Cost-efficiency of rainwater harvesting strategies in dense Mediterranean neighbourhoods

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\textbf{A R T I C L E  I N F O}
Article history:
Received 22 September 2010
Received in revised form 27 January 2011
Accepted 28 January 2011

Keywords:
Ecocities
Life Cycle Cost
Net Present Value
Rainwater infrastructures
Urban retrofit

\textbf{A B S T R A C T}
Rainwater harvesting (RWH) presents many benefits for urban sustainability and it is emerging as a key strategy in order to cope with water scarcity in cities. However, there is still a lack of knowledge regarding the most adequate scale in financial terms for RWH infrastructures particularly in dense areas. The aim of this research is to answer this question by analysing the cost-efficiency of several RWH strategies in urban environments. The research is based on a case study consisting of a neighbourhood of dense social housing (600 inhabitants/ha) with multi-storey buildings. The neighbourhood is located in the city of Granollers (Spain), which has a Mediterranean climate (average rainfall 650 mm/year). Four strategies are defined according to the spatial scale of implementation and the moment of RWH infrastructure construction (building/neighbourhood scale and retrofit action vs. new construction). Two scenarios of water prices have been considered (current water prices and future increased water prices under the EU Water Framework Directive). In order to evaluate the cost-efficiency of these strategies, the necessary rainwater conveyance, storage and distribution systems have been designed and assessed in economic terms through the Net Present Value within a Life Cycle Costing approach. The pipe water price that makes RWH cost-efficient for each strategy has been obtained, ranging from 1.86 to 6.42€/m\textsuperscript{3}. The results indicate that RWH strategies in dense urban areas under Mediterranean conditions appear to be economically advantageous only if carried out at the appropriate scale in order to enable economies of scale, and considering the expected evolution of water prices. However, not all strategies are considered cost-efficient. Thus, it is necessary to choose the appropriate scale for rainwater infrastructures in order to make them economically feasible.

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1. Introduction

Water management in cities is crucial since their present water usage is far from being sustainable (Sazakli et al., 2007), the main problems related to it being water shortage, stream degradation and flooding. Pressure on water resources is increasing, with growing demand and limited water sources (Fletcher et al., 2008; EEA, 2009). This increasing demand reduces fresh water reservoirs (Sazakli et al., 2007) and is followed by the use of more distant or inferior-quality sources (van Roon, 2007). For this reason water restrictions are becoming a fact of life in many cities (Fletcher et al., 2008). In addition, growing pressure on water resources affects ecosystems and threatens the ecosystem goods and services on which life and livelihoods depend (World Water Assessment Programme, 2009). Furthermore, observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems. Specifically, it seems that current water management practices may not be robust enough to cope with the impacts of climate change on water supply reliability and flood risk, among others (Bates et al., 2008).

Rainwater harvesting (RWH) is presented as a sustainable strategy to be included in urban water cycle management. It presents many benefits, i.e. it may reduce a city’s external water demand, alleviate water stress on the area, reduce non-point source pollutant loads, reduce treatable urban runoff volume, prevent flooding and help to alleviate climate change (Eroksuz and Rahman, 2010; Kim et al., 2005; RiverSides, 2009; van Roon, 2007; Villarreal and Dixon, 2005; Zhu et al., 2004). Despite this, until recently the collection of rainwater has all too often been ignored (Liaw and Tsa, 2008).
2004), while other alternatives such as desalination have been promoted in order to support water supply in urban developments (Tsiourtis, 2001). Nevertheless, in recent years there has been increasing interest in the use of water resources generated within the urban boundary for drinking water supply substitution, as a means of augmenting current supply capacity (Mitchell et al., 2005), and the use of decentralised, alternative water sources such as rainwater is increasingly promoted worldwide (Domènech and Saurí, 2010). This interest has grown particularly rapidly in semi-arid areas due to water scarcity and vulnerability, such as in the Mediterranean-weather areas (namely Mediterranean Sea basin, California, Cape Province in South Africa, central Chile and Southern Australia) (e.g. Zhang et al., 2009; Tam et al., 2010).

In this context, it is necessary to provide criteria for the spreading of RWH systems, bearing in mind that the proper application of economic principles to environmental problems is essential in order to identify and implement the most cost-effective solutions (Corbitt, 1998) and move towards sustainable strategies for urban water management. Tam et al. (2010) suggested that the biggest consideration in the decision whether to install a RWH system lies in terms of financial costs and benefits, remaining the issues about public acceptability and water quality in the background. For this reason, it is particularly important to determine the economic feasibility of RWH systems.

Some light has been shone on this issue by several authors. Table 1 summarizes the research carried out so far, identifying the scale of RWH infrastructures, their location, annual rainfall, the time in which the infrastructures are implemented (new construction or retrofit action), the approach of the research and two economic parameters ($r$, interest rate; $t$, discount period). From this review, it follows that most research is based on the single-family building level, which considers a neighbourhood consisting of single-family houses in a low density layout (between 15 and 40 households per hectare) (Mitchell et al., 2005). One of the findings of this research was that the spatial scale of the stormwater harvesting systems implemented to date has generally been determined by opportunistic drivers rather than strategic considerations such as the relationship between scale and cost (Mitchell et al., 2005).

Since access to information is crucial to the decision-making process of urban eco-design (Oliver-Solà et al., 2009a,b) in order to improve the sustainability of our cities, it is necessary to establish the most adequate scale for RWH systems (either at the building level or at the neighbourhood level). This is particularly important for dense urban areas, which generally suffer from most of the problems related to urban water management (external water dependence, flooding, stream degradation, etc.). However, to our knowledge there is no research on the economic feasibility of RWH infrastructures for neighbourhoods made up of multi-storey buildings. On the other hand, there is a lack of research on the differences in the financial implications of the implementation of RWH systems in new neighbourhoods compared to retrofit actions within existing urban developments.

The goal of this research is to evaluate the cost-efficiency of several strategies for urban RWH in Mediterranean weather conditions, comparing different spatial scales (RWH infrastructures at the building or at the neighbourhood level) and two implementation times (RWH infrastructures in new construction areas or in existing urban developments as a retrofit action).

### 2. Materials and methods

This section presents the case study area, which is a dense neighbourhood located in Spain, and the methods and approaches followed in this project.

#### 2.1. Dense Mediterranean neighbourhood case study

The case study area is a 2.6 ha neighbourhood of social housing located in Granollers, a city located 30 km north of Barcelona, Catalonia, Spain (Fig. 1). This area is part of the Metropolitan Region of Barcelona, which experienced one of the worst water shortages of its recent history in Spring 2008 (Otero et al., 2009). According to the land cover analysis developed with the aid of the software TNTMips (Microimages, 2005) based on the most recent aerial pho-
44.5% of the neighbourhood is covered by pedestrian areas, 29.0% buildings, 14.7% green areas (mostly grass but also trees and shrubs) and 11.8% roads (Fig. 1).

The two main criteria for the selection of this neighbourhood are its location in a water scarce region and its urban density. On the one hand, the climate in this area (with an average annual rainfall of around 650 mm – mostly concentrated on Autumn and Spring – representative of the average precipitation in Mediterranean climate areas, Di Castri and Mooney, 1973) together with high water demand result in water scarcity and droughts. On the other hand, the neighbourhood comprises a total of 43 multi-storey buildings (558 dwellings; 2.83 inhabitants/household) which results in a high net density (more than 600 inhabitants/ha).

2.2. Methods and approaches

2.2.1. Definition of strategies

Four RWH strategies have been defined based on the neighbourhood case study (Table 2). All of them assume that stormwater runoff from roofs would be collected, since roofs are the most common type of catchment used