for three locations of the infrastructures (underground tank, tank distributed over roof, tank below roof). An underground tank is used by default.
m^3	Concrete, normal, at plant/CH U	-	
m^3	Particle board, outdoor use, at plant/RER S	-	
kg	Brick, at plant/ES U	-	
m^3	Light mortar, at plant/CH S	-	
kg	Glass fibre, at plant/RER S	-	
kg	Polypropylene, granulate, at plant/RER S	Extrusion, plastic pipes/RER S	Base inventory of Angrill et al. (2011a) for pipes. Polypropylene pipes are used by default.
kg	Polyvinylchloride, at regional storage/RER S	Extrusion, plastic film/RER U	
kg	X22CrNi17 (431) I	Steel product manufacturing, average metal working/RER S	Base inventory of Angrill et al. (2011a) for pumps.
$kWh·m^{-3}$		Electricity, low voltage, production ES, at grid/ES S	
kg	Polypropylene, granulate, at plant/RER S	Extrusion, plastic pipes/RER S	Prefabricated rainwater tanks. Base inventory estimated for samples of five companies in Spain. For glass fibre tank, electricity was added to the filament winding process, consuming 2.7 MJ/kg (Song et al., 2009)
kg	Steel, low-alloyed, at plant/RER U	Zinc coating, coils/RER S	
kg	Concrete (reinforced) I		
kg	Glass fibre reinforced plastic, polyester resin, hand lay-up, at plant/RER S	Electricity, medium voltage, production ES, at grid/ES S	
kg	Polyethylene high-density granulate (PE-HD), production mix, at plant RER	Extrusion, plastic pipes/RER S	
tkm	Transport, lorry >32t, EURO3/RER S	-	

Units	Inputs Materials and transport (1)	Process (1)	Data source and observations (2)
Drinking water from surface			
kg	Chlorine, liquid, production mix, at plant/RER U	-	Base inventory of supplementary material for Muñoz et al. (2010) for drinking water treatment.
kg	Hydrogen peroxide, 50% in H2O, at plant/RER U	-	
kg	Ozone, liquid, at plant/RER U	-	
kg	Charcoal, at plant/GLO U	-	
kg	Aluminium sulphate, powder, at plant/RER U	-	
kWh/m^3		Electricity, medium voltage, production ES, at grid/ES S	

(1) Names of materials and processes used according to ecoinvent 2.2 database (Swiss Centre for Life Cycle Inventories, 2009). (2) For additional system data and water sources, greywater base inventory is similar to rainwater system data of storage, pipes and pumps; seawater desalinisation and wastewater base inventory are based on supplementary material for Muñoz et al. (2010) for seawater to drinking water treatment and for wastewater treatment, respectively.

3.5 Results

3.5.1 Parameters of design

For each of the scales analysed, Plugrisost showed differences in rainwater demand met between 0.5 and 3% for single-house buildings and between 1 and 6.5% for apartment buildings (Figure 3-4).

Using optimisation methods incorporated into the models and considering a 1% difference in the percentage of rainwater demand satisfied as a criterion, the results for the single-house scale were 14.2 m^3 using Aquacycle (A) and 13 m^3 using RainCycle (R) and Plugrisost (P). The average demand met for the 8 years of rainfall records studied was 59.2 (A), 59.3 (R) and 58.8 m^3/year (P) (Figure 3-4). The percentages of demand met were 36.8 (A), 37.2 (R) and 36.7% (P).

For apartment buildings, using the same criteria mentioned above, the volumes found were 77.6 m³ using Aquacycle (A), 89 m³ using RainCycle (R) and 80 m³ using Plugrisost (P). The average demand achieved for the 8 years of rainfall records studied was 418.4 (A), 418.6 (R) and 376.4 m³/year (P) (Figure 3-4). The percentages of demand met were lower than those for the single-house scale: 10.8 (A and R) and 9.7 % (P).

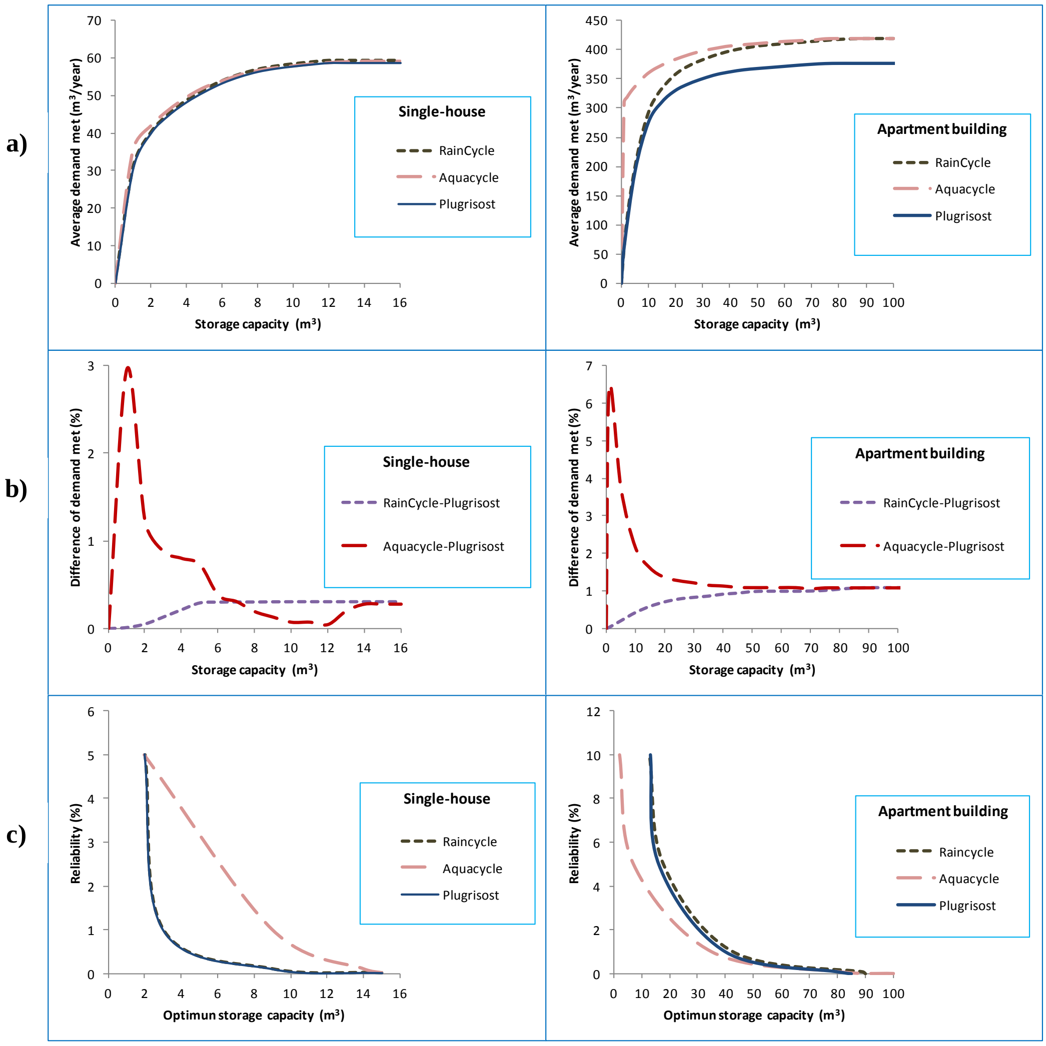


Figure 3-4. Performance achieved by the three models and two scales of analysis: a) demand met, b) difference in demand met, c) reliability

3.5.2 Cost of rainwater supplied

For the single-house scale, the cost indicator of rainwater shows favourable results only when the future cost of water (4 Euros/m³) is assumed in an optimistic scenario. In this case, deposits of up to 15 m³ could be viable (Figure 3-5). Conversely, on the apartment-building scale, this indicator shows favourable results even at a low cost of water (1.4 Euros/m³) in all scenarios. In this case, deposits of less than 40, 55 and 100 m³ in pessimistic, average and optimistic scenarios, respectively, could be viable (Figure 3-5).

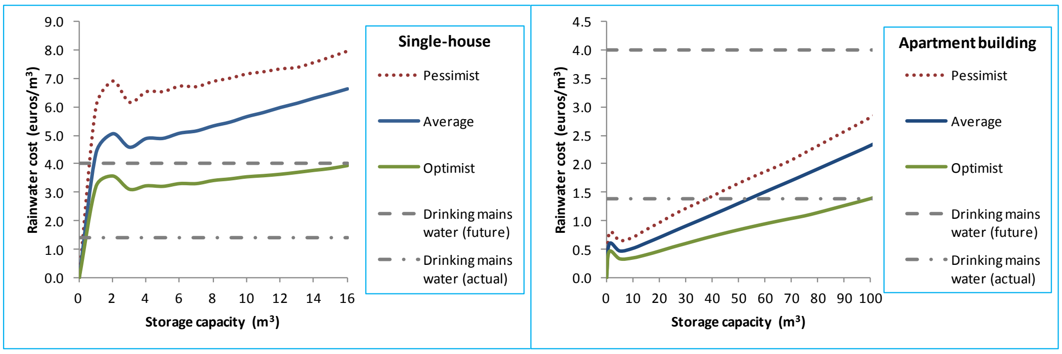


Figure 3-5. Rainwater cost and storage capacity in two case studies: single-house and apartment building

3.5.3 Environmental performance

The volumes estimated above may be too high when considering the behaviour of potential environmental impacts. The GWP indicator on the single-house scale and in an optimistic scenario (lowest environmental impact) shows that a storage volume above 5 m³ is not desirable because it would exceed the potential environmental impacts generated by the mains water system. In an average scenario, the tank volume should not exceed 2 m³, and for a pessimistic scenario, it should be less than 1 m³ (Figure 3-6).

The GWP on the apartment-building scale and in an optimistic scenario (lowest environmental impact) shows that deposit volumes below 10, 20 and 33 m³ for pessimistic, average and optimistic scenarios, respectively, are desirable. This result is explained by a lower potential environmental impact (at least with respect to this impact category) compared to the impact of tap water.

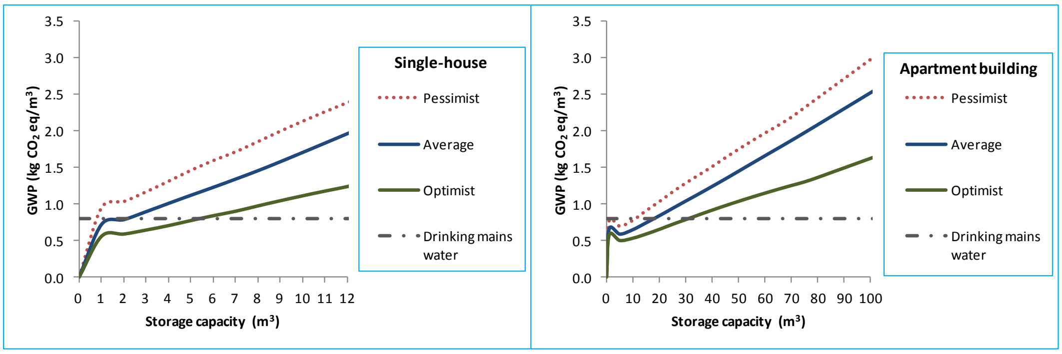


Figure 3-6. Global Warming Potential and storage capacity

The GWP for drinking mains water was calculated by Muñoz et al. (2010).

The Plugrisost model only considers the energy used to pump water for domestic distribution. On the single-house scale, these values are lower than those estimated for the distribution of a conventional network. This finding indicates that for this scale, a RWH system can be a good alternative (Figure 3-7). On the other hand, for the apartment-building scale, it is clear that there is high energy consumption, which is above the average of a combined energy production and water distribution network (Figure 3-7). However, there are other options that can be modelled in Plugrisost, as suggested by Angrill et al. (2011a); a tank distributed over a roof or a tank below a roof would keep energy consumption low and makes RWH systems feasible at this scale of analysis.

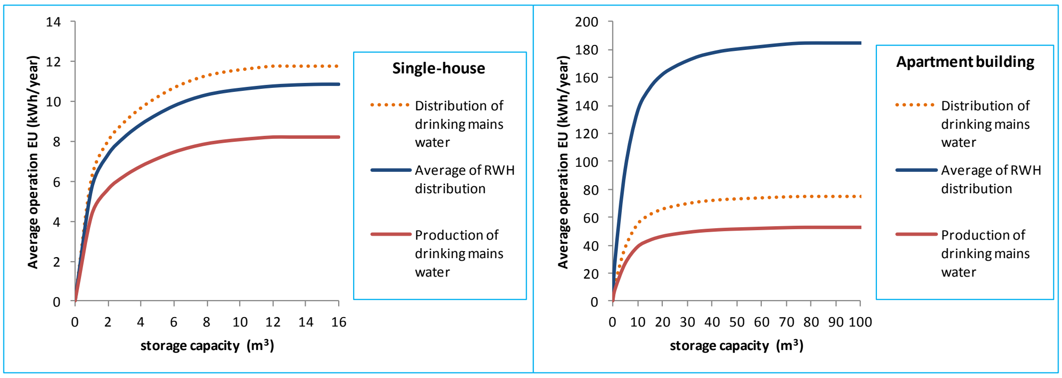


Figure 3-7. Energy use and storage capacity

The EU for drinking mains water was calculated by Muñoz et al. (2010).

It is important that there are different decision criteria that may have greater or lesser importance depending on the purpose of the system. Thus, in accordance with Farreny, Gabarrell and Rieradevall (2011), a high economic cost may be considered low if it is compared to future scenarios predicting increases in the price of tap water. Additionally, it is possible to have more-efficient pumping systems that reduce the consumption of RWH systems and make the use of decentralised systems more feasible.

3.5.4 Effect of rainfall variability

Rainwater was simulated using a gamma model because this model showed the best fit for the LKS test of the three available models in the software. The averages of the demands met in the average scenario were 21.5 and 6.5 %, and the associated averages of GWP were 0.9 and 1.0 kg CO_2 eq./m^3 for the single-house and apartment-building scales, respectively (Figure 3-8).

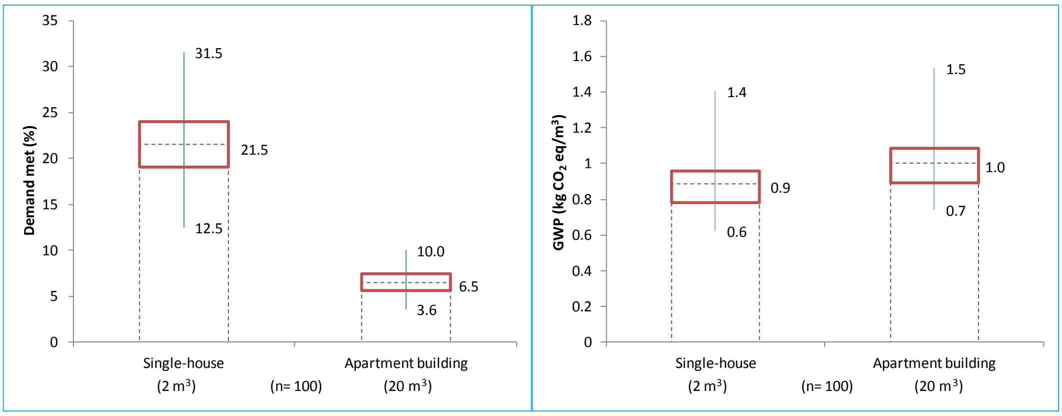


Figure 3-8. Behaviour of demand met and environmental potential impact for simulated rainfall

3.6 Discussion

For a better design of rainwater systems, it is necessary that the estimated parameters be consistent. Different criteria can help determine the feasibility of a RWH system. A good combination of economic cost and environmental impact are essential to aid the design of intelligent buildings, neighbourhoods and cities.

The analysis shows that the algorithm used in Plugrisost produces more conservative results than the YAS and YAB algorithms because it is able to give a conservative estimate of system performance irrespective of the model time interval. This is possible because our model uses continuous simulation, providing a better allocation of the demands of rainfall and potential supply.

The optimum volumes on the two scales that were analysed show similar behaviour in the Plugrisost and RainCycle models, while in the Aquacycle model it may be overestimated for small volumes, providing higher reliability. According to Mitchell (2005), this is due to a characteristic condition of the internal process of calculation for this model.

Although initial studies showed higher environmental impacts and economic cost in decentralised systems of stormwater reuse and waste water recycling, Crettaz et al. (1999) found favourable results when electricity cost and tap water treatment are high. Thus, pump energy use is a main factor in RWH systems (Grant and Hallmann, 2003). In some contexts, for example Australia, tap water saving would be more important than energy consumption (James, 2003). This finding corroborates our results obtained using Plugrisost, where RWH systems with higher energy consumption would be better in environmental terms compared to centralised systems.

Rainwater for domestic uses and LCA have been studied in Mediterranean areas by Angrill et al. (2010) and Angrill et al. (2011a). South American areas have been analysed by Angrill et al. (2011b) and Morales-Pinzón et al. (2011). All of these studies indicate some favourable scenarios for the implementation of rainwater as an alternative to the domestic water supply in urban areas. These results have been incorporated into Plugrisost, contributing to the analysis of these systems in different contexts in both Mediterranean and South America countries. This contribution makes our software more flexible and adaptable to different contexts.

In most of the cases that have been recently studied, the potential environmental impacts of RWH systems are lower than those produced by tap water. However, the sizing and selection of adequate infrastructure and the scale of urban design can become determining factors. Additionally, depending on the selected options and strategies for implementing a given system, we are likely to find favourable, unfavourable and contradictory results. Additionally, taking into account the local conditions that influence the results, stakeholders need to have modelling tools (as Plugrisost) to evaluate different alternatives and to the facilitate comparison of different scenarios.

Although Plugrisost can use at least ten years' worth of climate time series as input, as recommended by Mitchel et al. (2008), using simulated rainfall provides great flexibility in the types of scenarios to be analysed, and some indicators can be observed to affect the system. The results can be presented using the average values of a specific storage capacity. These results can be used to analyse the feasibility of the system versus the expected behaviour of precipitation, which is simulated using probabilistic models. Additionally, these random models can help analyse areas where rainfall records are not available or insufficient.

3.7 Conclusions

The Plugrisost software program contributes to a more comprehensive assessment of RWH systems, providing information regarding technical, economic and environmental aspects. Moreover, it offers additional tools for decision making and urban planning in systems that incorporate rainwater as a resource.

Rainwater supply, the use of rainwater, the economic cost and the environmental impact, as variables that affect the design of a RWH system, are directly associated with the scale of analysis.

In technical analysis, the estimates provided by the Plugrisost model are even more conservative than those provided by the YAS algorithm. Therefore, the use of Plugrisost is recommended for the design stage.

Technical analysis using indicators such as the volume offered and percentage of satisfied demand may tend to select oversized tank sizes.

The use of economic and environmental indicators can make the optimal size of a rainwater tank more restrictive when it is compared to the results regarding the satisfaction of the demand for rainwater. Economic and environmental analysis can help avoid oversizing tanks for rainwater and thus obtain greater benefits, where the estimated cost and GWP are two good indicators included in Plugrisost for this purpose.

Volume offered, demand satisfaction and economic cost cannot be the only decision criteria that are used. It is necessary to include at least some environmental impact indicators that are suggested in the lifecycle assessment.

The variability of rainfall and its simulation using stochastic models are factors that must be analysed because they help researchers understand the behaviour of system indicators and make better decisions.

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PART III

SOCIAL ASPECTS, POTENTIAL SUPPLY AND ENVIRONMENTAL BENEFITS OF RAINWATER IN URBAN AREAS

Different urban projects and neighborhoods in Colombia. Photography by Tito Morales Pinzón

Chapter 4
Potential of rainwater resources based on urban and social aspects in Colombia

4 Potential of rainwater resources based on urban and social aspects in Colombia

This chapter is based on fallowing paper:

Morales-Pinzón, T., Rieradevall, J., M. Gasol, C., Gabarrell, X. (2012). Potential of rainwater resources based on urban and social aspects in Colombia. Water Environment Journal, doi: 10.1111/j.1747-6593.2012.00316.x.

Abstract
The potential offered by non-conventional water resources (rainwater) associated with high or low urban density in new housing in different rainfall zones (800-2,300 mm) was studied. Ten (10) cities in Colombia with over 250,000 inhabitants were used as a case study. The potential of substitution of tap water by rainwater according to population groups with different socioeconomic status was estimated. This study reveals the favorable conditions for rainwater harvesting in the Colombian context, and enables the linking of supply and demand issues related to local climatic and environmental sustainability in order to integrate the use of rainwater into urban housing projects. For the current consumption scenario (greater than 160 Lcd), rainwater becomes a potential replacement for mains water in urban areas with rainfall of above 1,553 L/m^2/year.

Keywords
Housing, rainwater harvesting, social, urban development, water demand.

4.1 Introduction

South America has 26% of the total supply of fresh water on the planet and only 6% of the world population (UN / WWAP 2003). Colombia has a total renewable water resources exceeding 2,132 km^3/year (FAO Aquastat 2010), and having a theoretical water availability of 45,408 m^3/year per capita (WRI 2008), between 4.5 and 6 times the world average for developed and developing countries.

However, the distribution of water supply is highly variable and is not consistent with areas where most of the people are concentrated. The 49.8% Colombian municipalities have only 2.7% of water availability, while municipalities with more than 500,000 inhabitants, equivalent to 29.9% of the Colombian population, have only 2.2% (DPC 2009).

There are many potential benefits of rainwater harvesting, particularly associated with adaptability and resilience of urban infrastructure networks (Ward, S. 2010), however, the use of unconventional resources such as rainwater is viewed as a marginal alternative by people with little access to mains water [approximately 2% of urban households in Colombia use rainwater for cooking (DANE 2005a)].

Colombia has very few experiences of employing rainwater harvesting (RWH). According to Ballén et al. (2006a), two examples can be found in the service sector. The first is Alkosto Venice store in Bogotá where about 6,000 m^2 of the roof surface are used to catch approximately 4,820 m^3 of rainwater per year, thereby satisfying 75% of the building's current demand for drinking water. The other one is Alkosto store in Villavicencio, with a roof area of 1,061 m^2, which captures rainwater, stores it in a 150 m^3 tank and then purifies it at a treatment plant, to provide enough drinking water to satisfy all the store's needs throughout the year.

4.1.1 Domestic water demand

World Health Organization recommends 100 Lcd (Litres per Capita per Day) as responsible consumption, with the minimum requirements necessary for life and personal hygiene estimated at 80 Lcd. The minimum acceptable figure that would meet the consumption and basic sanitation needs (for drinking and food preparation) is between 20 and 50 Lcd, but the optimum would be to be able to supply a minimum of 100 Lcd continuously (Howard and Bartram 2003).

According to estimates made by Ballén et. al (2006b), the average domestic water consumption in Colombia is divided into laundering (27%) sanitary use (20%), showering (21%), dishwashing (16%), house cleaning (4.9%), lawn and garden (2.5%), washing cars (1.5%) and other uses (7.1%), where approximately 56% is spent on activities that do not require drinking water quality.

Besides domestic use, water consumption usually varies according to cultural and climatic features. In Colombia, socioeconomic strata have homogeneous characteristics within each group. Stratum 1 (known as the low-low stratum) is the most marginalized conditions, with little urban development and limited access to public services, while Stratum 6 (known as the high stratum) corresponds to areas of high urban development, with the full complement of public services and generally located in areas of low housing density. Thus, in 2005, a single-family house (average of 4 members) in Stratum 6 consumed 33 m^3/month, and a family in Stratum 1 only 12 m^3/month (103 Lcd) (DPC 2009).

4.1.2 Potential of non-conventional water (rainwater)

In order to calculate the potential RWH at a household level, Abdulla and Al-Shareef (2006) and Ghisi (2006), use the product of the average monthly or annual rainfall, the catchment area and the runoff coefficient, as an estimate for the available supply. Fewkes (2000) adjusted this calculation by incorporating an additional variable, which is the loss in storage due to effect of daily fluctuations. Abdulla and Al-Shareef (2006 and 2009) recommend adopting a value of 20% per year, which represents the total losses including those due to evaporation, and losses in collection, conveyance and storage. Ghisi (2006) presents the methodology for estimating the potential water savings, which is a percentage value expressed as the ratio between the total volume of rainwater captured and total demand.

The same expression is then used by Ghisi, Lapolli and Martini (2007) in their assessment for a residential area in southern Brazil. The equation for calculating the potential for savings in drinking water is again expressed in the same way by Abdulla and Al-Shareef (2006 and 2009) and Cheng, Liao and Lee (2006). Farreny et al. (2011) propose linear functions to estimate the potential catchment as a function of catchment area, type of roof (material) and runoff coefficient and to calculate the initial abstraction of rainwater.

Slys (2009) determined the savings of tap water used for flushing toilets and watering on the basis of the daily water outflows from the storage tank divided by the total water consumption for a specific purpose.

Villarreal and Dixon (2005), posit a large-scale development model, with rainwater harvesting on the rooftops of homes and buildings, to supply the entire city of Ringdansen (Sweden), especially for use in toilets, laundries, washing cars and watering gardens.

In adapting the MFA (material flow analysis) methodology used by Nuñez et al. (2009) to urban environments like Montjuic Park (Barcelona), they calculated the percentage of potential water savings needed to optimize service flows.

It is possible to estimate the potential catchment of rainwater in different urban areas of Colombia (with different rainfall) and to estimate the proportion expected of potential savings of tap water. Consequently, the objectives for this research are: (1) determine the potential supply of non-conventional water resources (rainwater) associated with diffuse and compact urban development in new housing projects in urban areas in Colombia; (2) estimate the potential degree to which mains water demand in these settlements can be replaced by rainwater, associated with urban development and depending on the socioeconomic level.

4.2 Methodology

4.2.1 Study area

Projects for new housing developments in Colombia were studied. A number of new housing projects located in 10 urban areas in Colombia with over 250,000 inhabitants were selected. These areas had populations ranging from 0.28 to 7.35 million inhabitants (DANE 2005b), with an average consumption of mains water ranging from 116 to 169 Lcd (IDEAM 2001), average rainfall of between 793 and 2,258 L/m^2/year, with an average of 77 to 230 rainy days per year, and an average temperature of 13 to 28° C (IDEAM 2008).

4.2.2 Sample size for estimating the potential for rainwater catchment

A general list from two data sources was drawn up, serving as the sampling framework that included the name of housing projects and construction companies associated with each of the selected urban areas. The first source was a database of construction companies available on the website of the Colombian Chamber of Construction (Camacol 2010), containing information on the respective existing housing projects. The second was the information on social housing projects available from municipal authorities, resulting in a list of 1,124 housing projects existing during 2008 and 2009 in the 10 urban areas defined.

A sample was selected from all the housing projects on offer, using a simple random sampling model with systematic selection (Figure 4-1). Variance was obtained from the buildings census (DANE 2009), which has been updated on a quarterly basis since 2007 year. The sample size was calculated using the following formula (Lohr 1999) (Eq. 4-1).

$$n = \frac{Z^2_{\propto/2} S^2}{e^2 + \frac{Z^2_{\propto/2} S^2}{N}} \qquad \text{(Eq. 4-1)}$$

where:

n is the optimal sample size in simple random sampling. The size of the sample was 348 projects

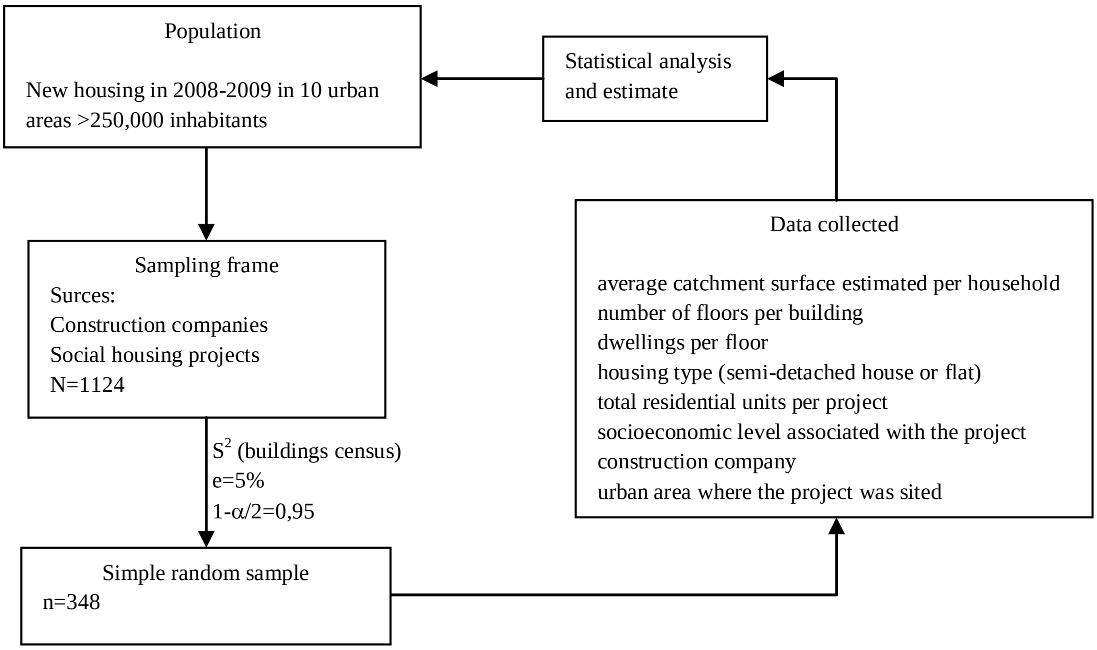
e= 5.1m² (maximum permissible error) is equivalent to 5% of the mean housing floor surface area according to the housing census for the years 2008 to 2009 (DANE 2009)

N = 1,124 is the total number of projects in the sampling framework

S = 58.4, which was calculated from the housing census (DANE 2009)

$Z_{\alpha/2}$ = 1.96 is the value assigned to a statistical certainty of 95%.

Figure 4-1. Sampling and analysis procedure



4.2.3 General model for calculating the potential of non-conventional water resources (rainwater)

Four scenarios were analyzed under different supply conditions, and real and responsible (theoretical) consumption levels. The scenarios established for the calculation of water savings potential (H) are showed in Table 4-1.

Table 4-1. Different scenarios for estimating the degree of potential non-conventional water (rainwater).

Scenarios	Rainfall	Water consumption
1	Average of each of the ten urban areas	Current average in urban areas per socioeconomic stratum
2	Average of each of the ten urban areas	Responsible (100 Lcd for 4 inhabitants per dwelling)
3	Minimum of all urban areas (793 L/m²/year)	
4	Maximum of all urban areas (2,258 L/m²/year)	

The water savings potential (H) proposed in this work does not include the storage phase and potential losses arising from the distribution network, and thus they were calculated using the following expressions:

H_d in a semi-detached house or flat (Eq. 4-2)

$$H_d = \frac{\varphi_d}{\tau_d} \qquad \varphi_d = P * A * RC; A = f(V) = \begin{cases} A_t, V = 0 \\ \dfrac{A_p}{p * a}, V = 1 \end{cases} \qquad \text{(Eq. 4-2)}$$

H_n in housing projects (Eq. 4-3)

$$H_n = \frac{\varphi_n}{\tau_n} \qquad \varphi_n = \sum_{i=1}^{k} P_i A_i RC_i \qquad A_i = f(V) = \begin{cases} A_{ti}, V = 0 \\ \dfrac{A_{pi}}{pi * ai}, V = 1 \end{cases} \qquad \tau_n = \sum_{i=1}^{k} D_i \qquad \text{(Eq. 4-3)}$$

φ_d is the potential supply by capturing rainwater by dwelling (m³/month)

τ_d is the water demand for domestic use per dwelling (m³/month)

φ_n is the potential supply by capturing rainwater by project (m³/month)

τ_n is the water demand for domestic use per project (m³/month)

P is the average monthly rainfall (m³/m²/month)

A is the potential catchment surface by roofs (m²), which depends on the type of dwelling

A_t is the roof catchment surface in semi-detached house (m^2)

A_p is the roof catchment surface per block of flats (m^2)

p is the number of floors per block flat

a is the number of flat per floor

RC is the runoff coefficient (a constant value of 0.9 was assumed)

V is a dummy variable that takes values 0 (semi-detached house) and 1 (flat)

i is the i-th building

d is a dwelling

n is a housing project

k is the number of buildings

Di is the water demand in building i

Note: "month" as the time unit is used because the water consumption data are recorded monthly in SUI (2009), and it is considered as the more stable unit for estimates.

4.3 Results and discussion

The results below are separated into three parts. The first describes the characteristics attributed to the housing projects sampled and initial estimates required for later use in the calculation of potential rainwater catchment. The second shows the results of the calculation of potential rainwater harvesting by roofs; and the third part gives estimates of the potential degree of substitution of mains water demand by rainwater.

4.3.1 Characteristics attributed to the housing projects

The sample included 193 "block of flats" projects (Type I) with an average of 203 flats per project, and 130 projects of semi-detached house (Type II) with an average of 193 dwellings per project (92.8% of the previously calculated sample). In no case did the projects presented have evidence of alternative uses of rainwater.

With regard to socio-economic stratification, the floor surface area in Type I housing is on average 74.9% greater in stratum S6 than stratum S1, while in the Type II housing the difference is 81.7%. Thus, floor areas are greater in higher strata housing. The Spearman Rho correlation coefficient was highly significant (p is less than 0.01) between the strata number and the average floor area of the dwelling (ϱ = 0.83).

The mean floor area ranged between 26.5 and 203.7 m^2 per dwelling in Type I housing, and between 22.5 and 204.3 m^2 in Type II housing. The mean floor area in Type I was 85.9 m^2 and in Type II 104.5 m^2, with a potential catchment area of 10.5 and 62.3 m^2, respectively. On average, looking at all the housing, Type I have 1.2 more floor area than Type II, and a larger potential in roof area (5.9 times).

The roof areas are between 7.0 and 13.8 m^2 per dwelling in Type I, and between 31.9 and 113.5 m^2 in Type II. In the variance analysis, differences were statistically significant (p less than 0.05) for the average catchment surface by stratum and by types of housing, but there were no significant differences (p is greater than 0.05) between the different urban areas analyzed. From data and using the equations 4-2 and 4-3, the surface potential of rainwater catchment was estimated. The Bonferroni test showed that the catchment surface of all the strata are statistically different, increasing consecutively from one stratum to the next. The mean area for Type I was greater than for Type II, with the greatest differences being observed from strata S3 to S6 (Figure 4-2).

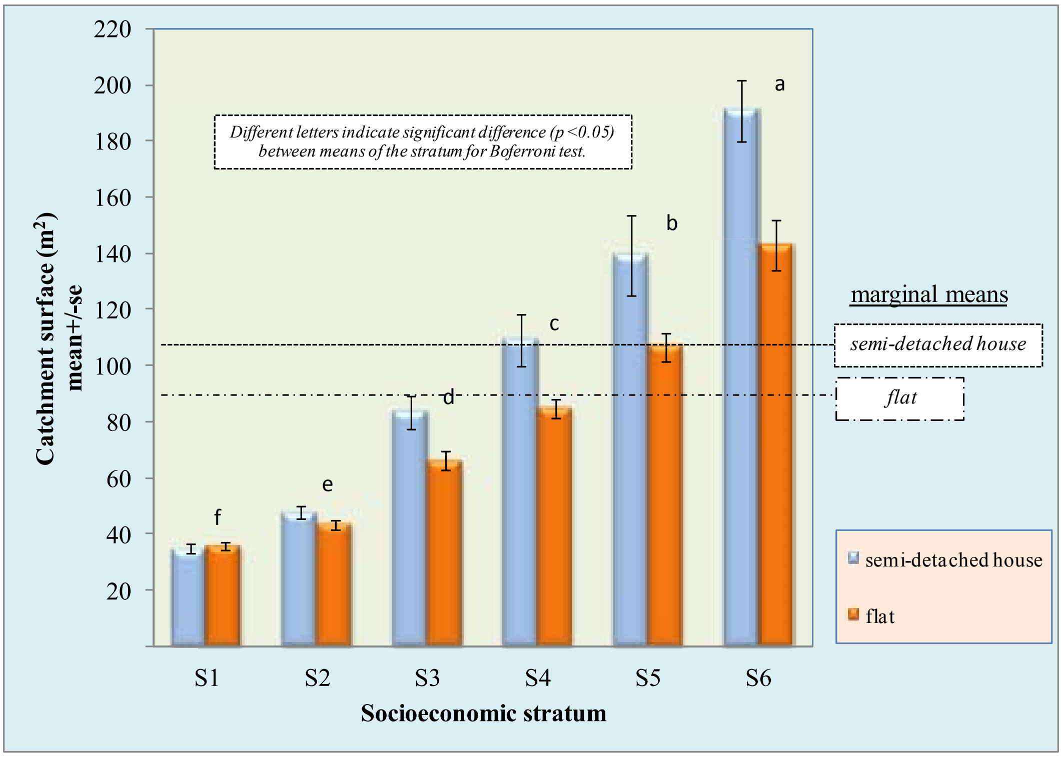


Figure 4-2. Potential catchment surface by socioeconomic stratum

The urban area with lowest average consumption is Bogotá, with 11.2 m^3/month per user, while the average consumption is higher (18.2 m^3/month) in Cali (Figure 4-3). Assuming that water consumption per user (from mains water) can be interpreted as the consumption per dwelling with an average of 4 inhabitants per dwelling (DPC 2009), the average consumption per capita per day is progressively higher from one stratum to the next.

On average, the S1 stratum consumes 14.7 m³/month mains water, with the average consumption increasing between 0.3 and 0.6 in the following strata until stratum S5, in which the average consumption is 16.8 m³/month. Stratum S6 was the largest consumer, at 20.9 m³/month (Figure 4-3).

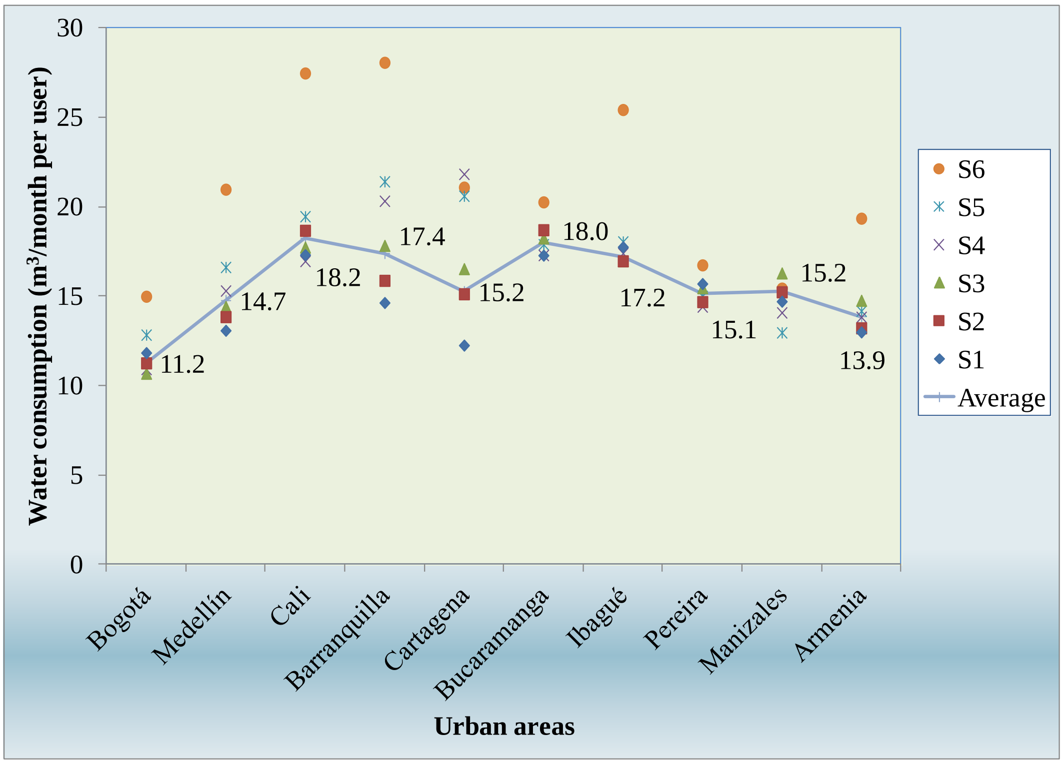


Figure 4-3. Water consumption according to stratum

Note: Compiled from the Single Information System for Public Services using average residential consumption estimates for each urban area based on consolidated reports for the year 2009 (SUI 2009). The words "user" and "dwelling" are equivalent.

4.3.2 Non-conventional potential rainwater in the systems studied

Using as reference the average catchment surface per stratum and taking a value of 12 m³/month per dwelling, which equals the total mains water consumption for a family of four, with a responsible consumption of 100 Lcd, 60% of the areas analyzed present an average rainfall of over 1,200 L/m²/year (100 L/m²/month). From this value, it was found a potential RWH of over 12 m³/month in Type II housing for higher strata (S5 and S6). This water supply would increase considerably during the wettest month of the year, from 44 to 200% (Table 4-2).

The non-conventional potential rainwater was between 0.4 and 2.3 m³/month per dwelling for Type I and 1.9 to 19.2 m³/month for Type II (Table 4-2). Besides, an apartment building has an average potential rainwater between 15.2 and 87.4 m³/month (38 times higher than Type I).

Table 4-2. Rainwater harvesting potential (RWH) by social stratum.

Urban area	Rainfall[a] $R_m-R_+-R_\%$	PCI[b]	TD[c]	RWH[d] (m³/month per dwelling) RWH$_m$						RWH$_+$					
				S1	S2	S3	S4	S5	S6	S1	S2	S3	S4	S5	S6
Bogotá	66.1−107.0−51	9.5	I	0.4	0.5	0.6	0.6	0.7	0.8	0.7	0.7	0.9	1.0	1.1	1.3
			II	1.9	2.2	3.1	3.4	4.3	6.8	3.1	3.6	5.0	5.6	7.0	10.9
Medellín	139.4−221.0−61	9.3	I	0.9	1.0	1.2	1.3	1.5	1.7	1.4	1.5	1.9	2.1	2.3	2.7
			II	4.0	4.7	6.5	7.3	9.2	14.2	6.4	7.4	10.3	11.5	14.5	22.6
Cali	75.7−112.8−39	9.6	I	0.5	0.5	0.6	0.7	0.8	0.9	0.7	0.8	1.0	1.1	1.2	1.4
			II	2.2	2.5	3.5	3.9	5.0	7.7	3.2	3.8	5.2	5.9	7.4	11.5
Barranquilla	67.9−162.6−21	13.9	I	0.4	0.5	0.6	0.6	0.7	0.8	1.0	1.1	1.4	1.5	1.7	2.0
			II	2.0	2.3	3.2	3.5	4.5	6.9	4.7	5.5	7.6	8.5	10.7	16.6
Cartagena	66.1−198.3−25	14.9	I	0.4	0.5	0.6	0.6	0.7	0.8	1.2	1.4	1.7	1.9	2.1	2.5
			II	1.9	2.2	3.1	3.4	4.3	6.8	5.7	6.7	9.2	10.3	13.0	20.3
Bucaramanga	101.2−157.0−50	9.2	I	0.6	0.7	0.9	1.0	1.1	1.3	1.0	1.1	1.3	1.5	1.6	2.0
			II	2.9	3.4	4.7	5.3	6.7	10.3	4.5	5.3	7.3	8.2	10.3	16.0
Ibagué	139.9−240.4−50	9.5	I	0.9	1.0	1.2	1.3	1.5	1.7	1.5	1.7	2.0	2.3	2.5	3.0
			II	4.0	4.7	6.5	7.3	9.2	14.3	6.9	8.1	11.2	12.5	15.8	24.6
Pereira	188.2−271.3−63	9.0	I	1.2	1.3	1.6	1.8	2.0	2.3	1.7	1.9	2.3	2.6	2.8	3.4
			II	5.4	6.3	8.8	9.8	12.4	19.2	7.8	9.1	12.6	14.1	17.8	27.7
Manizales	127.8−206.1−62	9.4	I	0.8	0.9	1.1	1.2	1.3	1.6	1.3	1.4	1.7	2.0	2.2	2.6
			II	3.7	4.3	5.9	6.6	8.4	13.1	5.9	6.9	9.6	10.7	13.5	21.1
Armenia	176.6−255.9−47	9.1	I	1.1	1.2	1.5	1.7	1.9	2.2	1.6	1.8	2.2	2.4	2.7	3.2
			II	5.1	5.9	8.2	9.2	11.6	18.0	7.4	8.6	11.9	13.3	16.8	26.1

Note: (a) R_m: average monthly rainfall; R_+: average rainfall in rainiest month; $R_\%$: days with rain per year (%). Average data for historical series over 30 years. Source: IDEAM 2008; (b) PCI: Precipitation Concentration Index$=100 * \sum x^2/(\sum x)^2$, where x is monthly rainfall (Oliver, 1980); (c) Type of dwelling (TD): flat (Type I), semi-detached house (Type II); (d) Calculated with 0.9 of runoff coefficient. RWH$_m$ for R_m and RWH$_+$ for R_+. Results highlighted in gray for values between 6.7 and 12 m³ and black values above 12 m³. The global mean catchment surface was used for each stratum.

When a proportional increase in the potential RWH is assumed for the month of highest average rainfall, it would be between 0.6 and 3.3 m³/month per dwelling for Type I and 3.1 to 27.7 m³/month for Type II (Table 4-2). On a block flats there is a big potential that cannot be neglected, although the potential for rainwater harvesting in an apartment is not sufficient to meet its domestic water demands. That would help to meet the demands of the building, thereby reducing the pressure on the network. In an apartment building the potential harvesting would be between 22.8 and 125.4 m^3/month.

Under the assumption that 56% of total mains water consumption would be for applications requiring lower quality, and an average monthly rainfall, rainwater harvesting would reach 100% demand in the middle strata (S3 to S6) for Type I projects in all the cities analyzed. The supply required to meet this consumption would be 6.7 m^3/month per dwelling (Table 4-2).

In the month with the highest average rainfall, 100% of this demand could be achieved for Type I projects from the lowest strata (S1 or S2) to highest (S6) in 6 cities: Medellin, Cartagena, Ibague, Pereira, Manizales and Armenia (Table 4-2). These cities showed the highest percentages of days with rain per year (47 to 61%), and the greatest rainfall stability, with a uniform Precipitation Concentration Index (PCI less than 10). In contrast, the city of Cartagena presents a lower percentage of days with rainfall (25%) and a moderately seasonal PCI (14.9) (Table 4-2).

4.3.3 Potential replacement of mains water demand by rainwater harvesting (H)

Theoretically, in conditions of higher average rainfall (above 2,100 mm) with a current average domestic water consumption (greater than 160 Lcd), it is possible that the catchment surface in the highest stratum (S6) for semi-detached house (Type II) may prove sufficient to satisfy all the demand met by mains water consumption (H greater than 100%). The H indicator for the current consumption scenario for each urban area (Scenario 1) was found to be between 3.1 and 15.5% in Type I, and between 14 and 127.8% for Type II. The overall trends were an increase in H as the average rainfall increases, except in Bogotá (794 mm) and Ibague (1,679 mm) where changes were observed in the H indicator trend (Figure 4-4).

Similarly, under conditions of average rainfall above 1,200 mm and responsible water consumption (100 Lcd), it is probable that the catchment surface of Type II in the highest stratum (S6) will be sufficient to meet demand (H greater than 100%). The H indicator in the responsible consumption scenario (Scenario 2), was found to be between 3.8 and 21.7% in Type I, and between 17.6 and 178% in Type II. The general trends are for the rate to increase as the average rainfall increases (Figure 4-4).

According to the percentage of mains water demand in Colombia estimated by Ballén et al. in 2006, the H indicator greater than 20% shows that it is possible to meet the total demand for non-potable quality water for domestic use in Scenarios 2, 3 and 4 in at least one of the socioeconomic stratum for both housing types analyzed. In addition, if H exceeds 56%, the use of rainwater in urban housing projects is an alternative that should be seriously considered even under current conditions of mains water consumption (Scenario 1). This is sufficient to satisfy all the demand for lower quality water in all cities studied (10) for Type I housing in higher socioeconomic strata (S5 and S6) and from lower strata in 6 cities.

The indicator H greater than 56% also reveals that other strata can harvest rainwater under current water consumption conditions. This is possible in Type I with rainfall higher than 1,500 mm. If a level of responsible consumption (100 Lcd) can be achieved, all the cities would present at least one socioeconomic stratum which could meet the total water consumption that does not require drinking quality water by harvesting rainwater.

In Type I projects, H greater than 20% was observed in Scenario 2 (responsible use) for a higher precipitation (greater than 2,119 mm / year) and upper strata (S5 and S6).

In Type II projects, H greater than 20% was found in Scenario 1 (current consumption under average conditions), from an average rainfall above 1,533 L/m^2/year, for all strata. In the same scenario for the same rainfall, H greater than 56% was found for at least the upper strata (4 and 5) (Figure 4-4). Similarly, H greater than 20% was seen in Scenario 2 with an average rainfall of 1,215 L/m^2/year. In this scenario, H greater than 56% was found in at least one stratum in all the cities analyzed (Figure 4-4).

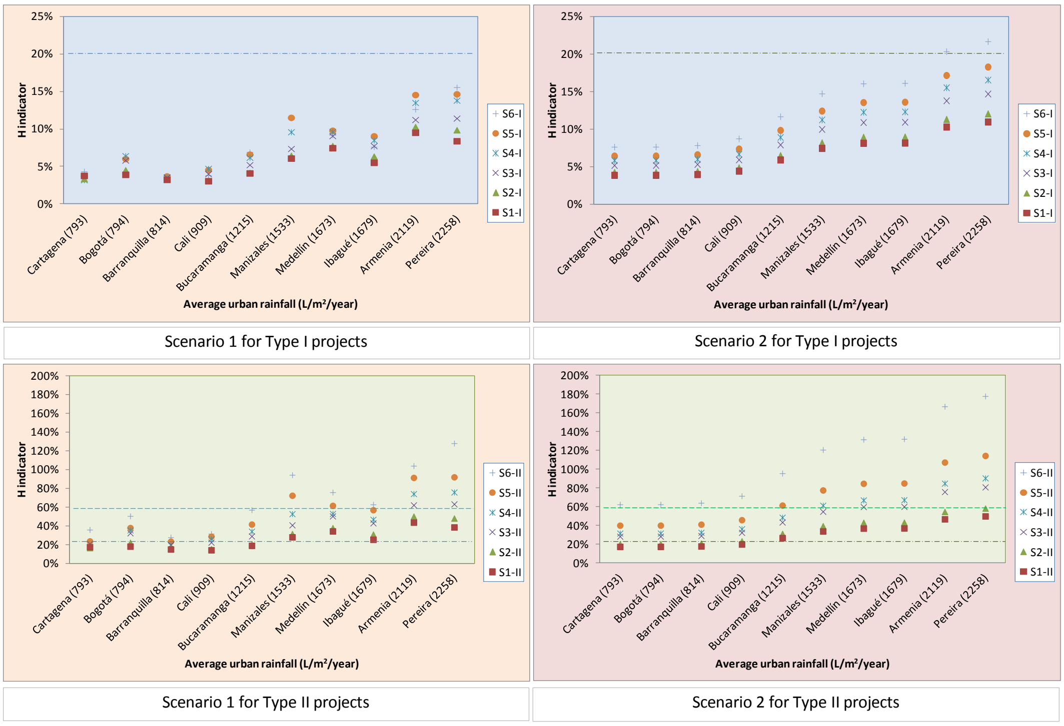


Figure 4-4. Potential for replacement of mains water with rainwater under 4 scenarios

In Scenario 3 (low rainfall supply) the H indicator was found to be between 3.9 and 7.6% for Type I housing, and between 17.6 and 62.6% for Type II projects, while in Scenario 4 (high rainfall supply) the H indicator was found to be between 11 and 21.7% for Type I and between 50.1 and 178% for Type II. The trend increases from the lowest social stratum to the highest one (Table 4-3).

Table 4-3. The H indicator in responsible consumption and minimum and maximum average precipitation rates (Scenarios 3 and 4)

Reference precipitation	TD	H (2)					
	(1)	S1	S2	S3	S4	S5	S6
Scenario 3: Minimum precipitation in urban areas (793 L/m²/year)	I_n	3.9%	4.2%	5.2%	5.8%	6.4%	7.6%
	II_n	17.6%	20.5%	28.5%	31.9%	40.3%	62.6%
Scenario 4: Maximum precipitation in urban areas (2,258 L/m²/year)	I_n	11.0%	12.0%	14.7%	16.5%	18.3%	21.7%
	II_n	50.1%	58.5%	81.0%	90.6%	114.6%	178.0%

(1) Type of dwelling (TD): average apartment in block of flats projects (Type I_n), average in semi-detached house projects (Type II_n).

(2) Results highlighted in gray for values between 20% and 56% and black values above 56%.

Rainwater as a non-conventional water resource becomes a potential replacement for mains water in urban areas with rainfall of above 1,553 L/m²/year. When the responsible consumption criterion (100 Lcd) is applied, rainwater harvesting could be an alternative possibility in dwelling projects in urban areas with precipitation higher than 1,215 L/m²/year. This is valid for all social strata of semi-detached house (Type II) and applying the criterion proposed by Ballén et al. (2006b) of satisfying 30% of the net domestic water demand, it is a theoretical limit beyond which rainwater harvesting projects are feasible, given the current domestic water consumption in the different urban areas studied. Similarly, it can be stated that the use of harvested rainwater for buildings is potential viable even in cases with low rainfall (793 L/m²/year) due to its stability.

Integrating the two approaches described above, we suggest the following definition: If two projects (p_1 and p_2) are adjacent, with H_1 and H_2 as indicators of potential replacement of mains water demand by rainwater harvesting respectively, then we can affirm that the housing project p_1 may become the potential export system when H_1 greater than 56%, and its surplus of water (H_s) would be sufficient to supplement the adjacent project p_2 until H_2 greater than 30%. In this case, both projects would make up an integrated system in terms of rainwater harvesting and use. This could be widely applied to urban network neighborhoods to create a more efficient management of rainwater resources.

4.4 Conclusions

This study includes a representative sample of the new housing construction from 2008 to 2009 in Colombia, which is expected to continue in the coming years. This helps to extrapolate the results of this work to the construction of housing projects in the different urban areas studied and other similar cities in the South American context.

The average mains water consumption in Colombia increases progressively from one socioeconomic stratum to the next, linked to areas of housing with similar behavior. Lower socioeconomic strata are, on average, closer to the responsible consumption of 100 Lcd, as recommended by World Health Organization.

Rainwater harvesting in urban housing projects could be an alternative possible since the H indicator exceeds 56%. This rainwater potential is sufficient to satisfy all the water demand for lower quality than that supplied by the tap water. This occur in 5 cities (Manizales, Medellín, Ibagué, Armenia, Pereira) for scenario of current average of water consumption and for higher socioeconomic strata (at least) of semi-detached house (Type II).

Local governments could generate a differential rate for charging for mains water consumption based on the H indicator. As a first step it would encourage rainwater harvesting practices in order to reduce environmental pressure on the sources used by the water supply network in those housing projects with a potential indicator H greater than 56%. Additionally, they need to generate differential charges for this resource when it is wasted as a result of inefficient management of rainwater.

Housing projects with H greater than 86% could become "export systems". These have the potential to export rainwater to other projects, contributing the consolidation of urban networks for rainwater harvesting as a sustainable alternative to the pressures of urban growth, particularly on water resources and the water supply network.

In the near future it is feasible to imagine the design of more sustainable urban housing projects, with the use of rainwater harvesting and integrating urban projects with a surplus (surplus systems) with other systems that are not in this position (deficit systems), thereby optimizing the use of rainwater. The social implications would be very positive in terms of social and environmental responsibility, since the upper strata could export rainwater surplus to deficit systems, thus promoting this resource in urban areas where rainwater supply has not been incorporated into planning.

Because of the potential savings in network infrastructure and consumption of tap water, the rainwater catchment systems are potentially viable to be subsidized by the state in social housing projects. Socially high strata would be able to pay investment. However, this would be conditional on the availability of payment or the regulation of such payment by some local or national law.

New neighborhood in Colombia. Photography by Tito Morales Pinzón

Chapter 5
LCM of Rainwater Harvesting Systems in Emerging Neighborhoods in Colombia

5 LCM of Rainwater Harvesting Systems in Emerging Neighborhoods in Colombia

Morales-Pinzón, T., Angrill, S., Rieradevall, J., Gabarrell, X., M. Gasol, C., Josa, A. LCM of rainwater harvesting systems in emerging neighborhoods in Colombia. In M. Finkbeiner, M. Finkbeiner (Ed.), Towards Life Cycle Sustainability Management (pp. 277-288). Berlin: Springer.

Abstract

Potential environmental impacts of water harvesting systems for rain to emerging neighborhoods in Colombia were studied. Two tools were integrated into a simulation model (life cycle analysis and system dynamics). This was performed as an application case study in two urban areas of Colombia (Pereira and Bogotá). We modeled a standard neighborhood with 10 residential 5-storey buildings of 24 apartments. The results show that it is possible to avoid in every neighborhood 150,729 kg CO_2 eq. and 44,857 kg CO_2 eq., respectively.

Keywords

Avoided impacts, LCA, system dynamics

5.1 Introduction

South American countries and particularly in Colombia, experiences in LCM are limited and can be considered a new subject, particularly in the environmental impact study of systems of rainwater harvesting (RWH) for urban domestic use in buildings.

Colombia is one of the top 20 countries of the world's water supply with an average rainfall greater than 2,612 L/m² per year (FAO-Aquastat, 2010). However, there is a great pressure on water resources and water supply networks, due to the growing increase in the construction of new neighborhoods. Some dwelling projects already executed and poorly planned with respect to the mains water supply available, usually with difficulty to grow and low efficiency of service delivery (MAVDT, 2008).

In Colombia, has not yet considered the benefits of rainwater harvesting (RWH) in the context of a sustainable management of this resource and urban design of new neighborhoods. Some benefits like free access to water supply, mitigation of pressure on aquifers and surface courses; prevention of floods caused by soil sealing attributable to urbanization, could be included. Besides, use of rainwater on very-large scale would be considered as an adaptation strategy to climate change against the reduction of water availability (Angrill et al, 2011).

The planning of water supply with rainwater systems is very important in Colombia to reduce the new water supply network (less infrastructure), because we expect more than 1,000,000 new houses according to policies of urban growth for the next 4 years (Urbana, 2010).

The life cycle analysis can be a tool for evaluating environmental RWH systems dynamics, contributing to identifying the more environmentally friendly strategy. This research helps to identify the environmental impacts attributable to these systems in two urban areas of Colombia.

5.2 Objectives

This research responds to the following objectives: a) To assess the potential environmental impacts in the life cycle of rainwater harvesting systems of emerging neighborhoods of Colombia, with different pluviometry ranks and similar constructive density; b) To propose a dynamic approach as a tool for life cycle assessment of these systems from the perspective of LCM and System Dynamics in developing countries.

5.3 Methodology

For this research, we regard the emerging buildings as sustainable construction as economic, social and environmental aspects. In this sense, our contribution to emerging neighborhoods is focused in environmental dimension. We have chosen as a pilot study of neighborhoods located in two important cities of Colombia: Bogotá and Pereira, each one with an average rainfall of 794 and 2,258 L/m²/year. These represent the conditions of urban growth leading the country (Table 5-1). We propose the construction of a new neighborhood with identical characteristics in each city.

Table 5-1. Population, domestic water consumption and general climatic data for the selected urban areas

Urban area	Population(a)	Domestic water consumption (Lcd) (b)	Altitude (MSL) (c)	Temperature (ºC) (c)	Rainfall (L/m²/year) (c)	Days of rainfall per year (c)
Bogotá	7,347,795	116	2,547	13.4	794	186
Pereira	383,623	118	1,367	21.3	2,258	230

Note: (a) Projections based on census population (Dane, 2005); (b) Average of water consumption in Colombia (IDEAM, 2001); (c) Average characteristics in urban weather stations for monthly series from 1970 to 2008 period (IDEAM, 2008).

According to estimates made by Ballén et al (2006), approximately 56% of average domestic water consumption in Colombia is spent on activities that do not require drinking water quality and 47% is used in laundry and toilet. This data was used as an estimate of the demand for rainwater in the neighborhoods studied.

The RWH system was divided into 2 subsystems: infrastructure and energy use. We analyze the location of the underground tank to be the most appropriate for a country with high earthquake risk.

5.3.1 Simulation model

We created a simulation model using the system dynamics methodology. This model was developed at the Stella software (High Performance Systems, 2011). The model considers RWH potential and tap water as input flows into the system. Water consumption has been divided into two flows, potable water demand and rainwater demand. Each water flow, has been assigned the environmental impacts calculated for the equivalent of the functional unit considered throughout the system [(Eq. 5-1), (Eq. 5-2), (Eq. 5-3)].

$$I_{(t)} = I_{(t-dt)} + (I_{Dr} + I_{Dp}) \cdot dt \quad \text{(Eq. 5-1)}$$

$$I_{Dr} = I_i + I_u \quad \text{(Eq. 5-2)}$$

where,

I matrix of potential environmental impact of the system

I_{Dr} matrix of potential environmental impact of RWH

I_{Dp} matrix of potential environmental impact of tap water

I_i matrix of potential environmental impact by infrastructure

I_u matrix of potential environmental impact by energy use

$$D = D_r + D_p \quad \text{(Eq. 5-3)}$$

where,

D water system demand

Dr rainwater demand

Dp potable water demand

5.3.2 Environmental calculation tools

The LCA methodology considers the entire life cycle of the RWH infrastructures for each scenario. However, the impact of the recycling process of materials at the end of its life cycle has been considered outside the boundaries of the system, as there is much uncertainty in the recycling process 50 years hence.

The aim of the system is the maximum uptake of rainwater with the lowest environmental impact infrastructure. The functional unit has been defined as the collection, storage and supply of $1m^3$ of rainwater provided per person and day to be used as non-potable water for a constant demand of laundry and toilet.

5.3.2.1 Description of the system under study

The system consists of a standard neighborhood of $100x100m^2$ with 10 residential five-storey buildings of 24 apartments (700 m^2/building). The average density of people per household has been assumed on 4 inhabitants per dwelling (DPC, 2009). We have focused on the analysis of an underground tank by the apartment building, leaving environmental analysis of the deposit to the neighborhood level for a future study.

5.3.2.2 Environmental modeling tools

Only the LCA classification and characterization stages (Swiss Centre for Life Cycle Inventories, 2009) have been considered. The method 2001 Baseline v2.04 CML has been used (PRé Consultants, 2010) and the impact selected categories were: Abiotic Depletion Potential (ADP, kg Sb eq.), Acidification Potential (AP, kg SO_2 eq.), Global Warming Potential (GWP, kg CO_2 eq.), Human toxicity potential (HTP, kg 1,4-DB eq.), Ozone Layer Depletion Potential (ODP kg CFC-11 eq.) and Photochemical Ozone Creation Potential (POCP, kg C_2H_4 eq.). The ecoinvent 2.2 database (Swiss Centre for Life Cycle Inventories, 2009) has been used, associated to the software SimaPro7.2.0 (PRé Consultants, 2010).

The data have been adjusted in the context of Colombia. We have estimated the impact associated with consumption of tap water from the average consumption of inputs of water treatment plants in Colombia (CRA, 2010). The impact of energy consumption was calculated on the basis of references (Ortiz-Rodríguez et al. 2010). The life span of the rainwater storage tank, pipes and pumps are 50, 25 and 15 years, respectively (Roebuck et al., 2010).

The size of the tank has been determined using the model previously mentioned, which allows to size the volume of a tank through a continuous daily balance of supply and demand along the year. Data from the weather station of airport El Dorado (Bogotá) and the airport Matecaña (Pereira) has been used, which are within the average rainfall of Colombian cities.

5.4 Results and discussion

Under current conditions mean monthly rainfall in a standard neighborhood, the model results shows in Bogotá city a potential consumes up to 3,900 m^3 of rainwater per year. The same case in the city of Pereira presents a potential consumption up to 15,500 m^3.

5.4.1 Model of environmental impacts

A potential consumtion would be possible in neighborhoods with rainwater storage tanks big enough. However, the potential environmental impacts could increase exponentially and therefore the environmental efficiency of the system could quickly diminish. At each impact category studied, we found a functional relationship between harvesting rainwater (used within the system) and the potential environmental impact. The results showed a potential limit of rainwater consumption in each urban area. Potential consume in Pereira neighborhood is significantly higher than Bogotá. All potential impacts of the system show a similar behavior as presented in the category GWP (Figure 5-1).

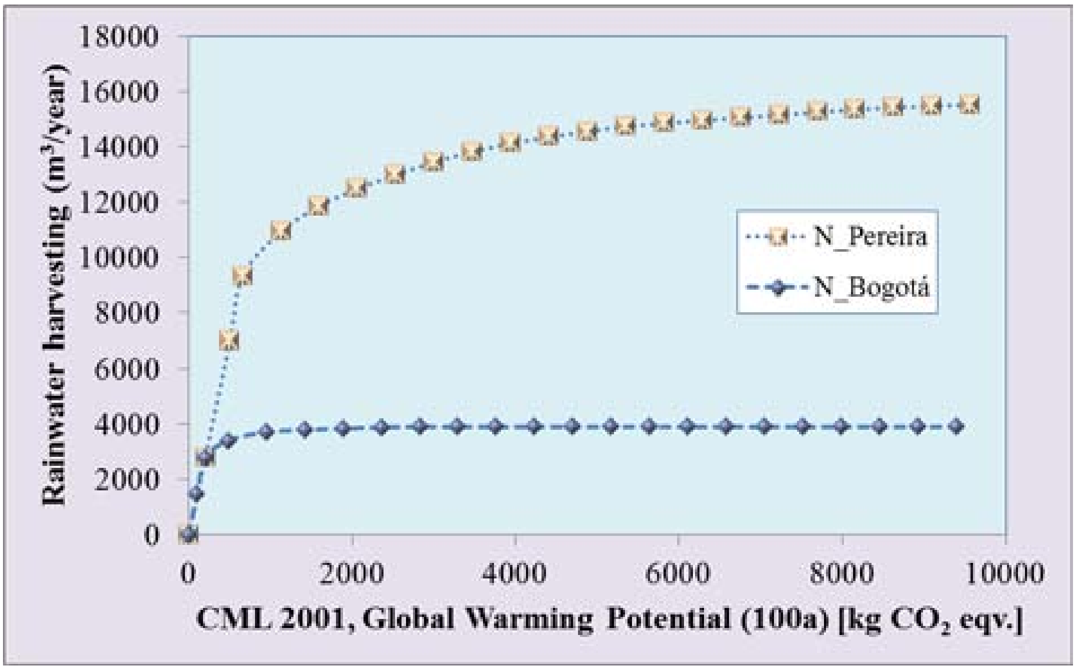


Figure 5-1. Global Warming Potential behavior based on RWH.

The model reveals a functional relationship between potential impacts and the supply of rainwater. The general model is exponential (Eq. 5-4).

$$I = ke^{RWH/a} \qquad \text{(Eq. 5-4)}$$

where,

I Potential Impact

RWH Rainwater Harvesting (m^3/year)

k, a constants

Models has higher fit in Pereira ($R^2 > 0.96$) than Bogotá ($R^2 > 0.67$) (Table 5-2). These can be used to estimate the potential environmental impacts of RWH systems in new neighborhoods. Knowing the demand for rainwater, we could estimate a minimum potential environmental impact on the system.

We found a functional relationship between the storage volume of rainwater and RWH. This harvesting tends to a limit as shown in Figure 5.2. The adjusted model is logarithmic. The model shows the best fit for Pereira (R^2=0.97) than

Bogotá (R^2=0.72). The limit of rainwater harvesting in the system is 15,522 m^3 and 3,921 m^3 for Pereira and Bogotá, respectively.

Table 5-2. Estimated parameters of exponential model for each urban area

CML 2001, Potential impact (I)		Urban area	a	k	R^2
Abiotic depletion potential	kg Sb eq.	Pereira	2.18E+03	1.24E+01	0.987
		Bogotá	1.20E+02	4.09E-13	0.677
Acidification potential	kg SO_2 eq.	Pereira	2.72E+03	8.93E+00	0.963
		Bogotá	1.22E+02	2.15E-13	0.673
Global warming potential (100a)	kg CO_2 eq.	Pereira	2.26E+03	8.47E+00	0.984
		Bogotá	1.20E+02	3.61E-11	0.677
Human toxicity potential	kg 1,4-DB eq.	Pereira	2.21E+03	3.77E+00	0.986
		Bogotá	1.20E+02	1.80E-11	0.678
Ozone layer depletion potential	kg CFC-11 eq.	Pereira	2.07E+03	1.26E+04	0.991
		Bogotá	1.19E+02	5.71E-16	0.680

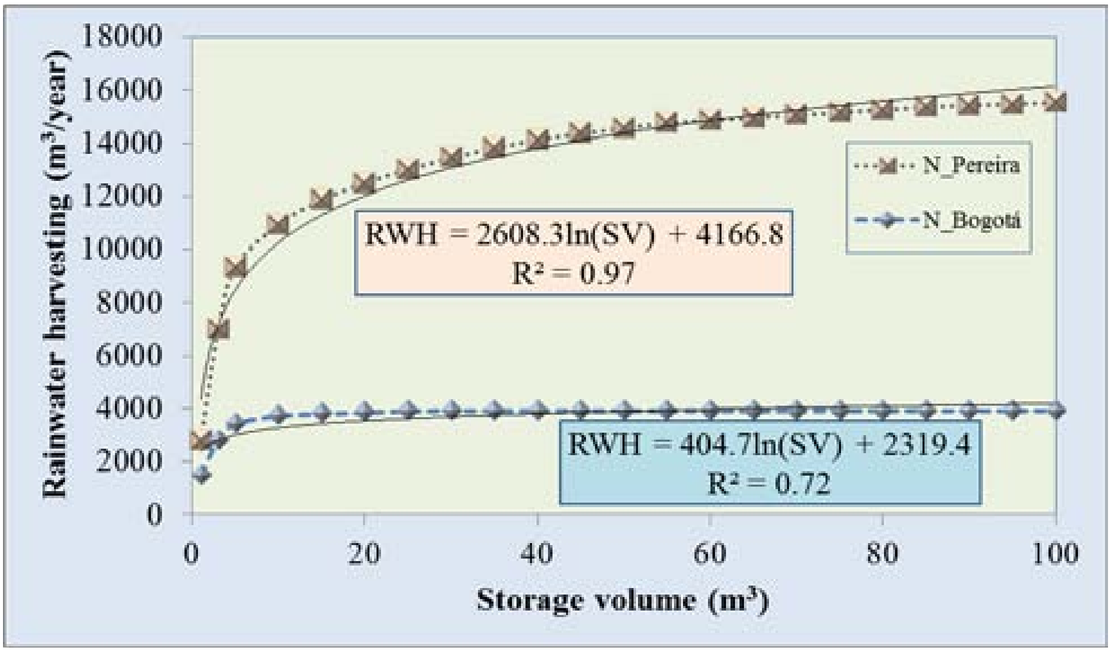


Figure 5-2. Relationship between storage volume and RWH.

5.4.2 Potential environmental impacts

Using the model, the greatest potential environmental impact is found associated with infrastructure in all categories. Since the potential rainwater supply, optimal volumes of 15 and 85 m^3/building (Pereira and Bogotá) were found. Higher impacts of both volumes were found in the 85 m^3 deposit. Except in Pereira for AP impact category, in all of them over 95% of the total potential impact is in infrastructure (Table 5-3).

Table 5-3. Potential environmental impacts of the RWH system in each urban area and storage volume of 85m^3

Potential Impacts	Total		Infrastruture		Energy use	
	Pereira	**Bogotá**	**Pereira**	**Bogotá**	**Pereira**	**Bogotá**
ADP kg Sb eq.	9.77E+01	9.65E+01	9.52E+01	9.64E+01	2.50E+00	1.00E-01
AP kg SO_2 eq.	3.43E+01	3.16E+01	2.85E+01	3.12E+01	5.80E+00	4.00E-01
GWP kg CO_2 eq.	8.16E+03	7.98E+03	7.78E+03	7.96E+03	3.77E+02	2.46E+01
HTP kg 1,4-DB eq.	4.22E+03	4.15E+03	4.08E+03	4.14E+03	1.41E+02	9.20E+00
ODP kg CFC-11eq.	1.38E-01	1.38E-01	1.38E-01	1.38E-01	1.84E-05	5.46E-07

For 85 m^3 of storage volume, we found Global Warming Potential of 7,783 kg CO_2 eq. per year in Pereira neighborhood and 7,960 kg CO_2 eq. per year in Bogotá (Table 5-3). However, for each case, we would be leaving to deliver for the environment near to 199,242 kg of CO_2 eq. in Pereira and 46,210 kg of CO_2 eq. in Bogotá if implemented RWH systems from the start of the new work (Table 5-4).

The avoided environmental impacts do not decrease the total water demand. This continues to grow as a result of the dynamics of urban growth of cities in Colombia. However, the consequences are positive as to reduce pressure on tap water and this influences the required infrastructure and inputs required for purification.

The analysis shows the contribution percentages impacts of each subsystem, but also allows to show the efficiency in the use of the deposit. Under the conditions of Pereira (P) and Bogotá (B), 15 m^3 tanks have higher rates of use. This implied greater use of pump and therefore a higher energy consumption (Figure 5-3). The total supply of rainwater is 11,856 m^3/year (P) and 3,806 m^3/year (B).

Table 5-4. Tap water potential environmental impacts avoided.

Potential Impacts	Potential impacts by 1 m^3 of tap water		15 m^3 of storage volume		85m^3 of storage volume	
	Pereira	Bogotá	Pereira	Bogotá	Pereira	Bogotá
ADP kg Sb eq.	8.05E-03	7.27E-03	954	277	1261	285
AP kg SO_2 eq.	8.71E-03	8.30E-03	1,033	316	1365	326
GWP kg CO_2 eq.	1.27E+00	1.18E+00	150,729	44,857	199,242	46,210
HTP kg 1,4-DB eq.	8.83E-01	8.12E-01	104,706	30,899	138,406	31,831
ODP kg CFC-11 eq.	1.29E-06	1.28E-06	1.53E-01	4.88E-02	2.02E-01	5.02E-02

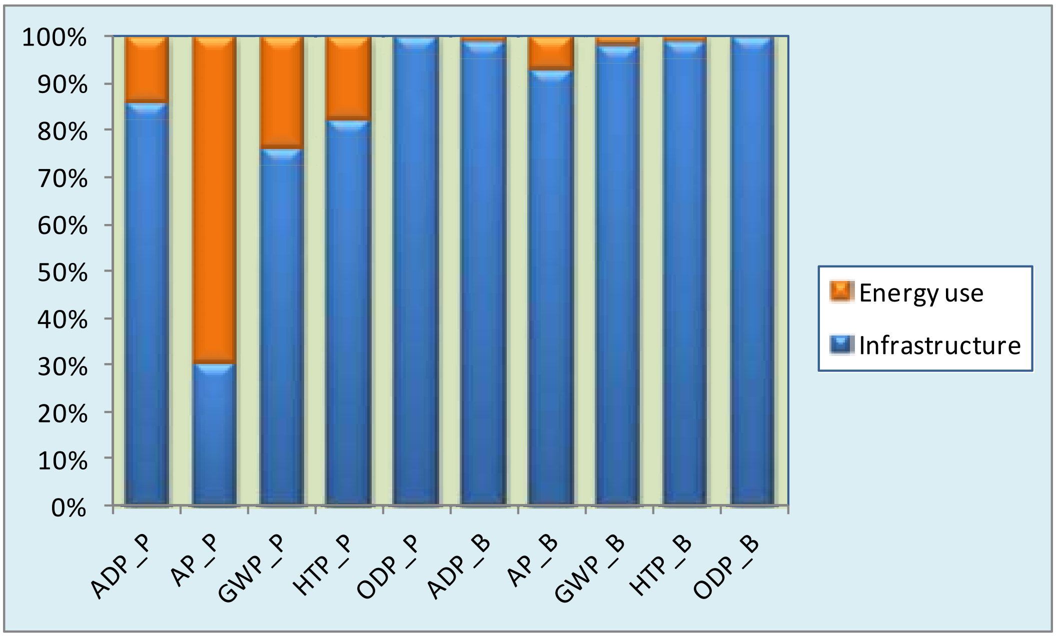


Figure 5-3. Proportion of total environmental impacts and contribution of the systems urban for 15m^3/building of storage volume and 11,856 m^3/year of RWH potential

Under the conditions of a standard neighborhood in Pereira (P) and Bogotá (B), 85 m^3 tanks have lower rates of use. This implied lower use of pump and therefore a lower energy consumption than 15 m^3 tanks (Figure 5-4). The total supply of rainwater is 15,251 m^3/year (P) and 3,921 m^3/year (B). In a standard neighborhood, 85 m^3 storage volume would be optimal for Pereira and 15 m^3 for Bogotá.

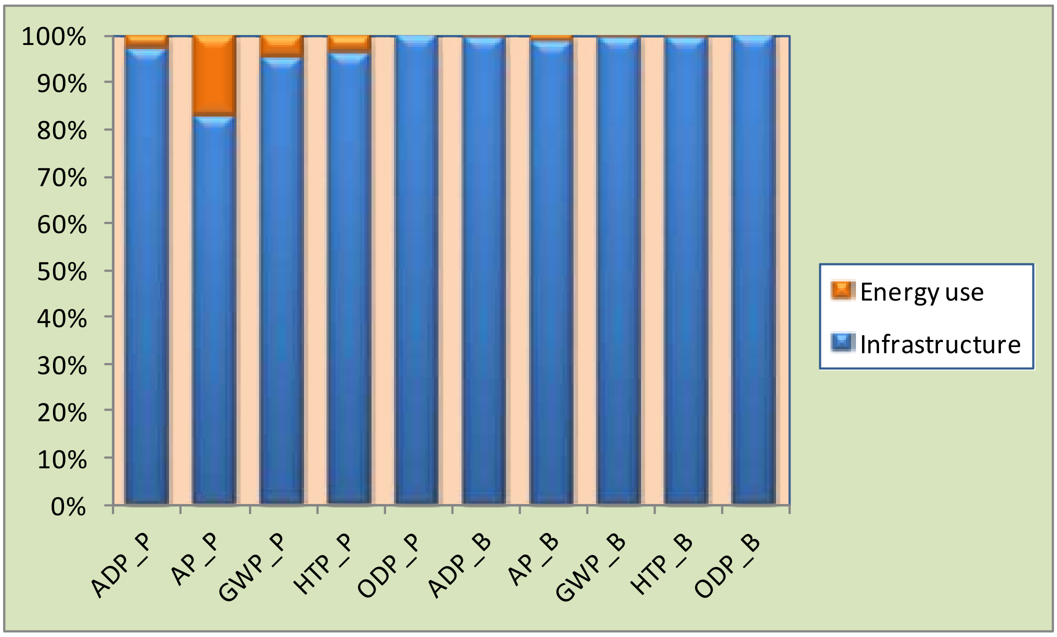


Figure 5-4. Proportion of total environmental impacts and contribution of the systems urban for 85m^3/building of storage volume and 3,806 m^3/year of RWH potential

The model allowed to estimate a function relating the storage volume (SV) with a GWP of all household water consumption (Figure 5-5). The model obtained is quadratic (Eq. 5-5). From the equations for Bogota and Pereira, we can deduce that the equilibrium point for the storage volume is given by the next expression (Eq. 5-6):

$$GWP = aV^2 + bV + c \qquad \text{(Eq. 5-5)}$$

$$V_e = -\frac{b}{2a} \qquad \text{(Eq. 5-6)}$$

Using Equation 5-6 we find that the equilibrium storage volume values are 75.4 m^3 and 45.8 m^3 to Pereira and Bogotá, respectively. These values change depending on the impact category analyzed and the model fit.

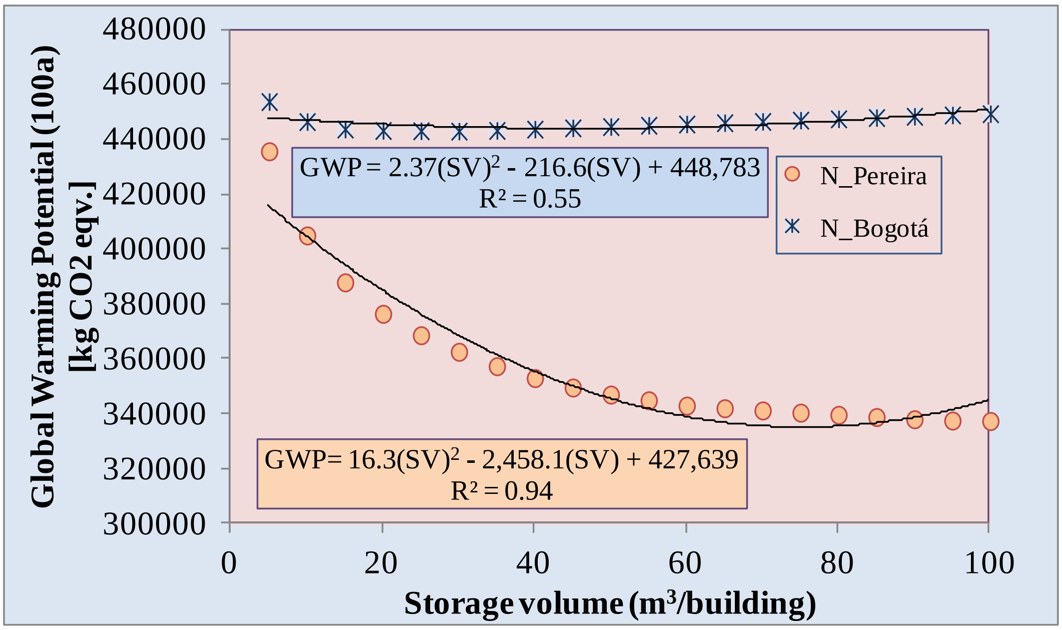


Figure 5-5. Relationship between storage volume and GWP (100a) of household water consumption.

5.5 Conclusions

We found functional relationships between the rainwater harvesting system required and the potential environmental impacts. This relationship can be expressed as an exponential model, where the impacts are calculated in terms of harvesting rainwater volume. These models have the higher coefficient of determination (R^2) in the urban area of Pereira, in principle for the rainwater potential.

In all other impact categories analyzed the greatest potential impact is associated with infrastructure. In the context of Pereira and 15m^3 storage volume, the percentage of Acidification Potential in energy use is higher than Infrastructure.

Although the potential impacts increases with the size of the deposit, the avoided impacts would be allowing a larger storage volume. This is related to the decrease in the consumption of mains water.

We have developed a methodology that helps to decide the best system of rainwater harvesting using two tools of Life Cycle Analysis and System Dynamics.

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PART IV

MAIN FACTORS IN THE ECONOMIC AND ENVIRONMENTAL ANALYSIS OF RWH SYSTEMS

Chapter 6
Financial Feasibility and Environmental Analysis of Potential RWH Systems in Spain

Chapter 7
The consideration of water hardness as an important factor for the environmental and economic analyses of rainwater use in domestic appliances


City of Barcelona (Spain). Photography by Tito Morales Pinzón

Chapter 6
Financial Feasibility and Environmental Analysis of Potential RWH Systems in Spain

6 Financial Feasibility and Environmental Analysis of Potential RWH Systems in Spain

This chapter has been used to present the following paper:

Morales-Pinzón, T., Lurueña, R., Rieradevall, J., M. Gasol, C., Gabarrell, X. Financial Feasibility and Environmental Analysis of Potential RWH Systems in Spain. Submitted and reviewed, second submission on May 2011 to Resources, Conservation and Recycling.

Abstract

Spain has one of the highest risks of water shortage due to the effects of global climate change. Government authorities and public and private institutions have stressed the need to develop alternative water supplies to respond to the growing demand in cities, which are home to more than 70% of Spain's population. Rainwater constitutes an alternative water supply for uses that require lower quality than that provided by tap water. Although there are financial-feasibility studies and other studies on the potential environmental impacts of Rainwater Harvesting (RWH) systems, there is no integration between these studies that allows for rapid assessment tools for these systems that can be used by planners and decision makers. This study shows that it is possible to model both conventional financial indicators (Net Present Value and Internal Rate of Return) and indicators of potential environmental impact (Global Warming Potential and Energy Use) using linear systems and an appropriate sizing scale for the majority of RWH systems. Some positive financial results of this study indicate negative environmental performance in some configurations of RWH systems. In addition, providing rainwater to meet domestic water demand for washing machines has a lower impact than using tap water. The determining factor in the design of RWH systems is the scale of the system, where the neighbourhood scale is the best alternative. The material used for storage tanks is not an outstanding factor.

Keywords

housing, rainwater harvesting, financial analysis, LCA, water demand.

6.1 Introduction

Water is an essential resource for life, and its role as a component of the global ecosystem is becoming increasingly evident. It is a resource that provides the basic needs of the human population and is the key to development, particularly in generating and sustaining wealth in agriculture, commercial fishing, power generation, industry, transport and tourism. In fact, water is vital to all world ecosystems. However, the facts show that we are facing a global water crisis (European Commission, 2002). The European Union is well aware of the importance of water, and through a program called the Water Frame Directive, it aims to help each member state take the necessary measures to assure the sustainable usage of water resources in Europe. Additionally, this directive appeals for citizen participation and considers it a key element for the success of this program (Environment Directorate-General of the European Commission, 2011).

This European water policy, started in the year 2000, must be implemented by the member states, and Spain is no exception. A good example of the integration between European and Spanish water policies is the new water management plan of Cataluña (2010-2015). The main goal of the Catalan plan is to guarantee water supply for all its different uses while protecting the environment and the rational use of water. In other words, it favours a new water culture by promoting environmental, economic, and social sustainability. To achieve its goal, this plan features a set of actions, including diminishing agricultural and industrial waste polluted water, recycling water, desalination, and rainwater harvesting, among others (ACA, 2010). Among these, water harvesting has been put on the backburner, and its ability to supply water, protect the environment, and provide social appeal appear to be undervalued. Thus, the underestimation of rainwater-harvesting (RWH) systems and their rare presence in Spain, together with a European water policy (DIRECTIVE 2000/60/EC) (Environment Directorate-General of the European Commission, 2011), are some of the main reasons for our interest in pursuing a thorough analysis to discover the benefits of implementing RWH systems in Spain.

There is great interest in pursuing this topic in the old continent, as revealed by the numerous research studies conducted by different authors addressing the topic of RWH systems. Some issues that have been studied include rainwater supply and quality (Farreny et al., 2011a) (Sazaklia, et al., 2007), financial analysis (Farreny et al., 2011b), social aspects (Domènech and Saurí, 2011) and environmental analysis (Angrill et al., 2011a). However, the studies are specific and limited to certain case studies, among which integration is not a main topic.

In Spain, the implementation of RWH systems appears promising in meeting the high water demand and encouraging sustainable development while providing significant economical benefits, depending on the region, equipment, and social acceptance. Furthermore, the domestic use of rainwater may be considered an adaptation strategy to climate change against the reduction in water availability. Nevertheless, none of these approaches has a macro-scale vision regarding the implementation of these kinds of systems in Spain. Therefore, we have decided to complement previous research with a more holistic perspective that allows us to analyse the economic and environmental feasibility of such a system in a country like Spain. Besides helping to evaluate Mediterranean climate scenarios, this study analyses a wide range of pertinent variables (water price, water hardness and rainfall).

There are many characteristics that vary among different regions, such as rainfall, water price and water hardness. Morales-Pinzón et al. (2012) found that social level can affect the urban planning of RWH systems. Khastagir and Jayasuriya (2011) looked at the financial impact of the size of tanks on low annual rainfall (≤ 450 mm) and found that the main variables that affect the payback period are tap water price, discount rate and inflation rate. Therefore, the cost and quality of the tap water that is replaced should be considered in the analysis of these RWH systems. These characteristics should be taken into consideration when analysing RWH systems.

Rainfall variability must be considered in the analysis because it may affect the economic viability of these systems, but it is unclear how great this effect is over the life span of a system. Similarly, the cost of the water supply is an important factor to consider because it affects the financial viability of RWH systems. This is especially true when the water-supply network includes high-cost treatments or infrastructure, for example, with desalination. In addition, the quality of tap water replaced by rainwater would be analysed. It is expected that a system that replaces very hard water with rainwater should at least show "positive results" in financial analyses.

6.2 Objectives

This study examines the economic and environmental feasibility of RWH systems because their construction and associated rainwater use offer an alternative in supplying domestic water.

Subsequently, this paper aims to propose a predictive model to estimate the feasibility, in financial and environmental terms, of using RWH systems for the types of housing that can be built in different urban areas in Spain.

6.3 Methodology

6.3.1 System design

The study was conducted on an urban scale by selecting the following 16 cities, which cover a major part of the bioclimatic geography of Spain: Badajoz, Barcelona, Logroño Agoncillo, Madrid, Murcia, Oviedo, Palma de Mallorca, Pamplona, Santander, Santiago de Compostela, Sevilla, Toledo, Valencia, Valladolid, Vitoria and Zaragoza.

The case study considered three types of semi-detached houses—two single houses (TSH), eight single houses (ESH) and groups of houses (GH)—and two types of apartment houses—apartment buildings (AB) and groups of apartment buildings (GAB) (see Figure 6-1).

The proposed analysis of the multiple subsystems found in each city, which attempts to explain the variability of the results based on theses 87 configurations and considers climatic uncontrolled variables such as 1) rainfall (the precipitation, the number of days with rain and the precipitation concentration index (PCI)), 2) water hardness and 3) water price (see Table 6-1). Moreover, controlled design variables such as storage material, tank volume and catchment surface are also considered.

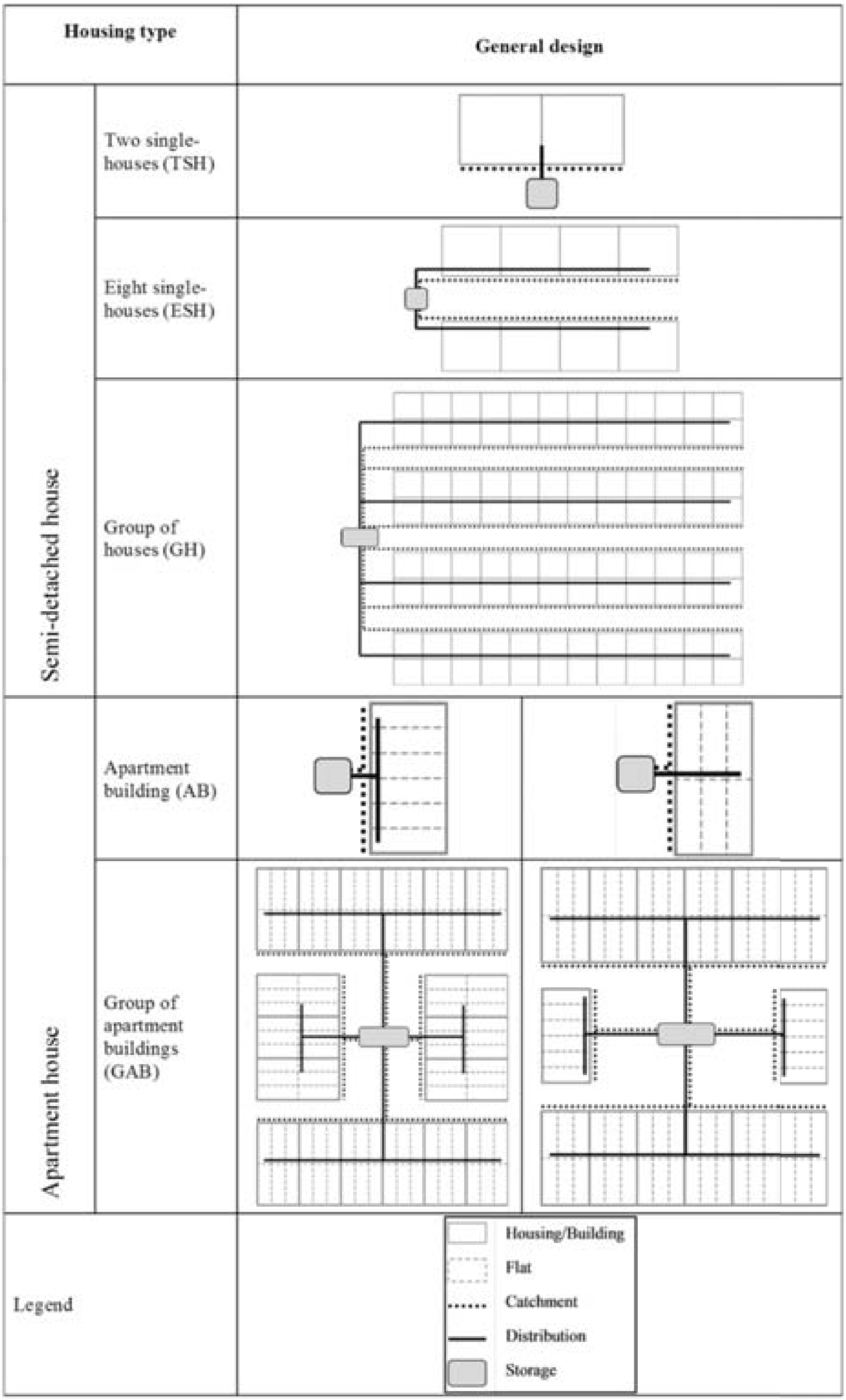

Figure 6-1. General RWH system designs.

Table 6-1. General characteristics of rainfall, water price and water hardness in the provinces studied

City	Rainfall (1) (L/m^2/year)	Precipitation Concentration Index (2)	Mean Number of Days with Precipitation (2)	Mean Number of Days with Precipitation >1 mm (2)	Tap-water price (3) (Euros /m^3)	Water hardness (4) (mg/L $CaCO_3$)
Badajoz	445	17	86	58	1.33	113
Barcelona	555	16	75	51	2.03	342
Logroño Agoncillo	436	13	115	67	1.06	150
Madrid	379	15	80	53	1.37	62
Murcia	284	19	61	34	2.34	209
Oviedo	993	11	178	120	1.31	188
Palma de Mallorca	470	15	81	53	2.65	262
Pamplona	787	12	130	94	1.11	368
Santander	1130	12	170	121	1.15	14
Santiago de Compostela	1794	13	177	136	0.85	na
Sevilla	532	20	69	49	1.62	124
Toledo	345	18	83	51	1.26	na
Valencia	472	19	68	42	1.18	440
Valladolid	446	15	104	67	0.91	650
Vitoria	737	12	153	96	0.94	136
Zaragoza	321	14	85	50	1.28	342
Average	768	15	115	79	1.40	113

(1) Average for 20 years (1991-2010) (Agencia Estatal de Meteorología, 2011)

(2) Average data estimated from rainfall data

(3) Average for 2009 year (AGA-AEAS, 2010)

(4) Data estimated from the concentration of calcium and magnesium from Millan et al. (2009)

na: data not available; assumed to be zero in the financial analysis

6.3.1.1 Potential Rainwater Supply and Optimum Storage Volumes

A simulation model developed by Morales-Pinzón et al. (2011) was used to calculate the potential rainwater supply of the systems (uncontrolled variables) for different storage volumes (controlled variable). We considered the potential catchment surface that can be used by the system. Then, an optimum range of storage volumes (SVs) was selected and compared with the actual available supply of market deposits. The storage tanks materials were concrete (c), polyester fibreglass (pf), high-density polyethylene (p) and steel (s). Although some companies may offer different volumes, we chose the dimensions of commonly used tanks. Daily time series of rainfall (from 1991 to 2010) recorded by local stations were used for each one of the selected urban areas. This information is made publicly available by the State Meteorological Agency of Spain (2011). Additionally, these results were used to simulate the potential of rainwater supply for the expected life span of the system (50 years) using the Monte Carlo method.

Low coefficients of variation in potential rainwater supply (<4%) were found in each subsystem. This criterion was used to create a small random sample of 5 for each one of the 87 scenarios for 16 urban areas. In total, for each scenario, 80 measurements were taken, creating a total of 6,960 individual results (total sample n) for the response variables.

6.3.1.2 Subsystems and scenarios analysed

Eighty-seven scenarios were analysed in each city: 39 semi-detached houses, 12 apartment buildings (ABs) and 36 groups of apartment buildings (GABs).

Table 6-2 shows a detailed description of the configuration of 87 scenarios considered in the assessment presented in this study.

Among the boundaries of the RWH systems considered, the entire life cycle and infrastructures and their use have been included. Nevertheless, the financial and environmental impact of the recycling of materials at the end of their life cycle falls outside the boundaries of this research because there is uncertainty in the recycling process with respect to the life span of the final system.

We studied the financial aspects and environmental impact of the tank materials and the infrastructure required for each system because, according to Angrill et al. (2011a), the greatest environmental impacts of storm water systems are due to the construction phase (materials). We also analysed the use phase with special interest because we suppose a high variability in this phase due to pluviometry.

The study focused on factors influencing the outcome of the financial analysis. Because previous studies (Farreny et al., 2011b) have concluded that large-scale systems give the best results in financial terms, we selected, for the TSH and ESH systems, the lowest deposit expenses reported by the various companies considered and the cheapest type of bomb that gave the performance required by the systems.

Table 6-2. Detailed description of the 87 configurations for each subsystem in each city and expected results

Housing type		Controllable variables				Scenarios	Uncontrollable variables	Response variables
		Storage-tank material	SV (m³)	Code	CS (m²)/wm			
Semi-detached house	Two single-houses (TSH)	Polyester fibreglass (pf)	3, 4, 5	3pf-TSH 4pf-TSH 5pf-TSH	60/2 80/2 100/2	9	1. Rainfall 2. Water demand-supply ratio (1) 3. Tap water price 4. Water hardness 5. Days with rain >1 mm 6. Precipitation Concentration Index (2)	Financial analysis 1. Net present value (NPV) 2. Internal rate of return (IRR) Environmental analysis 1. Global Warming Potential (GWP, kg CO_2 eq.) 2. Energy use potential of system (EUP, kWh)
	Eight single houses (ESH)	Concrete (c)	7	7c-ESH	240/8 320/8 400/8	9		
		Polyester fibreglass (pf)	6, 8	6pf-ESH 8pf-ESH				
	Group of houses (GH)	Concrete (c)	55, 75	55c-GH 75c-GH	2880/96 3520/88 4000/80	21		
		Polyester fibreglass (pf)	50, 60	50pf-GH 60pf-GH				
		Steel (s)	50, 56, 61	50s-GH 56s-GH 61s-GH				
Apartment house	Apartment building (AB)	Concrete (c)	10	10c-AB	220/30 340/30 400/30 480/30	12		
		Polyester fibreglass (pf)	8	8pf-AB				
		Steel (s)	10	10s-AB				
	Group of apartment buildings (GAB)	Concrete (c)	75, 80, 125	75c-GAB 80c-GAB 125c-GAB	3960/540 4760/420 4800/300 4800/360	36		
		Polyester fibreglass (pf)	60	60pf-GAB				
		High-density polyethylene (p)	80,90	80p-GAB 90p-GAB				
		Steel (s)	61, 82, 91	61s-GAB 82s-GAB 91s-GAB				
Total				25	17	87	6	7

(1) $WDS = {RWD}/{RWS} = RWD\ /\ (P \cdot CS)$; RWS: Rainwater Supply; RWD: Rainwater Demand; P: average rainfall; CS: Catchment Surface; wm: washing machines

(2) $PCI = 100 * \sum x^2/(\sum x)^2$; where x is monthly rainfall (Oliver, 1980)

$n = S_c \cdot n_{Sc} \cdot n_u = (87) \cdot (5) \cdot (16) = 6{,}960$; n: total sample; Sc: scenarios; n_{sc}: sample in scenarios; n_u: urban areas

6.3.2 Financial analysis

Regarding the financial aspects and viability of RWH systems, we identify the most important determinants for the development of such projects. The tools used include a) discounted cash flow analysis; b) net present value (NPV) (Eq. 6-1); c) net present value cost (NPVC) (Eq. 6-2); and d) internal rate of return (IRR) (Eq. 6-3). Each of these indicators provides useful information for making decisions, where NPV and IRR are the most often applied in financial studies to choose among several investment projects (Osborne, 2010).

The discount rate for NPV was assumed to be 5%, which is similar to the values used by other authors in analysing the financial performance of RWH systems in other countries; these include studies by Roebuck et al. (2011), Mitchell et al. (2005), Guisi and Mengotti de Oliveira (2007), Liaw and Tsai (2004) and Rahman et al. (2010). Moreover, we assumed a life span of 50 years (Roebuck et al., 2011).

We also considered a steady increase in the prices of energy, water, accessories, pumps and workmanship of 3% yearly.

$$NPV = \sum_{t=0}^{n} \frac{SW_t \cdot WP_t - I_t - MC_t}{(1+r)^t} \quad \text{(Eq. 6-1)}$$

$$NPVC = \sum_{t=0}^{n} \frac{I_t + MC_t}{(1+r)^t} \quad \text{(Eq. 6-2)}$$

$$0 = \sum_{t=0}^{n} \frac{SW_t \cdot WP_t - I_t - MC_t}{(1+IRR)^t} \quad \text{(Eq. 6-3)}$$

where

SW_t: water savings in t period (m^3)

WP_t: water price in t period (Euros/m^3)

I_t: investment required in t period (Euros)

MC_t: maintenance and operation costs in t period (Euros) (It also include energy use, laundry detergent and water)

n: system life span

t: year of system operation

r: discount rate

6.3.3 Environmental calculation tools

A life cycle analysis was used to analyse the environment based on four main steps: definition of the objectives and scope of the study, inventory analysis, impact assessment, and interpretation (ISO 14040, 2006).

According to ISO 14040 (2006), the functional unit was defined as the collection, storage and supply of 1 m^3 of rainwater to be used as non-potable water for a household washing machine with a constant demand of 56 L/cycle (12,320 L/year for 220 cycles) over a span of 50 years. This is a benchmark for household washing machines with a rated capacity of 8 kg (EU commission regulation, 2010).

An impact assessment was performed using classification and characterisation stages (International Organisation for Standardisation ISO, 2000). The environmental impact assessment is based on CML Baseline v2.04 (Guinée et al., 2001), and the selected impact categories were the Global Warming Potential (GWP, kg CO_2 eq.) and the energy use potential of the system (EUP, kWh). The ecoinvent v2.2 database (Swiss Centre for Life Cycle Inventories 2009) was used in combination with the software program SimaPro7.2.0 (PRé Consultants, 2010) for these assessments.

To compare the environmental performance of the RWH systems in the 87 case studies, the impact associated with the consumption of tap water was estimated from the average consumption of the inputs of potable water plants in Spain using data from previous studies (Muñoz et al., 2010). The life spans of rainwater storage tanks, pipes and pumps are 50, 25 and 15 years, respectively (Roebuck et al., 2011).

Based on the different conditions of each of the selected urban areas, the boundaries of the systems were defined as the standard treatment processes of water of surface origin, which for some systems was compared with those used to treat desalinated water using average scenarios of consumption of chemical inputs and the energy required for treatment.

In each of the 87 case studies, we estimated the potential environmental impacts with a simulation tool developed in the software program Stella (High Performance Systems, 2011). This model gives an estimate of these impacts using two methodologies, Life Cycle Assessment and System Dynamics (Morales-Pinzón et al., 2011).

6.3.4 Data source applied

Basic information about suppliers, costs and inputs requested to build systems to capture rainwater was obtained from different sources: direct consultation with suppliers, internet catalogues and a database developed by our research group. This report includes specific information about RWH systems. Thus, the data used for the costs of tanks, pumps and accessories were obtained from 8, 2 and 2 suppliers, respectively.

The cost of installation and renovation of the equipment and accessories used in RWH systems was divided into two parts: cost of RWH installation and the cost of digging. Regarding the RWH cost of installing, we used the information provided by one manufacturer specialist in Barcelona. Next, we used the database of ITeC (2011) to determine the cost of renting a bulldozer and an operator.

Concerning the potential money savings afforded by the use of rainwater to replace tap water in Spain, we used the average prices found in different provinces for 2009 (AGA-AEAS, 2010). Additionally, we used the statistics calculated by the INE (2011) to obtain a measure of the annual demand for water per habitant and estimate the fraction of the water used for laundry.

Finally, to calculate the benefits of the RWH systems in terms of detergent and energy savings, we used data from a specific study (Water Quality Association 2010). Using this study, we were able to estimate the possible income gains depending on the hardness of water in each Spanish province.

6.3.5 Model proposal: Statistical analysis and linear model by system

The main hypothesis is that within each subsystem, the behaviour of the response variables can be explained by linear models. This asseveration was deemed possible after verifying the linearity of the data.

To explain the potential for rainwater obtained by the simulation model, within each system, we analysed the variables of greatest influence using the Pearson correlation coefficient. Regression analysis was performed to find generic models that explain the high variability found in the financial indicators and the GWP and EUP (as potential environmental impact) for each of the systems analysed.

The coefficient of determination (R^2) and the standard error of estimation were used as criteria for selecting the best models. The linear model described by Equation 6-1 facilitates the interpretation of the results and helps to estimate others in specific situations in which new RWH projects can be implemented. Coefficients were estimated upon verification of compliance with the assumptions of the analysis (linearity, homoscedasticity, statistical independence and normal distribution). The explanatory power of the regression model is improved by incorporating the variables most correlated with the response variables.

Financial indicators (NPV and IRR) and environmental indicators (GWP and EUP) can be expressed as the following general linear function (Eq. 6-4):

$$I = \beta_0 + (\alpha_1 D_1 + \cdots + \alpha_m D_m) + \beta_1 X_1 + \cdots + \beta_n X_n + e \qquad \text{(Eq. 6-4)}$$

where

I	response variable
X_n	n-th quantitative variable (controllable or uncontrollable) that contributes a satisfactory explanation of total indicator variability.
Dm	m-th dummy variable
β_0	independent term
β_1 to β_n	constants for quantitative variables
α_1 to α_m	constants for dummy variables
e	error

We used the water demand-supply ratio (WDS), storage volume (SV), tap water price (TWP) and precipitation concentration index (PCI) as quantitative variables. Dummy variables for concrete (c), steel (s) and polyethylene (p) were created to model the storage tank materials. For water hardness, ranges of soft (<75), moderately hard (75-150), hard (150-300) and very hard (>300) are typically used (Nazaroff and Alvarez-Cohen, 2001). In this case, a dummy variable was created for water hardness (WH) to compare only two categories (soft and very hard). The resulting equation for a financial indicator (FI) is as follows (Eq. 6-5):

$$FI = \beta_0 + \beta_1 WDS + \beta_2 SV + \beta_3 TWP + \beta_4 PCI + \alpha_1 WH + \alpha_2 c + \alpha_3 s + \alpha_2 p + e \qquad \text{(Eq. 6-5)}$$

Additionally, for GWP and EUP, an analysis of variance was performed for each system to find equivalent subsystems with equal average impact. We used a high significance level (p> 0.2) to accept the hypothesis of equality of means. The resulting equations for the environmental impact indicators are as follows [(Eq. 6-6)(Eq. 6-7)]:

$$GWP = \beta_0 + \beta_1 WDS + \beta_2 SV + \beta_4 PCI + \alpha_1 WH + \alpha_2 c + \alpha_3 s + \alpha_2 p + e \quad \text{(Eq. 6-6)}$$

$$EUP = \beta_0 + \beta_1 WDS + \beta_2 SV + \beta_4 PCI + \alpha_1 WH + e \quad \text{(Eq. 6-7)}$$

6.4 Results and Discussion

6.4.1 Financial results

The general results show that the effect of material type is not a fundamental financial factor. On the other hand, planning on the neighbourhood scale as a collective action is a determining factor (see Table 6-3).

The analysis of the relationship between the investment cost and the NPV indicator shows that subsystems with high investment costs present the highest values of NPV, though without a linear relationship between cost and NPV (see Table 6-3).

The net present value cost (NPVC) for each RWH subsystem is between 10,559 Euros to 96,951 Euros, and the functional unit cost is 0.94 to 10.59 Euros/m^3. The lowest cost was obtained for the GAB system among all the sub-systems considered (an average of 229 Euros by housing), and the highest cost was obtained for the TSH system (an average of 5,386 Euros by housing). Similarly, after taking into account the functional unit, the lowest NPVC was found in GAB systems, and the highest was found in TSH systems, with averages of 1.1 and 10.5 Euros/m^3, respectively (see Table 3). This can be explained by the required infrastructure and efficiency in their use. For AB subsystems, which feature the largest pumping system and higher energy consumption, costs are high, while GAB subsystems provide more efficient use of infrastructure favoured by the scale factor.

For the NPV indicator, the results obtained for all systems is between -12,839 to 38,424 Euros, with an average of -4.5 to 0.4 Euros/m^3. The IRR is negative in three systems (THS, ESH and AB) and positive in GH and GAB. The highest values of IRR were obtained for GAB (15%) (see Table 3**)**.

The high standard deviation indicates that in addition to storage volume and material, there are other sources of variation that must be considered. The NPVC showed lower variability in the TSH, ESH, GH and AB systems, with less than 1% variability, while in GAB, the variability was less than 5% (see Table 6-3). The variability in the financial indicators was high, but it was nearly constant within each system (see Table 6-3). This behaviour favours the construction of the proposed models.

Table 6-3. RWH and Financial indicators. Average by system and functional unit

Housing type		VM-HT (1)	RWHh (2)	Financial indicators				
				NPVCh (3)	NPVCm (4)	NPV (5)	NPVm (6)	IRR (7)
Semi-detached house	Two single houses	3pf-TSH	10.17 (1.5)	5280 (6)	10.6 (1.6)	-4,243 (468)	-4.3 (0.8)	-21 (6)
		4pf-TSH	10.43 (1.47)	5358 (4)	10.5 (1.6)	-4,368 (490)	-4.3 (0.9)	-21 (6)
		5pf-TSH	10.61 (1.41)	5519 (4)	10.6 (1.6)	-4,656 (499)	-4.5 (0.9)	-20 (6)
		Average	**10.4 (1.47)**	5386 (100)	10.5 (1.6)	**-4,422 (515)**	-4.3 (0.9)	**-21 (6)**
	Eight single houses	6pf-ESH	9.21 (1.73)	1685 (4)	3.8 (0.7)	-3,632 (1,627)	-1.0 (0.5)	-7 (9)
		7c-ESH	9.47 (1.68)	1808 (4)	3.9 (0.7)	-4,463 (1,693)	-1.2 (0.5)	-7 (8)
		8pf-ESH	9.68 (1.61)	1958 (3)	4.2 (0.7)	-5,516 (1,749)	-1.5 (0.5)	-7 (8)
		Average	**9.45 (1.68)**	1817 (112)	4.0 (0.7)	**-4,537 (1,856)**	-1.2 (0.6)	**-7 (8)**
	Group of houses	50p-GH	8.72 (1.83)	481 (36)	1.1 (0.2)	13,286 (16,611)	0.4 (0.4)	11 (7)
		50s-GH	8.72 (1.83)	566 (42)	1.3 (0.2)	6,208 (16,611)	0.2 (0.4)	6 (5)
		55c-GH	8.86 (1.81)	609 (45)	1.4 (0.3)	3,237 (16,954)	0.1 (0.4)	5 (5)
		56c-GH	8.89 (1.8)	570 (43)	1.3 (0.2)	6,623 (17,023)	0.2 (0.4)	6 (5)
		60pf-GH	9.05 (1.8)	503 (37)	1.1 (0.2)	12,944 (17,500)	0.3 (0.4)	10 (7)
		61s-GH	9.08 (1.79)	572 (43)	1.3 (0.2)	7,324 (17,556)	0.2 (0.4)	6 (5)
		75c-GH	9.43 (1.73)	643 (48)	1.4 (0.2)	2,948 (18,356)	0.1 (0.4)	5 (4)
		Average	**8.96 (1.81)**	564 (67)	1.3 (0.3)	**7,510 (17,638)**	0.2 (0.4)	**7 (6)**
Apartment house	Apartment building	8pf-AB	5.22 (2.18)	951 (5)	4.3 (1.8)	-6,443 (3,482)	-1.0 (0.8)	-10 (10)
		10c-AB	5.46 (2.3)	954 (6)	4.1 (1.8)	-6,192 (3,727)	-1.0 (0.9)	-10 (10)
		10s-AB	5.46 (2.3)	1189 (6)	5.1 (2.2)	-12,901 (3,727)	-1.9 (1.2)	-11 (9)
		Average	**5.38 (2.26)**	1032 (112)	4.5 (2)	**-8,512 (4,788)**	-1.3 (1.1)	**-10 (10)**
	Group of apartment buildings	60pf-GAB	4.59 (2.01)	191 (41)	0.9 (0.3)	38,003 (36,200)	0.4 (0.4)	15 (10)
		61s-GAB	4.6 (2.01)	207 (44)	1.0 (0.3)	32,487 (36,334)	0.4 (0.4)	12 (8)
		75c-GAB	4.77 (2.08)	224 (48)	1.1 (0.3)	29,568 (38,222)	0.3 (0.4)	10 (6)
		80c-GAB	4.83 (2.1)	226 (48)	1.1 (0.3)	29,997 (38,900)	0.3 (0.4)	10 (6)
		80p-GAB	4.83 (2.1)	241 (51)	1.1 (0.4)	24,338 (38,900)	0.3 (0.4)	8 (6)
		82s-GAB	4.85 (2.11)	246 (52)	1.1 (0.4)	22,892 (39,171)	0.2 (0.4)	8 (5)
		90p-GAB	5.09 (2.23)	251 (53)	1.1 (0.4)	25,598 (41,660)	0.2 (0.4)	8 (6)
		91s-GAB	5.1 (2.23)	229 (49)	1.0 (0.3)	33,887 (41,756)	0.3 (0.4)	11 (7)
		125c-GAB	5.37 (2.32)	243 (51)	1.0 (0.3)	34,002 (45,072)	0.3 (0.4)	10 (6)
		Average	**4.89 (2.15)**	229 (52)	1.1 (0.4)	**30,086 (39,898)**	0.3 (0.4)	**10 (7)**

Table shows mean with standard deviation in parentheses.

(1) VM-HT: volume (m^3), material of storage tank and housing type. (2) RWHh: rainwater harvesting supply collected by the housing (m^3/year). (3) NPVCh: net present value cost by housing (Euros). (4) NPVCm: net present value cost by functional unit. (5) NPV: net present value of system. (6) NPVm: net present value by functional unit. (7) Internal rate of return of the system (%).

6.4.1.1 Correlations between controlled and uncontrolled variables

Significant positive correlations were found for the mean annual precipitation and the average cumulative days with precipitation greater than 1 mm (see Table 4). The

Pearson correlation coefficient was higher in the GAB system, with R^2 values >0.9, while the lowest values were obtained for the TSH system. Significant negative correlations were found for the precipitation concentration index and water demand-supply ratio (WDS), suggesting that rainfall variability adversely affects the uptake of rainwater and that WDS is very high when a system uses little water as a result of lower surface catchment or lower rainwater supply (see Table 6-4).

Table 6-4. Significant Pearson's correlations between the potential rainwater supply for each system and some representative variables

Variable	Housing type				
	Two single houses (TSH)	Eight single-houses (ESH)	Group of houses (GH)	Apartment building (AB)	Group of apartment buildings (GAB)
Rainfall (L/m²/year)	0.74**	0.79**	0.81**	0.87**	0.93**
Days with rain >1 mm	0.77**	0.89**	0.92**	0.88**	0.95**
Precipitation Concentration Index	-0.59**	-0.74**	-0.76**	-0.57**	-0.62**
Water demand-supply ratio	-0.85**	-0.81**	-0.69**	-0.83**	-0.68**
Storage volume (m³)			0.78**		
System catchment surface (m²)			0.79**		

6.4.1.2 Rainwater supply

It is possible to explain the rainwater potential used by each system by considering the catchment surface, storage volume and area-specific rainfall.

Figure 6-2shows a linear relationship between rainwater potential and these variables. It is evident that a higher surface area and a larger reservoir catchment are best achieved at higher values of rainwater supply. This relationship is consistent with the system under study.

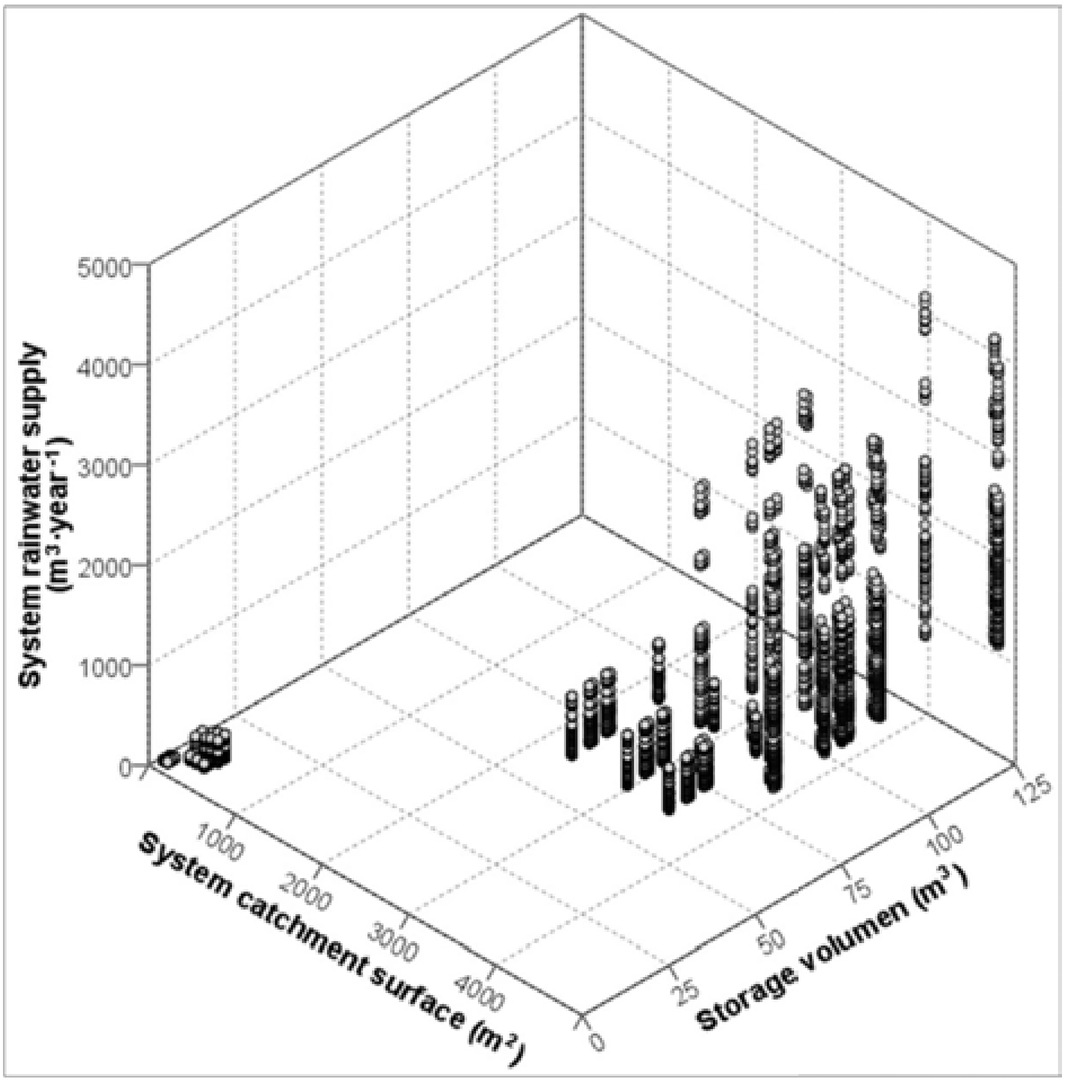

Figure 6-2. Potential of rainwater supply by catchment surface and storage volume.

6.4.1.3 Water hardness and tap water price

Figure 6-3 shows that the effect of the tap water price is one of the most influential variables. The graph shows that, on average, the district-scale systems exhibit positive values with a marked tendency for the price of water; however, this trend is not maintained over all of the cost ranges studied, indicating that other factors may cause a decrease in the expected NPV.

The analysis of rainwater systems in which tap water quality is soft reveals the direct effect of the price of water. Higher tap water prices increase the NPV. However, when rainwater replaces hard water, the effect of tap water price does not show a definite trend (see Figure 6-3). It is therefore important to consider the effect of the hardness factor during the planning of RWH systems in areas with hard water.

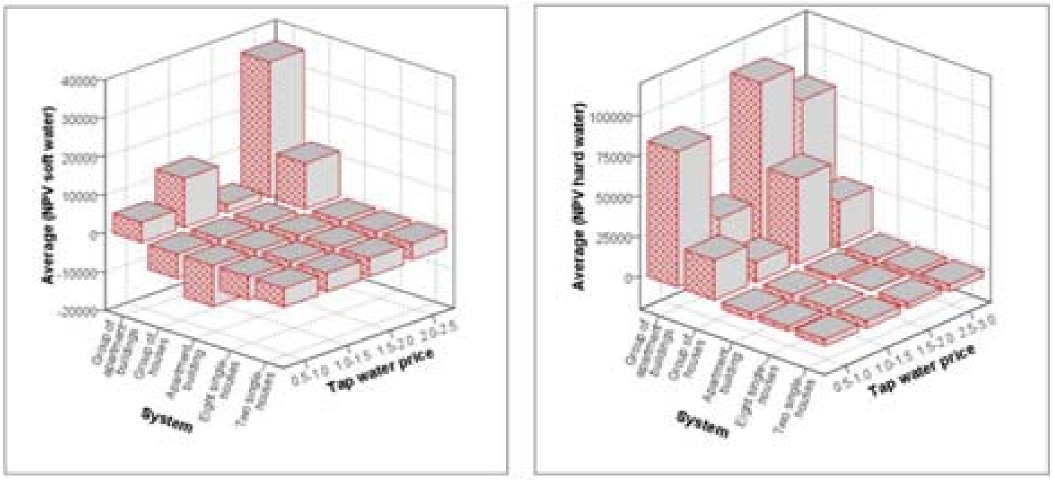

Figure 6-3. Effect of tap water price and water hardness on NPV.

6.4.1.4 Linear financial models

The effect of rainwater supply and other variables helps to obtain a higher coefficient of determination and provides a better explanation of the underlying linear model. The potential of rainwater harvesting is a function of controllable variables, such as catchment area and storage volume, while others, such as precipitation and water hardness, are uncontrollable variables.

We created linear models to explain the variability of financial indicators in RWH systems. A high coefficient of determination above 0.9 was estimated for NPV and low-density systems (TSH and ESH). In all systems, it was possible to explain more than 70% of the total variability for at least one financial indicator. Each variable included in the linear model makes an important contribution.

All variables included in the regression model show linear behaviour as a result of the use of values within the optimal range of the storage volume selected for each system. The linearity and ease of interpretation of the obtained results provides an overview of the behaviour of financial indicators against changes in the values of the independent variables.

For example, if we increase the water demand-supply ratio by 1 unit (which means an increase of 100%), the NVP indicator for TSH, ESH, GH, AB and GAB decreases by 259, 987, 6,667, 1,200 and 7,253 Euros, respectively. For storage volume in TSH and ESH, the coefficient is negative (more volume, less NPV) but is positive in GH and GAB. Tap water cost and hardness are important variables, especially in GH, AB and GAB systems. If the price of water increases by one Euro, NPV will increase by 14,211, 3,026 and 39,089 Euros, respectively, and if the tap water replaced by collected rainwater is hard, the NPV is 47,145, 7,125 and 74,008 Euros more than if it is replaced by soft tap water, respectively. The material used to build storage tanks in GH and GAB systems affect the NPV. In GAB systems, concrete, steel and polypropylene tanks decrease the NPV with respect to polyester-fibreglass by 8,328, 9,786 and 14,172 Euros, respectively (see Table 6-5).

The material used for water deposition in an RWH system also affects profitability. This was determined by comparing the effects of different types of material in the systems (ESH, GH, AB and GAB) in which we had the option of changing the material. For example, according to the results shown in Table 5, the NPV of the ESH system, which only had the option of being constructed from polyester-fibreglass and concrete, remained constant regardless of the type of material used; in GAB systems, however, four different materials can be used, all of which contribute differently to the NPV. The following storage tank materials are listed in order of ascending cost: polyester-fibreglass, concrete, steel and polyethylene (see Table 6-5).

Table 6-5. Coefficients of regression models with better fits to describe the financial indicators

System	Financial indicator	B_0	WDS	SV (m^3)	TWP	PCI	WH	c	s	p	R^2
Two single houses	NPV	-3,782	-259	-206	356	-29	1,426	-	-	-	0.90
	IRR	-22.49	-0.95	0.20	3.01	-0.40	18.76	-	-	-	0.91
Eight single houses	NPV	2,118	-987	-942	1,307	-153	4,758	113	-	-	0.91
	IRR	-5.99	2.27	ns	8.26	-1.19	11.85	ns	-	-	0.68
Group of houses	NPV	17,662	-6,667	ns	14,211	-1,998	47,145	-10,041	-6,478	-	0.89
	IRR	12.31	-0.89	ns	5.73	-0.77	12.53	-5.09	-3.95	-	0.82
Apartment building	NPV	-3,303	-1,200	130	3,026	-467	7,125		-6,710	-	0.88
	IRR	-4.54	-2.36	0.32	9.28	-1.35	15.05		-1.16	-	0.75
Group of apartment buildings	NPV	89,212	-7,253	51	39,089	-7,208	74,008	-8,328	-9,786	-14,172	0.76
	IRR	25.55	-1.37	-0.02	7.61	-1.26	10.00	-4.88	-5.16	-6.76	0.71

WDS: water demand-supply ratio; SV: storage volume (m^3); TWC: tap water cost (Euros /m^3); WH: water hard; c: concrete; s: steel; p: polyethylene; PCI: precipitation concentration index; R^2: coefficient of determination. ns: no significance

6.4.2 Environmental potential impacts

For each system, we considered constant emissions from the construction stage and equipment replacement. In contrast, in the use stage, the variability in rainfall affects the potential CO_2 equivalent emissions of the system. This behaviour is similar in the financial analysis. Thus, the cash flows in the use stage, in addition to those associated with rain, are affected mainly by the price of tap water and water hardness.

On average, the potential environmental impacts for each functional unit indicate that ESH produces less GWP than others systems (0.36 kg CO_2 eq/m^3), and the greatest is produced by TSH (0.95 kg CO_2 eq/m^3). The 5pf-TSH (5 m^3 of storage volume) and 50p-GH (50 m^3 of storage volume) subsystems are those with the greatest and lowest potential environmental impact, each with an average of 0.27 and 1.38 kg CO2 eq/m^3, respectively (see Figure 6-4).

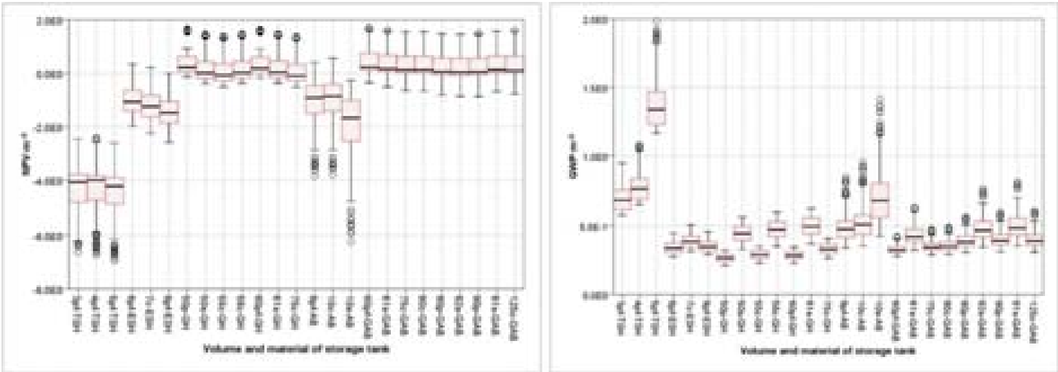

Figure 6-4. NPV and potential environmental impacts of RWH systems by functional unit.

The potential use of energy is between 0.16 and 4.0 kWh/m^3 for rainwater supply (see Figure 5). The potential for energy consumption per household is on average higher in AB and GAB systems than in other systems. The 6pf-ESH subsystem has the lowest average energy use, while 10c-AB and 10s-AB have the highest average energy use, with 1.5 and 2.2 kWh/housing/year, respectively (see Figure 6-5).

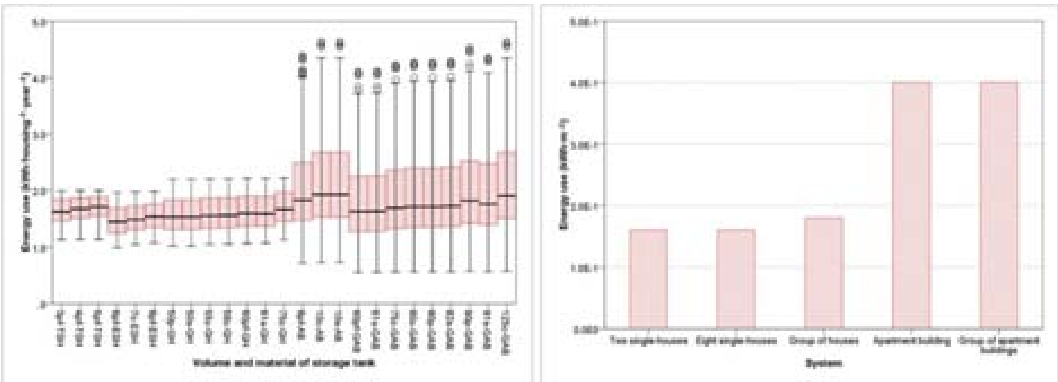

Figure 6-5. Energy use potential of RWH systems by functional unit.

In general, the potential impacts of the systems with better financial results are lower. For the GH and GAB systems, the potential impacts per functional unit were the lowest with respect to the GWP. GH and GAB systems show higher energy consumption and better environmental performance according to the GWP indicator. Thus, urban planning on a large scale is the most efficient strategy.

6.4.2.1 Linear environmental models

The environmental impact of the systems analysed can be expressed using a linear model for each system. The coefficients of determination in the GWP models show a high level of fit ($R^2 > 0.9$) for the AB, GH and ESH systems and a moderate level of fit for TSH and GAB systems (see Table 6). In some systems, the tank material has a lower effect on the potential impact. In these cases, the storage tank material is a variable that has little effect on the selection of the system to be used. The coefficients found also help define certain relationships between the materials of the deposits. In ESH systems, polyester-fibreglass tanks are compared with concrete tanks, the latter of which has a greater environmental impact. In AB systems, an 8 m^3 tank of polyester-fibreglass has a lower impact than a steel tank with a volume of 10 m^3. In these systems, concrete has a greater environmental impact than the other materials. For GH systems, polyester and steel are compared, showing that, on average, a greater impact is caused by steel tanks (see Table 6-6).

Table 6-6. Linear models used to estimate GWP (kg CO_2 eq./m^3) in RWH systems

System	k	WDS	SV (m^3)	c	s	p	PCI	R^2
TSH	-7.9E-01	3.9E-01	3.4E-01	-	-	-	1.2E-02	0.82
ESH	1.1E-01	1.2E-01	6.2E-03	4.2E-02	-	-	8.7E-03	0.92
GH	-7.9E-02	9.5E-02	2.6E-03	9.1E-03	1.9E-01	-	1.1E-02	0.94
AB	-3.7E-02	9.3E-02	1.9E-02	1.8E-01	-	-	9.3E-03	0.92
GAB	6.3E-02	2.9E-02	1.2E-03	-	1.2E-01	3.8E-02	7.9E-03	0.80

WDS: water demand-supply ratio; SV: storage volume; c: concrete; s: steel; p: polyethylene; PCI: precipitation concentration index; R^2: coefficient of determination

It is possible to estimate the potential use of energy by a RWH system in a household. Using linear models helps explain the study results. Although the level of fit of the linear models was moderate ($0.65<R^2<0.9$), the models show the same behaviour with respect to the signs of the variables. It is emphasised that WDS has the opposite effect in models that describe the GWP. This indicates that higher rainwater supplies produce higher energy use and lower GWP per functional unit (see Table 6-7).

Table 6-7. Linear models to estimate energy-use potential by year in RWH systems

System	k	WDS	SV (m^3)	PCI	R^2
TSH	4.6	-1.31	0.07	-0.06	0.84
ESH	19.1	-5.14	0.30	-0.42	0.90
GH	235.3	-51.01	0.45	-6.25	0.80
AB	138.7	-14.43	1.47	-3.47	0.79
GAB	1,661.3	-119.69	1.96	-51.60	0.65

WDS: water demand-supply ratio; SV: storage volume; PCI: precipitation concentration index; R^2: coefficient of determination

Although water hardness could not be included in these models (hardness did not reach the significance level expected), it shows a trend that contributes to the EUP and GWP models.

6.4.2.2 Equivalents systems

The analysis shows that it is possible to have equivalent systems. For example, the subsystem 125c-GAB (concrete) showed no significant differences ($p>0.20$) from the 90pf-GAB and 80pf-GAB (polyester) systems. Other systems are equivalent: 91s-GAB is similar to 82s-GAB, and 80c-GAB is similar to 75c-GAB. In addition, the subsystems 55c-GH and 60pf-GH statistically have the same potential environmental impact. These systems are equivalent because a larger tank is offset by the lower environmental impact of the materials used. These effects should be taken into account in planning future projects to implement RWH systems.

6.5 Conclusions

From a financial standpoint, RWH systems appear to fit better (an average > 7500 Euros) in large-scale and high-density constructions such as groups of houses (GH) and groups of apartment buildings (GAB). Under the conditions stated above, in larger-scale systems (GH and GAB), one would expect a short-term return on investment. Systems with higher energy consumption show better performance with respect to the financial indicators and the potential environmental impact, as measured by GWP. Thus, the best strategy is found in neighbourhood-scale systems.

The price of water affects the financial results; however, this effect is not as significant as the effect of water hardness. RWH systems can provide more important gains for buildings when the cost of water and the level of water hardness are high, without even taking into consideration the rainfall in the region.

The variability of rainfall is an important factor to be considered in detail in the designs of RWH systems. It is therefore necessary to have specialised tools to facilitate the study of these systems, as simulation models are widely used in this research.

The relationship between storage tank material and NPV is most evident in the GAB system, which features a broader set of material options including polyester-fibreglass, concrete, steel, and polypropylene. This relationship appears to have different values of NPV depending on the type of material selected. Thus, we can conclude that polyester-fibreglass is the best material, which appears to contribute to a higher NPV. However, in the overall analysis, the material of the shell is not a determining factor in planning RWH systems.

According to the integration between financial and environmental indicators, we can conclude that systems that are more financially viable are not necessarily the best in terms of potential environmental impacts. This is mainly due to the great effect of infrastructure on total impact, which implies the need to have very good estimates of the use stage as the most variable component throughout a system's life span, which depends primarily on the amount of rainwater that can be effectively harvested.

Domestic appliances using hot water. Photography by Tito Morales Pinzón

Chapter 7

The consideration of water hardness as an important factor for the environmental and economic analyses of rainwater use in domestic appliances

7 The consideration of water hardness as an important factor for the environmental and economic analyses of rainwater use in domestic appliances

This chapter has been used to present the following paper:

Morales-Pinzón, T., Lurueña, R., Gabarrell, X., M. Gasol, C. Rieradevall, J. The consideration of water hardness as an important factor for the environmental and economic analyses of rainwater use in domestic appliances. Submitted on May 2011 to Water Reseach.

Abstract

A study was conducted to determine the economic and environmental effects of water quality on rainwater harvesting systems. The potential for replacing tap water used in washing machines with rainwater was studied. A wide range of weather conditions, such as rainfall (300-1800 mm); water hardness (14-354 mg/L $CaCO_3$); water prices (0.91-2.65 Euros/m^3) in different urban areas (from individual buildings to whole neighbourhoods); and other scenarios (including materials and water storage capacity) were analysed. Rainfall was not considered to be an important factor, while the tap water prices and the water hardness were the main factors for consideration in the economic and the environmental analyses, respectively. The local tap water hardness and prices can cause greater economic and environmental impacts than the type of material used for the water storage tank or the volume of the tank. We found that the benefits to the environment outweighed the harm caused to the environment, such that the feasibility of being more environmentally friendly was greater than the economic viability. When hard tap water needed to be replaced, we found that a water price of 1 Euro/m^3 could render the use of rainwater economically feasible when using large-scale rainwater harvesting (RWH) systems. When the water hardness was greater than 300 mg/L $CaCO_3$, an economic analysis revealed that an NPV greater than 100,000 Euros could be obtained at the neighbourhood scale, and there could be a reduction in the Global Warming Potential ranging between 35 and 101 kg CO_2 eq./dwelling/year.

Keywords

Rainwater harvesting, economic feasibility, LCA, washing machine

7.1 Introduction

Rainwater harvesting has been considered as an alternative to the freshwater supply in urban areas. Recently published papers studying the feasibility of rainwater harvesting (RWH) have focused on the use of conventional economic indicators, such as the net present value (NPV) and the internal rate of return (IRR). Khastagir and Jayasuriya (2011) showed the cost effectiveness analysis of rainwater in Melbourne, Australia, and Farreny, et al. (2011b) presented the life cycle cost of rainwater harvesting in Mediterranean neighbourhoods. The social aspects of rainwater harvesting have also been analysed by Domènech and Saurí (2011) and Morales-Pinzón et al. (2012).

New approaches have been proposed to incorporate environmental analysis into life cycle assessments (LCA), highlighting the use of midpoint indicators, such as Global Warming Potential (GWP) analysis, as has been investigated by Angrill et al. [(2011a), (2011b)] and Morales-Pinzón et al. (2011). Most of these studies have focused on analysing RWH systems based on the local rainfall and water prices.

All of these approaches only give a report about the outcomes of the indicators studied, but there was no analysis on the potential benefits of implementing RHW systems. The economic and environmental feasibility studies performed have assumed that the quality of the water networks has remained consistent; therefore, they have not considered the potential effects of variable water hardness on the results of their analyses. Consideration of water hardness could be an important factor because different studies have found that the hardness of rainwater is low.

The presence of calcium and magnesium in water gives rise to water hardness. Hard water is observed by the formation of soap scum when soap is mixed with water, which necessitates the use of more soap for cleaning purposes. Consumers are able to tolerate water hardness in excess of 500 mg/L $CaCO_3$, and there are no health-based guideline values proposed for the hardness of drinking water (OWH, 2011).

Tap water hardness has been associated with health issues and detergent consumption (Rygaard et al. 2011), and it can also shorten the lifespan of home appliances that use hot water (Van der Bruggen et al. 2009), such as washing machines and dishwashers (Godskesen et al. 2012), because the solubility of $CaCO_3$ decreases at higher temperatures, which leads to its precipitation.

The hardness of rainwater was found to be low. Farreny et al. (2011a) determined that the total carbonate concentration found in rainwater ranged between 12 and 162 mg/L, while Domènech and Saurí (2011) reported that rainwater contained between 20 and 30 mg/L of $CaCO_3$. The water hardness found in cisterns ranged between 50 and 270 mg/L $CaCO_3$ according to Abdulla and Al-Shareef (2009), while Nolde (2007) reported values less of 15 mg/L $CaCO_3$. A detailed study by Sazaklia et al. (2007) found that rainwater hardness ranged between 24 and 74 mg/L of $CaCO_3$, and Vialle et al. (2011) found hardness values that were less than 58 mg/L of $CaCO_3$.

There are no studies that evaluate the potential effect of using rainwater as a substitute for tap water as a function of water hardness. Water substitution is one of the main criteria to be considered, especially when rainwater could be used in home appliances.

As a result of these uninvestigated aspects, this paper aims to analyse the potential effect of rainwater hardness on domestic water consumption activities, such as washing clothes, in greater detail. The study analyses different scenarios, including the material used to fabricate the storage tank, the storage tank capacity, the use of RWH systems at an urban scale and the variation in weather conditions, such as rainfall.

7.2 Objectives

Through this research, we will contribute to the study of the rainwater supply in cities, focusing on evaluating the water hardness, the tap water price and the amount of rainfall in different systems. This paper also compares the potential environmental impacts that can be avoided and the economic costs of constructing the RWH systems. The specific objectives of this paper are:

- to evaluate the economic viability of rainwater harvesting under different conditions when considering the rainwater hardness and the urban scale,
- to calculate the economic costs that could be reduced or avoided for different RWH systems in relation to tap water hardness and
- to estimate the potential environmental impacts that could be avoided by substituting tap water with rainwater in washing machines.

7.3 Methodology

The potential effects of a variable rainfall, the price of tap water and water hardness on the environment were studied. Current actual scenarios of the most important urban areas in Spain were selected as case studies. These case studies represent a wide range of real situations that can be found in many European cities. The variability in the different factors, such as rainfall (284-1794 mm), tap water prices (0.85-2.65 Euros/m^3) and water hardness concentrations (14-315 mg/L $CaCO_3$) were analysed using different storage capacities and storage tank fabrication materials, as well as an urban scale system, as shown in Table 7-1.

7.3.1 Areas of study

Sixteen different urban areas distributed throughout Spain were selected as the study areas. The general conditions in each area represent a wide range of variability in terms of the main factors that were considered in this research, as shown in Table 7-1. The motivation behind the selection of these urban areas was their high variability in rainfall, water prices and water hardness concentrations. Further, the results of this study could be useful for the analysis of developing RWH systems in other cities.

Table 7-1. General characteristics of selected urban areas

Water hardness (mg/L $CaCO_3$)		Urban areas (2)	Rainfall (mm) (3)	Days with rain (4)	Tap water price (Euros/m^3) (5)	Energy price (Euros/kWh)
Category (1)	Range					
Very hard (vh)	≥300	Barcelona	555	75	2.03	0.14 (6)
Hard (h)	150-300	Valencia, Valladolid	446 to 472	69 to 200	0.85 to 2.34	
Moderately hard (mh)	75-150	Palma de Mayorca, Pamplona, Zaragoza	321 to 787	85 to 130	1.11 to 2.65	
Soft (s)	<75	Badajoz, Logroño Agoncillo, Madrid, Murcia, Oviedo, Santander, Santiago de Compostela, Sevilla, Toledo, Vitoria	284 to 1794	68 to 123	0.91 to 1.18	

(1) A water hardness quality scale obtained from Nazaroff and Cohen (2001).

(2) Classification of water hardness in different urban areas as reported by companies that provide water services, as well as the concentrations of calcium and magnesium in the different waters as analysed by Millan et al. (2009)

(3) A 20-year average value over the 1991-2010 period (Agencia Estatal de Meteorología, 2011)

(4) Average values estimated from rainfall data

(5) The average price in 2009 (AGA-AEAS, 2010)

(6) The average cost of electricity mix in Spain when the power consumption is less than 10 kW (CNE, 2012)

The average annual rainfall in all urban cities is 768 mm, where the lowest annual rainfall is in Zaragoza (321 mm) and the highest annual rainfall is in Santiago de Compostela (1794 mm). According to Michiels et al. (1992), the precipitation concentration index (PCI) that is used as an indicator of rainfall variability of the cities ranges from 11 and 20, indicating that the rainfall distribution is caused by a moderate seasonal distribution or a seasonal distribution, which are two of the four possible categories used to describe rainfall variability. The number of rainy days in a year ranges between 68 and 200 days, and 62% to 73% of these days are characterised by an accumulated rainfall amount greater than 1 mm.

The price of tap water is the highest in Palma de Mallorca at 2.65 Euros/m^3, while the tap water price is the lowest in Santiago de Compostela at 0.85 Euros/m^3. The water hardness is the highest in Barcelona at 315 mg/L $CaCO_3$ and the lowest in Santander at 14 mg/L $CaCO_3$. This variability was grouped as a function of water hardness ranges defined by Nazaroff and Cohen (2001), as shown in Table 7-1.

7.3.2 Urban scale and scenarios analysed in each area

Twenty-five scenarios were compared in each urban area. The scale of analysis took into consideration single houses, buildings and neighbourhoods. The study considered three types of semi-detached houses: a set of two single houses (TSH), another set of eight single houses (ESH) and eighty-eight single houses or groups of houses (GH). Two types of apartment houses were also considered: one apartment building (AB) and fourteen apartment buildings or groups of apartment buildings (GAB).

Each scenario included the main factors considered for the different RWH system designs that were available in the market: the material used to construct the storage tank, which consisted of polyester fibreglass, steel, concrete and high-density polyethylene; the storage capacity of the tank according to the housing type and the rainwater demand; and the catchment surface, which was defined as a minimum useful area, as shown in Table 7-2.

Table 7-2. A detailed description of the 25 scenarios analysed in each system

Urban scale	Housing type	Code (1)	Storage-tank material	Storage capacity (m³)	Catchment surface (m²)	Dwellings	Sample size
Semi-detached house							
Single-houses	Two single-houses (TSH)	3pf-TSH	Polyester fibreglass (pf)	3	80	2	240
		4pf-TSH		4			
		5pf-TSH		5			
	Eight single houses (ESH)	7c-ESH	Concrete (c)	7	320	8	
		6pf-ESH	Polyester fibreglass (pf)	6			
		8pf-ESH		8			
Neighbourhood	Group of houses (GH)	55c-GH	Concrete (c)	55	3470	88	
		75c-GH		75			
		50pf-GH	Polyester fibreglass (pf)	50			
		60pf-GH		60			
		50s-GH	Steel (s)	50			
		56s-GH		56			
		61s-GH		61			
Apartment house							
Building	Apartment building (AB)	10c-AB	Concrete (c)	10	360	30	320
		8pf-AB	Polyester fibreglass (pf)	8			
		10s-AB	Steel (s)	10			
Neighbourhood	Group of apartment buildings (GAB)	75c-GAB	Concrete (c)	75	4580	405	
		80c-GAB		80			
		125c-GAB		125			
		60pf-GAB	Polyester fibreglass (pf)	60			
		80p-GAB	High-density polyethylene (p)	80			
		90p-GAB		90			
		61s-GAB	Steel (s)	61			
		82s-GAB		82			
		91s-GAB		91			
Systems/ Scenarios/ Sample	**5**	**25**	**4**	**25**	**5**	**5**	**6960**

(1) The code represents the analysis scenario, which includes the tank storage capacity, the tank material and the general system.

The potential rainwater supply of the systems was estimated using a simulation model developed by Morales-Pinzón et al. (2011). The sample size was calculated using the following equation:

$$n = \frac{Z_{\alpha/2}^2}{\sigma^2 \cdot e^2} \qquad \text{(Eq. 7-1)}$$

where

n optimal sample size in simple random sampling

$Z_{\alpha/2}$ number of standard deviations in the normal distribution for a specified confidence level

σ^2 variance of interest

e maximum permissible error

Using preliminary simulation data obtained from the model, the averages and the variances of the potential rainwater supply for each housing type was estimated. The variances of the potential rainwater supply to the semi-detached houses and the apartment houses were 5.2 and 3.9 $m^6/dwelling^2/year^2$, respectively. The value of the maximum permissible error was 0.25 m^3/dwelling/year, which was equivalent to 5% of the average potential rainwater supply. A total of 240 semi-detached houses and 320 apartment houses were sampled. The sample size was proportionally distributed among the sixteen urban areas, as shown in Table 7-1. A sample size of 15 semi-detached houses and 20 apartment houses was used in each of the twenty-five scenarios, for a total sample size of 6,960, as shown in Table 7-2. This number represents the "number of simulation runs" for the model.

7.3.3 Selected indicators used in the economic analysis of RWH systems

The indicators used include a) the net present value (NPV) as shown in Equation 7-2, b) the return of invest (ROI) as shown in Equation 7-3, c) the benefit-cost ratio (BCR) as shown in Equation 7-4 and d) the payback period (PBP) as shown in Equation 7-5. The discount rate for the NPV was assumed to be 5%, as used by Roebuck et al. (2011), Mitchell et al. (2005), Guisi and Mengotti de Oliveira (2007), Liaw and Tsai (2004) and Rahman, Dbais and Imteaz (2010). Additionally, we assumed a system lifespan of 50 years as suggested by Roebuck et al. (2011) and Angrill et al. (2011a).

We also considered a constant 3% increase in the prices of energy, water, accessories, pumps and labour. This value is similar to the stable inflation rate of 2.7% in Europe (Eurostat, 2012).

$$NPV = \sum_{t=0}^{s} \frac{S_t \cdot P_t - I_t - M_t}{(1+r)^t} \qquad \text{(Eq. 7-2)}$$

$$ROI = \sum_{t=0}^{s} (S_t \cdot P_t - I_t - M_t) \Big/ \sum_{t=0}^{s} (I_t + M_t) \qquad \text{(Eq. 7-3)}$$

$$BCR = \sum_{t=0}^{s} \frac{S_t \cdot P_t}{(1+r)^t} \Big/ \sum_{t=0}^{s} \frac{I_t + M_t}{(1+r)^t} \qquad \text{(Eq. 7-4)}$$

$$PBP = N_{BCR} > 1 \qquad \text{(Eq. 7-5)}$$

where

S_t volume of water saved over a period of time t (m^3)

P_t cost of water over a period of time t (Euros/m^3)

I_t investment required for a period of time t (Euros), assumed to be sufficient until the end of the period

M_t maintenance costs over a period of time t (Euros), including the costs of energy use, laundry detergent and water

N_{BCR} minimum time required (years) to obtain a BCR value that is greater than 1

s system life span

t system operation period

r discount rate

7.3.3.1 An economic sensitivity analysis of the RWH systems

A sensitivity analysis was conducted to observe the effects of a price increase on the NPV. These results allow us to systematise the NPV of the systems studied as performance curves related to the water cost and water hardness.

7.3.4 Potential costs to the environment

The potential environmental costs were obtained from the ecoinvent v2.2 database (Swiss Centre for Life Cycle Inventories, 2009) as unit values and processed by SimaPro7.2.0 software (PRé Consultants, 2010) based on four main steps: the definition of the objectives and the scope of the study, an inventory analysis, the impact assessment and the interpretation (ISO 14040, 2006). These values were incorporated into the model developed by Morales-Pinzón et al. (2011) using basic data from Angrill et al. (2011) to estimate the environmental impacts in each scenario. We then calculated the potential costs that could be avoided by replacing tap water with rainwater for use in laundry machines.

The functional unit was defined as the collection, storage and supply of 1 m^3 of rainwater to be used as non-potable water for the operation of a household washing machine on a constant demand of 56 L/cycle (12,320 L/year for 220 cycles) over a span of 50 years as suggested by the ISO 14040 method (2006). This assumption is a benchmark for household washing machines operating at a rated capacity of 8 kg according to the EU commission regulations (2010).

An impact assessment was performed using classification and characterisation stages obtained from the ISO 14042 standards (2000). The environmental impact assessment, according to Guinée et al. (2001), is based on the CML Baseline v2.04, and the selected impact categories were the Global Warming Potential (GWP in terms of kg CO_2 eq.), the Abiotic Depletion Potential (ADP in terms of kg Sb eq.), the Acidification Potential (AP in terms of kg SO_2 eq.), the Eutrophication Potential (EP in terms of kg PO_4^{3-} eq.), the Human Toxicity Potential (HTP in terms of kg 1,4-DB eq.), the Ozone Depletion Potential (ODP in terms of kg. CFC-11 eq.), the Fresh Water Aquatic Ecotoxicity (FAETP in terms of kg DCB eq.), the Terrestrial Ecotoxicity (TETP in terms of kg DCB eq.) and the Photochemical Ozone Creation Potential (POCP in terms of kg C_2H_4 eq.). The energy use potential of the system (EUP in terms of kWh) was also calculated.

As suggested by Roebuck et al. (2011) and Angrill et al. (2011), the estimated lifespans assumed for the rainwater storage tanks, pipes and pumps were 50, 25 and 15 years, respectively.

7.3.4.1 The estimation of the total amount of energy saved in relation to water hardness

The study conducted by the Water Quality Foundation (2010) estimated the average temperature required for the optimal washing of clothes based on the water hardness, assuming that an adequate amount of detergent was used for each wash cycle. We then estimated the temperature that washing machines could operate at if tap water was replaced by rainwater. A basic model can be described using the following set of equations:

$$D_T = T - T_{min} \qquad \text{(Eq. 7-6)}$$
$$T = 0.22 \cdot D - 6.67 \qquad \text{(Eq. 7-7)}$$
$$D = 0.19 \cdot H + 100 \qquad \text{(Eq. 7-8)}$$
$$E = 0.05 \cdot m \cdot H \qquad \text{(Eq. 7-9)}$$

where

D_T temperature reduction (ºC)

T temperature required for the optimal washing of clothes (ºC)

T_{min} minimum temperature required at a water hardness of zero (ºC)

D amount of detergent used relative to the amount used at T_{min} (%)

E amount of energy saved (kWh)

m volume of tap water replaced by rainwater (m^3)

H water hardness (mg $CaCO_3$/L)

Eq. 9 suggests that the potential energy savings for the highest water hardness analysed in this study is 0.882 kWh/cycle. This value is equivalent to an electricity demand of 0.81 kWh/cycle for heating purposes in washing machines using a standard programme operated only by electricity (Persson, 2007), without considering any effects of water hardness.

7.4 Results and Discussion

From the five types of buildings defined in our study of "macro-systems" (i.e., TSH, ESH, AB, GH and GAB), the analysis of these RWH systems would include the quality of the tap water that is being substituted with rainwater. When the tap water was of a greater hardness, the implementation of the RWH systems showed better economic results. The type of buildings that house the RWH systems is also an important factor when assessing the feasibility of the rainwater harvesting projects. For the 16 Spanish cities that were analysed (i.e., Badajoz, Santander, Palma de Mallorca, Zaragoza, Pamplona, Logroño, Vitoria, Valencia, Murcia, Sevilla, Toledo, Madrid, Valladolid, Oviedo, Santiago de Compostela and Barcelona), we found that the installation of the RWH systems within the GH and the GAB macro-systems demonstrated the highest profitability.

7.4.1 Main factors affecting economic results

The results show the general effects of rainfall (R), tap water price (WP) and water hardness (WH) on the economic indicators. A higher water price and a greater water hardness result in a better NPV. Additionally, the RWH systems are more economically feasible on the larger urban scales, as shown in Figure 7-1.

The scale of the RWH systems is a factor that must be considered in urban planning, as the economic benefits increased with the RWH system scale. Conversely, when the NPV is negative, a smaller scale corresponds to a lower capital outflow, as shown in Figure 7-1.

Among the 16 urban areas, the minimum NPV in the GH macro-system is -13,346 Euros in Toledo, while the maximum NPV is 53,552 Euros in Barcelona. The NPV mean for all urban areas considered in this study was 5,447 Euros, as shown in Figure 7-1. Toledo is a city with low annual rainfall (R= 345 mm/year), low water prices (WP= 1.26 Euros/m^3) and low water hardness (WH< 70 mg/L $CaCO_3$). However, Barcelona is a city with moderate annual rainfall (R= 555 mm/year), high water prices (WP= 2.03 Euros/m^3) and high water hardness (WH> 300 mg/L $CaCO_3$).

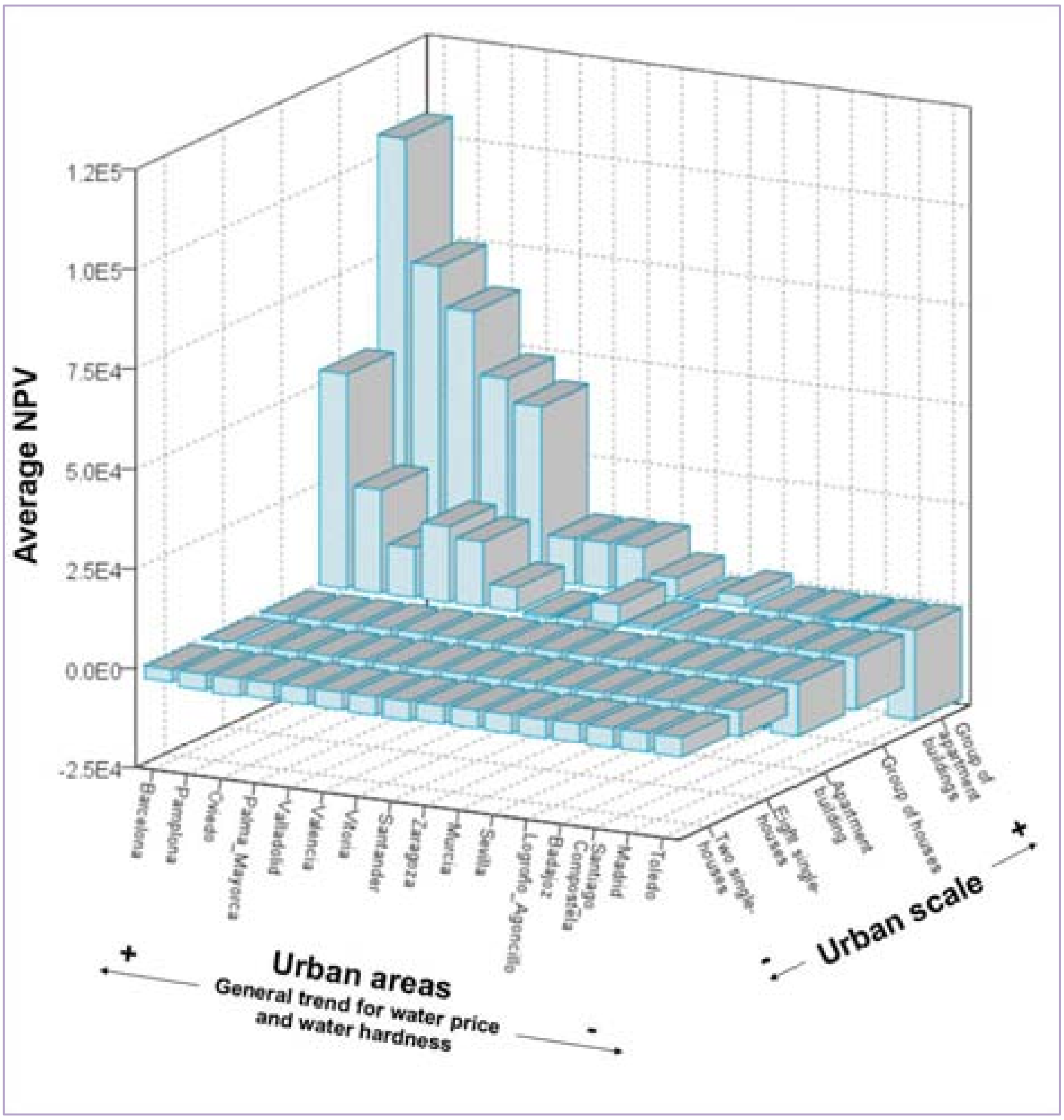

Figure 7-1. The average NPV for five rainwater systems in Spanish cities.

The minimum NPV in the GAB macro-system is -22,654 Euros in Madrid, and the maximum NPV is 105,959 Euros in Barcelona, with a mean NPV of 20,805 Euros, as shown in Figure 7-1. Madrid experiences conditions that are similar to Toledo in terms of low annual rainfall (R= 379 mm/year), low water prices (WP= 1.37 Euros/m^3) and low water hardness (WH<70 mg/L $CaCO_3$).

However, the construction of RWH systems within the TSH macro-system appears to be the least efficient system of all, with a minimum NPV of -4,983 Euros in Santiago de Compostela, a maximum NPV of -3,053 Euros in Barcelona and a mean of -4,474 Euros, as shown in Figure 7-1. Santiago experiences high annual rainfall levels (R= 1794 mm/year), low water prices (WP= 0.85 Euros/m^3) and low water hardness (H<70 mg/L $CaCO_3$).

Economic analyses conducted on all urban areas found a viable configuration for RWH systems. The cities of Barcelona, Pamplona, Oviedo, Palma de Mallorca and Valladolid had the best economic returns. The water hardness and the price of tap water were the variables that influenced these results the most, as shown in Figure 7-1.

The least favourable economic returns were found in the urban areas of Toledo, Madrid, Santiago de Compostela and Badajoz because their tap water supplies had low water hardness concentrations and the price of tap water was not high. Furthermore, Toledo and Madrid are cities that have a low annual rainfall, as shown in Figure 7-1.

7.4.1.1 The effect of rainfall on NPV

Rainfall was not a main factor in the economic analysis of the RWH systems, even though it is important to satisfy rainwater demand. This finding is possible because the demand for rainwater can be met under any of the climate conditions that were surveyed in this study.

The systems with the best economic returns were found in places where the annual rainfall ranged from 400-700 mm or 700-1000 mm. Within these rainfall quantity ranges, the average NPV was 29,300 Euros and 50,400 Euros for the GAB system and the average NPV was 11,800 Euros and 12,500 Euros for the GH system, as shown in Figure 7-2.

Similar NPV values were found at annual rainfall quantities that were less than 400 mm or that were more than 1000 mm, except for the GAB system, as shown in Figure 7-2.

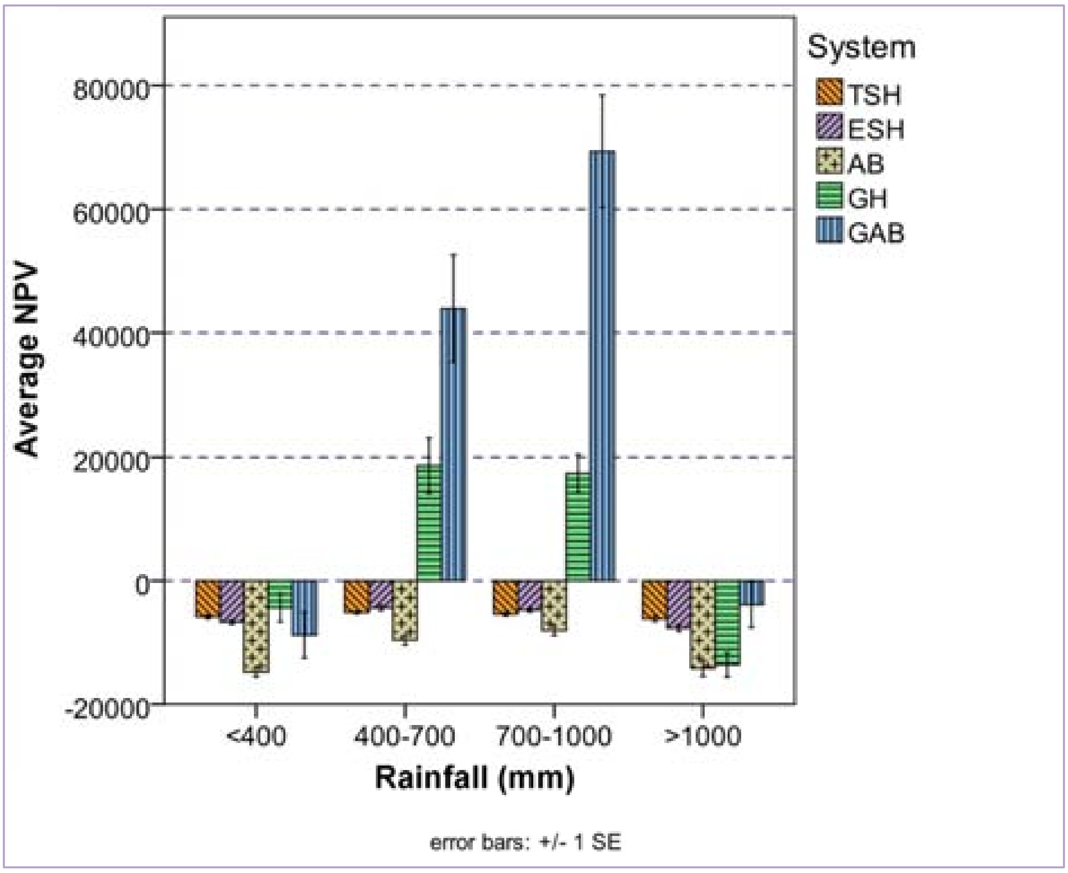

Figure 7-2. NPV values at different annual rainfall quantities

7.4.1.2 The effects of water hardness on the economic indicators

The best results among all economic indicators were observed to be when the tap water that was replaced by rainwater was moderately hard water (75 to 150 mg/L $CaCO_3$) or very hard (H 300 mg/L $CaCO_3$). The NPV equivalent per household was the highest in the GH and the GAB systems, with values of 612 and 274 Euros/dwelling respectively as shown in Table 7-3.

The return of investment (ROI) was always positive in the GAB and the GH systems, with average values of 2.4 and 1.7, respectively. For the AB and the ESH systems, there was a positive ROI only when the tap water was very hard. For the TSH system, all ROI values were negative, as shown in Table 7-3.

The benefit cost ratio (BCR) was favourable (BCR> 1) in the GAB and the GH systems. The highest BCR values were obtained in scenarios where the water was hard. In these cases, the BCRs for the GAB and the GH systems were three times higher than the average value, as shown in Table 7-3.

The payback period (PBP) was shorter in the GAB and the GH systems and more favourable when the analysis took water hardness into consideration. For "very hard" waters, we found the PBP values to be 5.5 and 6.0 years for the GAB and the GH systems respectively, as shown in Table 7-3.

Table 7-3. The effects of water hardness on the economic analysis in different neighbourhoods

W_h	NPVd (1) (Euros/dwelling)	ROI	BCR	PBP (years)
Group of apartment buildings				
s	11.4 (12.7)	1.3 (2.3)	1.1 (1.0)	20.8 (1.0)
mh	71.7 (3.7)	3.2 (1.9)	1.6 (1.3)	11.5 (1.3)
h	111.5 (3.1)	3.5 (1.9)	1.9 (1.4)	11.2 (1.5)
vh	274.1 (1.7)	7.7 (0.8)	3.1 (0.8)	5.5 (0.7)
GAB	**54.1 (3.3)**	**2.4 (1.6)**	**1.4 (1.0)**	**16.9 (1.0)**
Group of houses				
s	-44 (6.5)	0.7 (3.3)	0.9 (1.0)	25.9 (1.1)
mh	126.7 (4.1)	2.6 (2)	1.4 (1.4)	12.8 (1.3)
h	190.1 (3.3)	2.8 (1.8)	1.6 (1.4)	12.5 (1.3)
vh	612.1 (1.0)	7.0 (1.5)	3.0 (1.5)	6.0 (1.2)
GH	**62.2 (7.7)**	**1.7 (2.6)**	**1.2 (1.3)**	**20.5 (1.2)**

The standard error (%) for each quantity is given in parentheses

7.4.1.3 The effect of a price increase on the NPV

The sensitivity analysis shows that an increase in price is one factor that may contribute to better economic returns. There were no substantial changes to the NPV when prices were increased by 1-3%. However, there was a significant effect on the NPV of the GAB and the GH systems when the expected price increase was greater than 5%, as shown in Figure 7-5a. The price increase causes a nonlinear increase in the average NPV, as shown in Figure 7-5b.

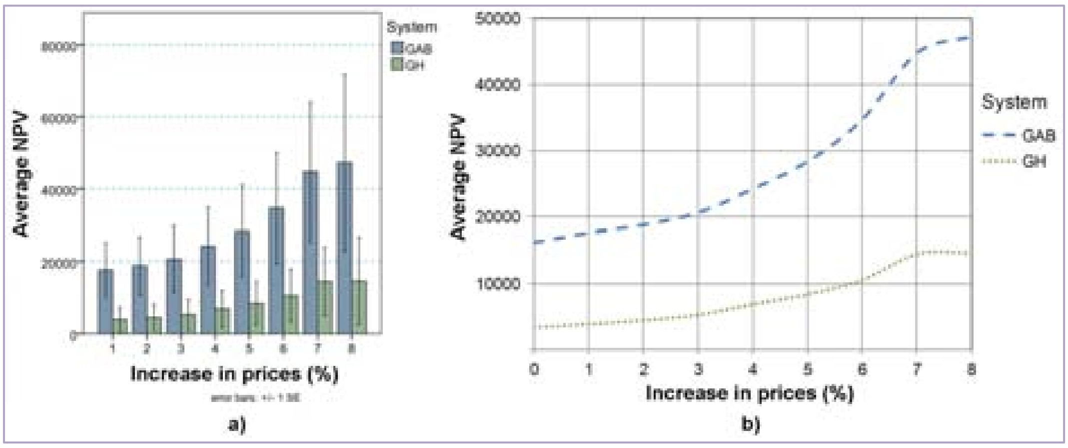

Figure 7-3. NPV sensitivity analysis when prices are increased at different percentages in different neighbourhoods.

7.4.2 A sensitivity analysis of the water price and the water hardness

When the water is soft (H<75), it is necessary for water prices to be greater than 1.5 and 2 Euros/m^3, respectively, in the GH and the GAB systems at the neighbourhood scale for the implementation of the RWH systems to be economically feasible, as shown in Figure 7-4a and Figure 7-4b. When the tap water was moderately or very hard (H>75), a tap water price of 1 Euro/m^3 would be the minimum value required for the GH and the GAB systems to be economically feasible, as shown in Figure 7-4a and Figure 7-4b. The ESH and AB systems serving a lower population and a low urban scale were only viable when the tap water was hard or very hard and the water prices were at least 1 and 1.4 Euros/m^3, respectively, as shown in Figure 7-4c and Figure 7-4d. The sensitivity analysis found that the TSH system was not economically feasible at all, as shown in Figure 7-4e.

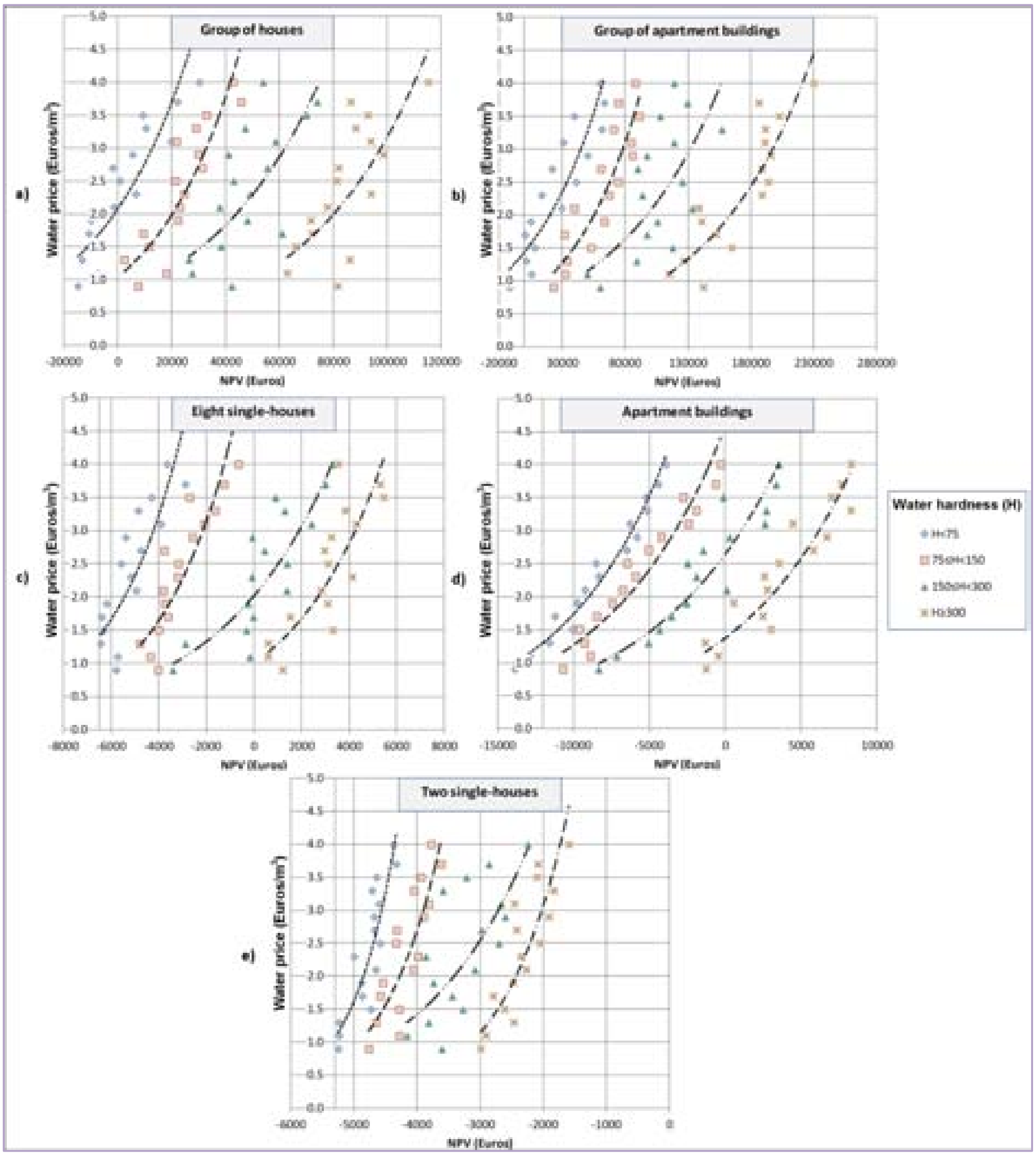

Figure 7-4. Economic sensitivity curves of water price and water hardness

7.4.3 Water hardness and reduced economic costs

The water hardness significantly affects the economic balance when the cost of saving energy is considered. The economic costs that could be saved per dwelling were found to be higher in low density systems. For the TSH and the ESH systems, the costs saved per dwelling could be eight times higher when the tap water was hard than when the tap water was soft, as shown in Figure 7-5a. In all scenarios that were analysed, there was a potential savings that could be realised when hard water was substituted with rainwater. The lowest total economic costs that could be saved correspond to Scenario 3pf, which used a TSH system and soft water, while the highest amount that could be saved was found in scenario 125c-, which used a GAB system with very hard water, as shown in Figure 7-5b. On average, the economic savings increased by 1.4, 3.4 and 5.8 times when the water hardness went from soft to moderately hard, hard and very hard, respectively, as shown in Figure 7-5.

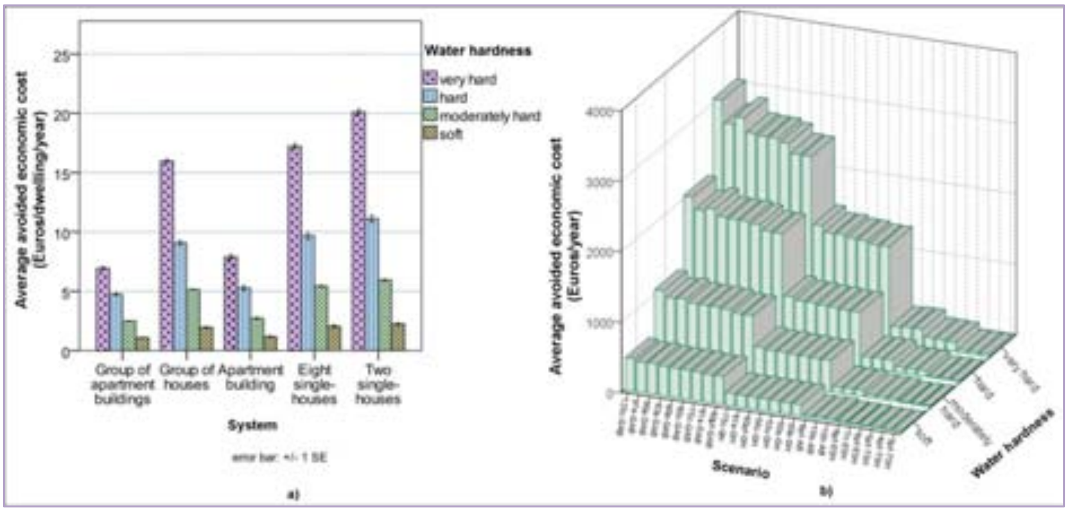

Figure 7-5. Cost savings based on the water hardness used in the systems and different RWH construction scenarios.

7.4.4 Water hardness and potential environmental benefits

When rainwater was used to replace hard water, the environmental benefits can be significant and higher than the potential environmental costs exerted by the RWH systems.

Low density systems possessed the highest potential energy savings, saving 35, 37 and 42 kWh/dwelling/year on average for GH, the ESH and the TSH systems, respectively. High density systems showed energy savings of approximately 17 and 19 kWh/dwelling/year on average for the GAB and the AB systems, respectively. These values are comparable to the data by Godskesen et al. (2012), who estimated an annual heat energy savings of 11.4 kWh/person/year when the water hardness was reduced from 362 to 145 mg/L $CaCO_3$.

7.4.4.1 Energy savings and the potential environmental impacts of RWH systems

When the tap water to be replaced is considered to be "very hard", the estimated energy savings were 3.9 and 3.5 times more for the low density systems (GH, ESH and TSH) and the high density systems (GAB and AB), respectively, as shown in Figure 7-6. These energy savings represents an average GWP reduction of 35, 40, 80, 87 and 101 kg CO_2 eq./dwelling/year for the GAB, the AB, the GH, the ESH and the TSH systems, respectively, as shown in Figure 7-6.

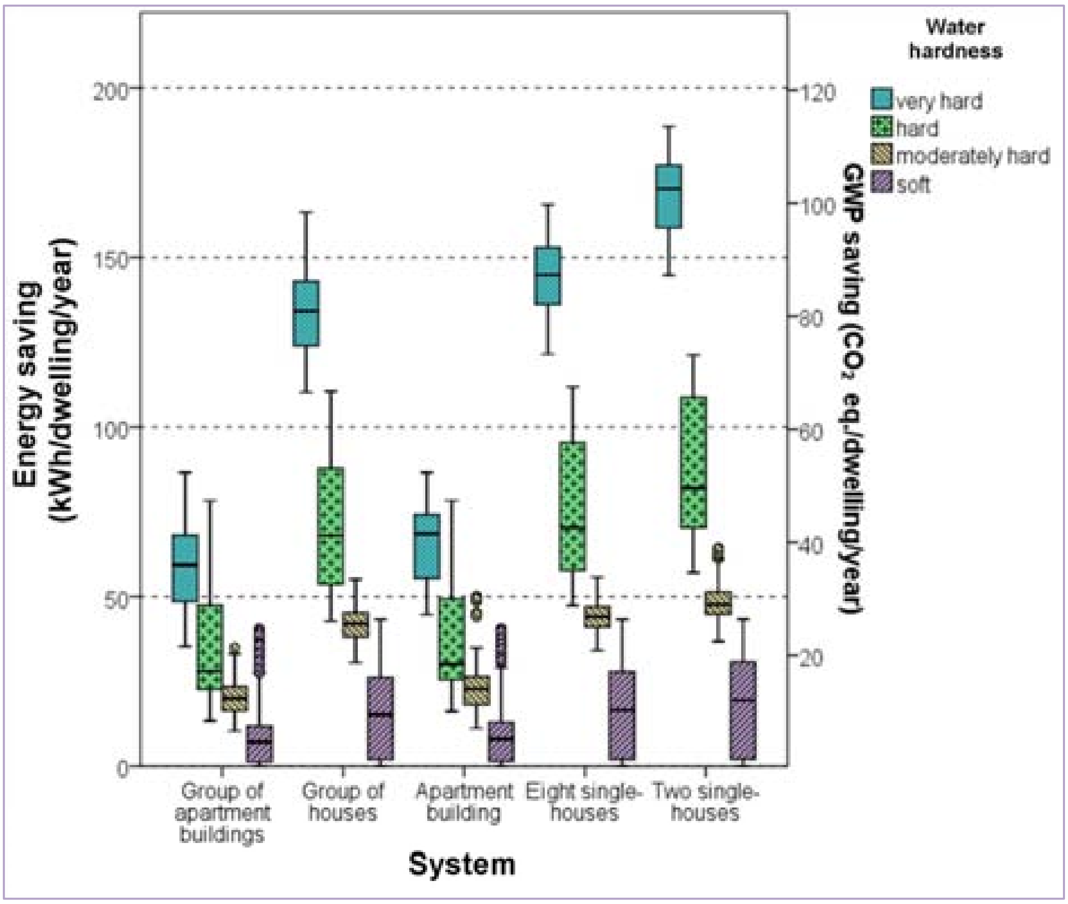

Figure 7-6. Energy savings and the reduction in the GWP as a result of the implementation of the RWH systems.

7.4.4.2 Potential environmental benefits based on water hardness

We found that the potential benefits to the environment based on water hardness increased were 3, 5 and 9 times higher when the water was moderately hard, hard and very hard, respectively, than the benefits were when the water was soft for systems operating at the neighbourhood scale, as shown in Table 7-4. For example, the reduced GWP was 9.5 kg CO_2/m^3 for very hard waters, in comparison with a reduced GWP was 1.1 kg CO_2/m^3 for soft waters, as shown in Table 7-4. These values are comparable with the data presented by Angrill et al. (2011), and they show that the environmental benefits to implementing a RWH system outweigh the environmental costs. This result is possible by incorporating the environmental benefits of replacing hard water with rainwater in home appliances, like washing machines, into the analysis.

Table 7-4. The environmental benefits per functional unit at the neighbourhood scale

water hardness	ADP	AP	EP	GWP	ODP	HTP	FWAP	TEP	POP
very hard	6.9E-02	9.2E-02	1.9E-02	9.5E+00	5.1E-07	5.0E+00	3.1E+00	1.7E-01	4.6E-04
hard	3.9E-02	5.2E-02	1.0E-02	5.4E+00	2.9E-07	2.8E+00	1.8E+00	9.3E-02	2.6E-04
moderately hard	2.3E-02	3.0E-02	6.1E-03	3.2E+00	1.7E-07	1.6E+00	1.0E+00	5.5E-02	1.5E-04
soft	7.8E-03	1.0E-02	2.1E-03	1.1E+00	5.8E-08	5.6E-01	3.5E-01	1.8E-02	5.1E-05
average	1.8E-02	2.4E-02	4.9E-03	2.5E+00	1.4E-07	1.3E+00	8.2E-01	4.4E-02	1.2E-04

7.4.4.3 The effects of different storage materials and different storage volumes on the benefits of RWH system construction

It was found on average that the benefits outweighed the costs within all categories analysed. The benefits (E) in all scenarios can be as many as 26 times greater than the costs (C) of implementing an RWH system, as shown in Figure 7-7a. The E/C ratio is significant when the main water supply to be replaced is considered to be hard. In scenarios where TSH systems were used with very hard waters, we found that the E/C ratio was at least 5, as shown in Figure 7-7b. Similarly, in scenarios where ESH systems were used, the E/C ratio was more homogeneous and was consistently higher than 20, as shown in Figure 7-7c. For scenarios where AB systems were used with very hard waters, the E/C ratio was more than 10, as shown in Figure 7-7d. For scenarios corresponding to systems at the largest urban scale with very hard tap waters, we found that the potential benefits were greater and that the E/C ratios were greater than 15 and 10 in the GH and the GAB systems, respectively, as shown in Figure 7-7e and Figure 7-7f.

The materials used in tank construction and the overall tank sizes used in the different scenarios do not significantly affect the costs or the benefits of system implementation because factors such as the water hardness and the scale of the system contribute more towards the cost-benefit analysis.

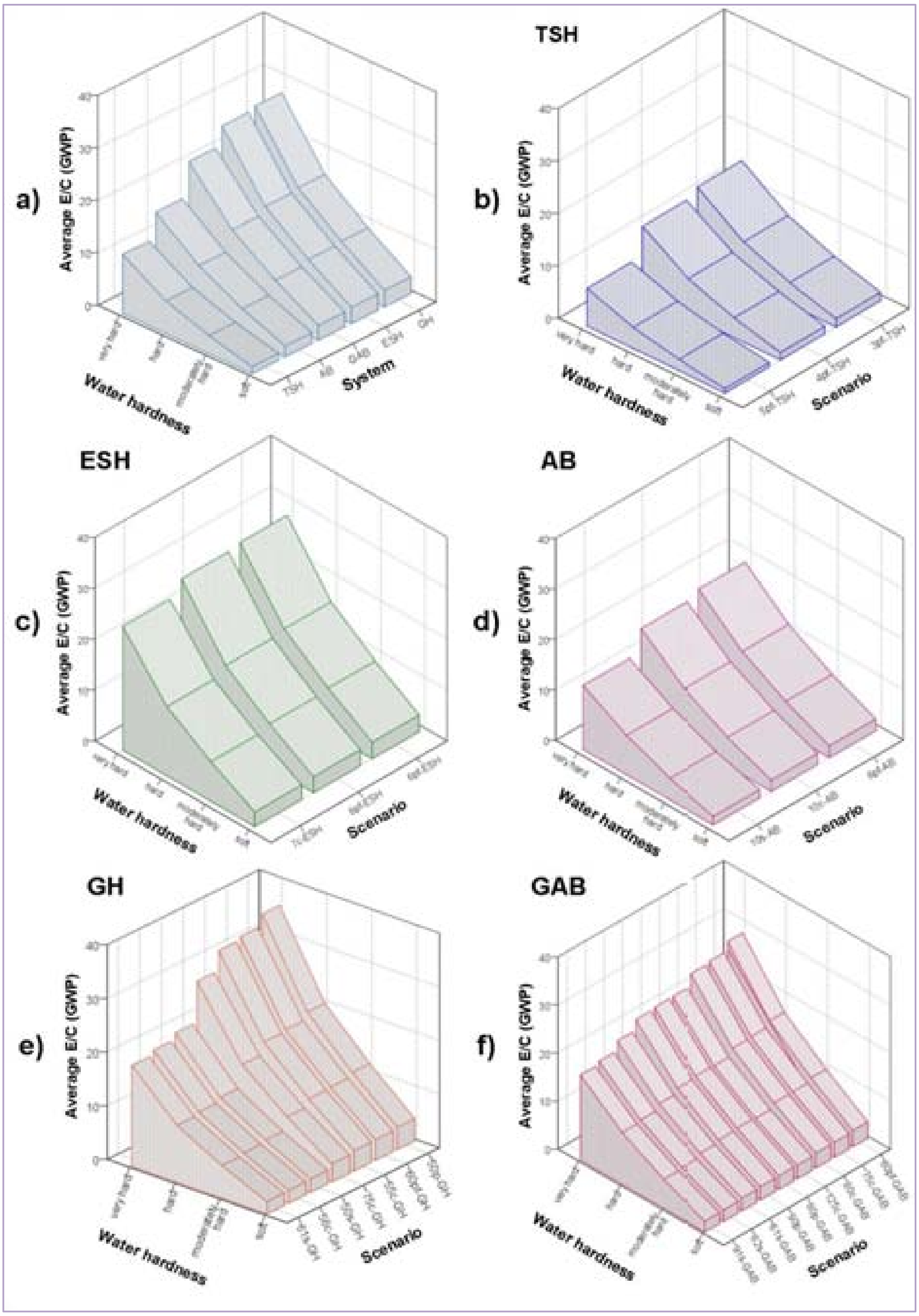

Figure 7-7. Cost-benefit relationships in each system

7.5 Conclusions

The economic and environmental analyses for implementing a RWH system to replace tap waters of varying hardness can improve the conventional approaches taken in the economic and environmental studies by including the tap water hardness as an important factor that must be analysed.

Using this approach had many benefits, and many RWH systems could be considered environmentally viable. When the water hardness was higher than 300 mg/L $CaCO_3$, an economic analysis revealed that an NPV greater than 100,000 Euros could be obtained for systems operating at the neighbourhood level, and the reduction in Global Warming Potential as a result of a reduced energy consumption would be between 35 and 101 kg CO_2 eq./dwelling/year.

The tap water price is an economic variable that restricts the viability of the RHW systems implemented for serving a smaller number of people.

Large-scale RWH systems (the GAB and the GH systems) are economically viable when the price of water is greater than 1.5 Euros/m^3 regardless of how hard or soft the water is. However, when the water hardness factor is considered, the water prices can be less than 1.5 Euros/m^3 when the tap water is hard, and the implementation of a large scale RWH system is still beneficial.

The economic savings is low relative to the total economic costs. However, the potential benefits to the environment can outweigh the environmental costs of the rainwater system.

There are greater economic and financial benefits when using rainwater as a substitute for tap water in home appliances like washing machines in urban areas where the tap water is hard. Under these conditions, many RWH systems can be viable for implementation.

Within the range of values studied (300-1800 mm), in general, the amount of rainfall is not as decisive a factor in the economic viability of RWH systems.

The materials used for the construction of the storage tank and the storage volume of the tank are both important factors that must be taken into account in each of the RWH systems. However, the more important considerations in the economic and environmental analyses are the local tap water hardness and the local water prices.

The use of rainwater and tap water hardness are factors to be considered in urban planning because they may contribute favourably to energy-saving strategies.

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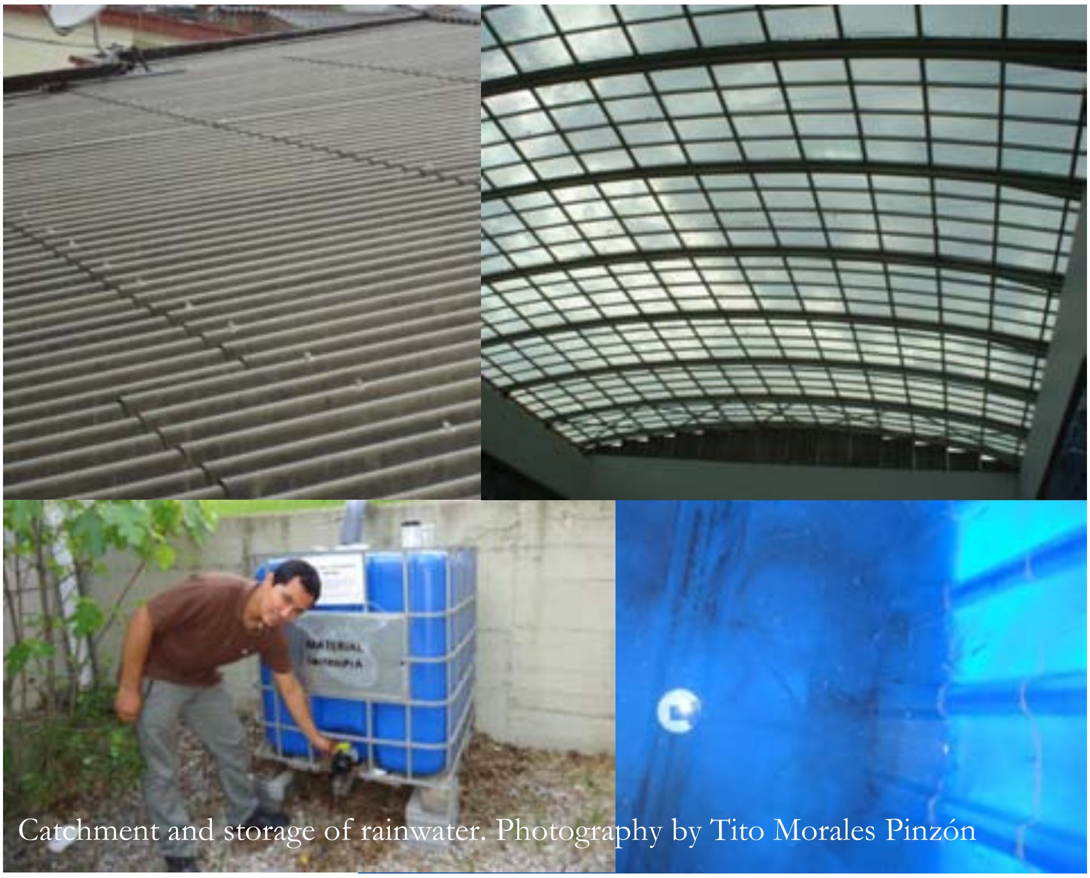
PART V

CONCLUSIONS AND NEXT STEPS

Chapter 8
Conclusions and future research



Catchment and storage of rainwater. Photography by Tito Morales Pinzón

Chapter 8
Conclusions and future research

8 Conclusions and future research

The development of a simulation model and the study of the technical, economic, environmental and social aspects of rainwater harvesting systems led to several conclusions. These conclusions can help address the management of rainwater in urban planning in developed (e.g., Spain) and developing countries (e.g., Colombia). Furthermore, a set of recommendations for the sustainable management of rainwater harvesting in urban areas has been generated.

Following the structure presented at the beginning in this dissertation, the main conclusions of the investigation are presented below. Additionally, a scheme has been included to facilitate the findings from the developed research with respect to the modelling process, aspect analysed (technical, economic, environmental and social) and case study (see Figure 8-1).

This chapter is structured as follows:

- **Conclusions**
- **Future research**

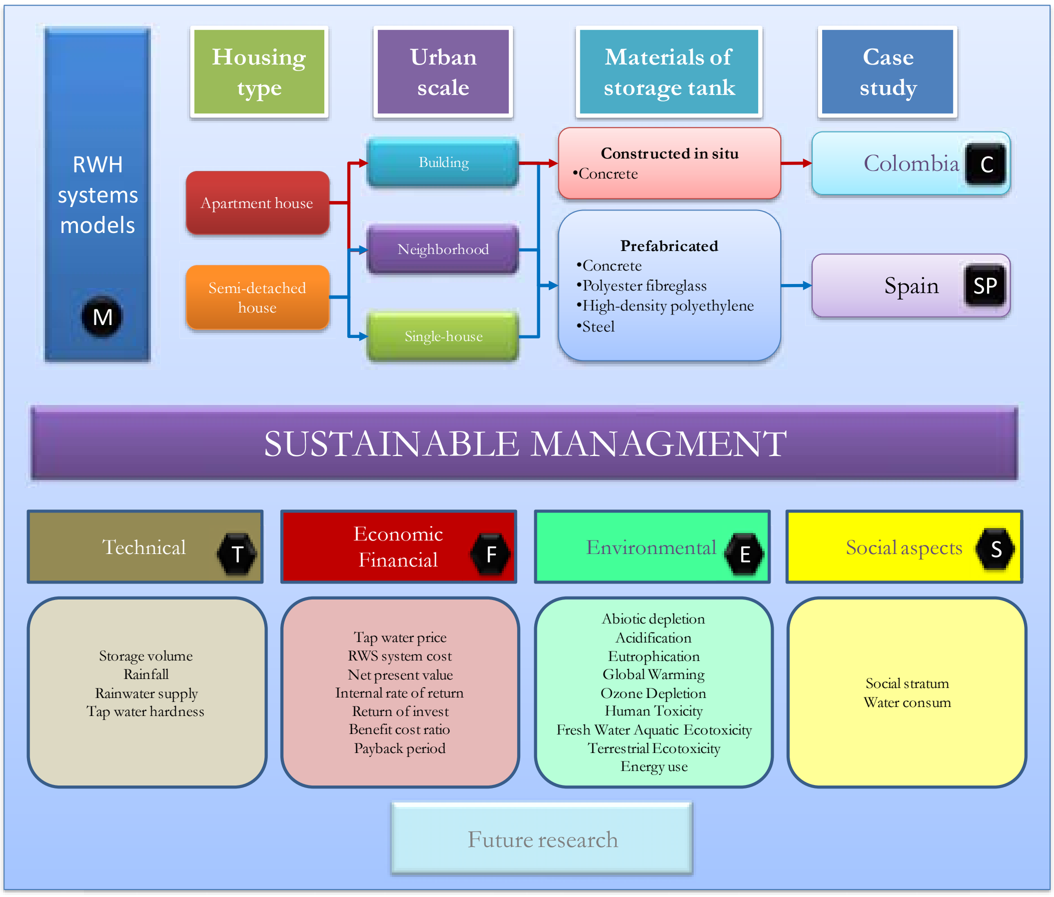


Figure 8-1. Outline of the final conclusions of this dissertation.

8.1 Conclusions

The main conclusions that resulted from the modelling and the Plugrisost software will be presented. Next, the social, economic and environmental findings will be presented according to the objectives formulated in Part I.

8.1.1 Modelling aspects

Modelling rainwater harvesting (RWH) facilitates the development of the different studies (technical, economic, environmental and social) that are needed to assess the sustainability of these urban systems.

According to the analysis and the model assumptions, the most **sensitive variables are water hardness, water price, rainfall and water demand** (in order of importance).

The **quality of the input data** used in the proposed models affects the results.

- The **variability within the input data for modelling is important** and should always be considered. However, when a specific system is analysed **in terms of environmental effects** (**except for rainfall**), all variables can be considered **constants**.
- Similarly, the variability in prices during **economic analysis** can be modelled with a **constant increase in price**.
- To determine an adequate storage capacity volume, **the variability of rainfall should be considered** in detail during the RWH system design. The **variability and the uncertainties of the future rainfall behaviour** do not lead to exactly one optimal storage volume. Thus, it is preferable to assess a range of feasible storage capacity values with different rainfall data (historical or simulated).
- Similar to the behaviour of other natural resources, the **potential rainwater supply can only be estimated**. Thus, it is necessary to access the detailed historical rainfall records for the analysed site. These records must cover a period of at least 20 years.
- There are large differences between using annual, monthly or daily rainfall **time series**. In particular, there is a tendency to overestimate the potential supply when the data frequency is less detailed.
- The **simulation of precipitation** is a robust alternative for evaluating RWH systems when adequate historical data and detailed pluviometry records are available.

- Weibull, log-normal and gamma **parametric models are useful for analysing the rainfall variability,** the economic costs and the potential environmental impacts.

8.1.2 Plugrisost software

This research provides the Plugrisost software for the studied RWH systems. This software includes technical, economic and environmental (quantitative) indicators and is **better adjusted than other software** to water supply and demand scenarios for urban use in developed and developing countries.

The Plugrisost software is a tool that contributes to the **smart design of cities** and helps to **integrate technical, economic and environmental** aspects into RWH systems in different types of cities (diffuse and compact construction). Furthermore, the Plugrisost software is used to analyse the single house, apartment building and neighbourhood scenarios at an urban scale. It provides relevant indicators (for example, rainwater supply, percentage of rainwater demand met, economic cost and potential environmental impact) for RWH infrastructure decisions and urban planning.

- The Plugrisost software includes the technical, economic and environmental aspects required for the **sustainability assessment of RWH systems**.
- The Plugrisost software **can successfully model RWH systems at different urban scales** using technical, economic and environmental indicators (such as single house, apartment building and neighbourhood scales at both low and high density).
- The Plugrisost software helps to **avoid the over sizing of storage tanks** by using better technical, economic and environmental evaluations.
- The **estimation of the rainfall in Plugrisost that is used by the RWH system is more conservative** than the estimates from other software that use YAB or YAS algorithms. Furthermore, this estimate is more restrictive when using indicators such as economic cost and environmental impact.
- The system dynamics methodology used to build the Plugrisost software has facilitated the **integration of the various developed models.** The Plugrisost software is **very flexible for representing the studied RWH systems**. The Plugrisost software presents reference values as input parameters for models that can be adjusted according to the availability of the user information.
- Using the Plugrisost software, it was found that the urban scale of analysis is related to rainwater supply, rate of rainwater use, economic cost and

environmental impact. The **optimum size of the storage tank is not proportional to the urban scale** and different models explain the results in each one of the urban scales.

- The Plugrisost software is able to **model domestic water use,** including rainwater, greywater, tap water and waste water. The resulting model provides technical, economic and environmental indicators for all systems.

8.1.3 RWH in socioeconomic scenarios in developing countries

Colombia provides a good scenario for studying rainfall (793 to 2,258 L/m^2/year) and **housing conditions** that could be **applied to RWH systems in other South American urban areas**. There is an interesting conjunction between the new neighbourhood growth, the increased demand for water mains and the opportunity for rainwater use that results from the potential supply of urban areas. The sample size used (64,000 housing) is large enough to facilitate the implementation of the results in other countries with similar construction dynamics.

- **Housing in high socioeconomic levels** is related to a **higher water consumption and rainwater supply**. Otherwise, **housing in lower socioeconomic levels** can have **levels of water consumption recommended by WHO.**
- The **best potential RWH scenario** is when high precipitation (2,258 L/m^2/year) occurs in high socioeconomic stratum housing with low density (semi-detached house with a rainwater supply of 19.2 m^3/dwelling/month). The captured rainwater could meet 92% of the total demand for main water.
- **Social housing projects** (average 193 dwellings/project) **have significant potential for catchment rainwater**. Low density social housing projects have a potential rainwater supply of between 1.9 and 6.3 m^3/dwelling/month. High density projects have a potential rainwater supply of between 0.4 and 1.3 m^3/dwelling/month.
- High density urban cities have a **greater potential for rainwater harvesting in apartment buildings**. The potential harvesting would be between 22.8 and 125.4 m^3/building/month (6% of the total demand for main water).
- Neighbourhoods with **low-density housing and high socioeconomic strata** that have a water demand of between 16.2 and 20.9 m^3/dwelling may satisfy the total rainwater demand (equivalent to 56% of the total

demand for water supply) and **generate surplus rainwater** that can be used by other urban areas.

- The **catchment surface** in a **building** is between 7 and 13.8 m^2/dwelling with a **RWH potential** of between 0.6 and 3.3 RWH m3/dwelling/month. However, in a **single house** the catchment area is between 31.9 and 113.5 m^2/dwelling with a RWH potential of between 3.1 and 27.7 m^3/dwelling/month.

The **potential use of rainwater could lead to a differential charging rate** for main water consumption (based on the potential of RWH). **Higher socioeconomic levels** and urban housing projects with **low-density housing** should include RWH in urban planning first. This inclusion will play an important role in resource management and will contribute to the consolidation of a sustainable urban network of rainwater in a sustainable city with high social responsibility.

In these sustainable cities, urban areas of greater development and greater RWH potential could **provide the surplus rainwater to adjacent areas** with a lower RWH potential and a lower socioeconomic level.

In **social housing projects**, the state **would finance the cost of installing a RWH system**. However, in socially high strata, the owners would be able to pay for this investment. Nevertheless, this investment would be conditional by local or national laws. These laws could be modified to benefit the urban water sustainability.

8.1.4 Potential environmental impacts of RWH in developing countries

In South American countries (**considering a scenario with the electric mix of Colombia** (80% hydroelectricity) and added to local availability (<30 km) in materials for the construction of RWH system), the potential environmental **impact of infrastructure and the use of a RWH system** can be calculated with an **exponential function.** The coefficients of this function must be estimated for the **urban area's specific climatic conditions** and applied under similar circumstances.

- In urban areas with average rainfall of 794 and 2,258 L/m^2/year, the **potential supply of rainwater (for nondrinking quality)** is between 16.34 and 64.68 m^3/dwelling/year in a neighbourhood consisting of ten residential five-storey buildings with 24 apartments (700 m^2/building). Using the exponential model estimate, the GWP of the RHW systems with **concrete tanks that are constructed on site** is between 0.53 and 1.47 kg CO_2 eq./m^3 of used rainwater.

- The **rainwater supply of urban areas potentially affects environmental impacts that are avoided by using a RWH system**. Under optimal infrastructure, a greater rainwater potential allows for increased avoided impact values. The avoided GWP during a life cycle of RWH system (50 years) and rainfall with 794 and 2,258 L/m^2/year is between 44,857 and 150,729 kg CO_2 eq. Each cubic meter of rainwater harvested can reduce the GWP by 0.22 and 0.25 kg CO_2 eq.
- **The potential environmental impact of in use stage can be higher than the construction** of a RWH system (for example, for an AP Impact category). When the storage capacity of a rainwater tank is optimised, this behaviour is caused by a high rainwater supply (rainfall 2,258 L/m^2/year), a RWH system with a high neighbourhood housing density and a higher energy consumption for pumping rainwater.

8.1.5 Economic analysis of RWH in developed countries

The scale and type of housing affects the equivalent cost of a RWH system. This cost is low (<2%) compared with the cost of a new home (in Spain) and can easily be factored into the total housing cost.

- In low density neighbourhoods (ranging from a single house to a group of houses) with between 88 and 2 dwellings per housing project, the cost of a RWH systems is between 564 and 5,386 Euros/housing, respectively. In apartment-style housing with between 540 and 30 houses per project, the cost is between 229 and 1,032 Euros / housing, respectively.

RWH projects are financially viable in large scale systems, at a neighbourhood scale and for both low and high housing density. The NPV is between 0.1 and 0.4 Euros/m^3 of rainwater used by the system. Similarly, IRR values are expected to be between 5 and 15%.

When the RWH system was analysed within a range of optimal storage capacity values, the regression models showed that the **variables that influence the financial results** are rainfall, storage capacity, storage tank material and tap water price. In addition, a relationship between NPV and the hardness of tap water was identified for the first time.

- Under the same mean annual precipitation conditions at a neighbourhood scale, the **precipitation concentration index (PCI) increased by 1 unit**. This increase indicated greater rainfall variability and resulted in a decreased NPV (between 23.9% and 26.6%).

- **The size of the storage tank barely contributes to NPV regression models** when a range of optimal storage volume values is used according to the urban RWH system scale.
- The **price of tap water greatly affects** financial performance. If the initial price of water increases by 10%, the NPV would increase from 13.0% to 18.9%.
- The **increase in prices should be considered** in financial analysis. This consideration would be particularly useful when changes are expected to exceed 5% annually.
- The **material of the storage tank** (polyester-fibreglass, concrete, steel and polypropylene) hardly **affects the balance sheet** in comparison with the effects of water price and hardness. This finding must be taken into account for high water prices (> 1 Euros/m^3) or high water hardness.
- Regression model coefficients indicate that **replacing hard tap water with rainwater** for use in washing machines would potentially increase the NPV by between 2.46 and 6.28 times.
- The **wide ranges of studied scenarios allow for a quick financial assessment** of urban areas with linear regression models. In these regression models, the independent variable values are adjusted to local conditions.

8.1.6 Environmental impacts of RWH in developed countries

M E SP

A **high intake of rainwater produces a high energy consumption** of RWH systems at a neighbourhood scale. Thus, these conditions **favour a greater use of rainwater infrastructure** and reduce the potential environmental impact by a functional unit (cubic meter of rainwater used).

The **potential environmental impact of an optimised RWH system is less than the environmental impact of a tap water** supply.

- The environmental impact by GWP of a RWH system with prefabricated storage tanks (polyester-fibreglass, concrete, steel and polypropylene) is between 0.27 and 1.38 kg of CO_2 eq./m^3 of rainwater. In addition, the energy consumption is between 1.5 and 2.2 kWh/housing/year.
- By comparing the maximum impact of a RWH system with the avoidable impact in hard tap water scenarios, it was found that the impact is always higher in most analysed categories. Therefore, the avoidable impacts from using 1 m^3 of rainwater are 4.82E-02 (ADP), 7.14E-02 (AP), 1.45E-02 (EP), 6.96 (GWP), 3.36E-07 (ODP), 1.05E (HTP), 1.84E (FWAP) and 1.43E-01 (TEP). The POP impact category was the only variable where the avoided impact was less than that caused (6.64E-05).

For a **rapid environmental assessment of a RWH system,** only three variables are required. First, it is important to select the appropriate scale (single house, apartment building or neighbourhood) that represents the system. In addition, it is important to know the water demand-supply ratio, the water storage capacity and the storage tank material to estimate the potential environmental impact of 1 m^3 of rainwater use by the system.

- **Rainwater linear models fit best for the neighbourhood scales**. When the water demand of the system is doubled, the energy use is increased or the potential rainwater supply is divided in half, the potential environmental GWP impact of a RWH system increases by between 0.058 and 0.19 kg CO_2 eq./m^3 eq. of rainwater used.
- At the neighbourhood scale, comparing the four types of storage tank material analysed (polyester-fibreglass, concrete, steel and polypropylene) resulted in a GWP impact that was lowest for polyester-fibreglass or concrete.

8.1.7 Water hardness and RWH for domestic use in home appliances

M F E SP

An approach that defined both **rainwater and main water as important factors** in the financial analysis and environmental RWH systems was used.

The use of rainwater as a substitute for **hard water in washing machines favours financial analysis**.

- When the hardness of tap water is high (> 300 mg/L $CaCO_3$), **rainwater use in home appliances provides financial benefits** because rainwater is soft. Specifically, when rainwater is used the NPV is between 263 and 656 Euros/dwelling, the ROI reaches values that are 7 times higher than when only main water is used, the PBP ranges from 26 to 6 years and the BCR is 3 times higher.
- Tap water prices are expected to **increase in the European zone.** Combining the higher water prices (up to 4 Euros/m^3), the neighbourhood scale and a "very hard" tap water quality, the NPV could reach values greater than 230,000 Euros.

Although hardness significantly affects the financial analysis, **the greatest effect was found in the environmental analysis**.

The use of **rainwater as a potential substitute in home appliances that use hot water** (e.g., washing machine) in urban areas that provide hard tap water **significantly reduces the environmental impact of households**.

At any of the studied urban scales, **low density RWH systems showed potential energy savings relative to the higher density RWH systems when hardness was high**.

- The **potential energy savings** for low density RWH systems that use rainwater in washing machines is between 35 and 42 kWh/dwelling/year. For high-density housing, the potential energy savings is between 17 and 19 kWh/dwelling/year.
- When tap water is very hard (>300 mg/L $CaCO_3$) (in all environmental impact categories analysed), the **potential impact avoided by using rainwater in washing machines is between 1.1 and 5.7 times the maximum impact of RWH systems**. Particularly, the potentially avoided GWP can reach values greater than 8.0 kg CO_2 eq./m^3 of rainwater used.

The strategy of substituting rainwater for main water in home appliance that use hot water are taken seriously within the **policies that promote energy saving**, especially in regions with hard water supply to urban households.

8.2 Future research

It is important to continue **integrating unconventional water resources management** (rainwater and greywater) in urban planning of new neighbourhoods.

In addition, research projects should **study the dynamics of urban environmental changes** (in terms of urban density, homogeneity of constructions and networks and space distribution) that affect the management of water resources. In particular, these studies should take place where rainwater harvesting is a possible technique for creating sustainable buildings and smart cities.

In the future, constructed models should be expanded to **analyse other urban scales** (department store) **and to integrate the results of rainwater with greywater in the system**. In addition, it is expected that a better fit will be achieved with the estimated linear models. These models can help to calculate the potential environmental impacts and the financial indicators for other scenarios of interest. In particular, scenarios related to variations in the discount rate, inflation and water demand in developed and developing countries.

In **developing countries with high housing construction and urban growth dynamics**, future research may involve the impact of rainfall changes as a result of climate change. In addition, the resulting consequences on the rainwater resource supply may be analysed. Furthermore, other aspects that may affect the viability of such projects should be subjected to multivariable evaluations. This analysis could include alternative rainwater harvesting technologies at a household or a housing type level (apartment/semi-detached house/single house). In addition, the eco-design and optimisation of the storage tanks and the energy use in should be emphasised in developing urban areas (such as South American countries).

The **impact of building rehabilitation** should be studied further in developed countries. Building rehabilitation results in more sustainable buildings with increased self-sufficiency.

Next, **the Plugrisost software should be integrated into urban planning by using geographical information systems** (GIS).

The viability (social, economic, financial and environmental) of RWH systems in urban **areas with high impact from tourism** should also be investigated. These studies should emphasise the dynamic high and low activity cycles of the tourist resorts.

Furthermore, the advanced **development of low-impact technology** for rainwater treatment for higher quality domestic use should be investigated.

In the future, it is necessary to **compare the effects of different energy saving strategies** for the use of rainwater as a function of urban characteristics and the quality of the supplied main water. One of these effects is that of water hardness, which is an important quality factor for defining strategies that sustain water supplies for urban domestic use.

Future work is expected to **expand the Plugrisost software database** to different urban areas of developed and developing countries. This expansion will facilitate the implementation of the various models included in the analysis module.

Finally, a tool that evaluates the sustainability of RWH systems for the **selection and integration of social indicators** should be developed in the Plugrisost software.

PART VI

ANNEXES

Annexe 1
How to use the Plugrisost software: samples and applications

Annexe 1. How to use the Plugrisost software: samples and applications

The enclosed DVD contains the software Plugrisost and its manual in Spanish. Some files are also included with the data that formed the basis for **Chapter 3**. To use the software Plugrisost, the program "isee Runtime" is required. This program is the company "isee systems" or formally "High Performance Systems".

You can check their availability on the web http://www.iseesystems.com/. Additionally, Plugrisost integrates some functions with the Excel spreadsheet (Microsoft Office Excel versions 2003 and 2007). The attached manual describes detailed examples and applications that must be made in advance before use the Plugrisost software in custom applications.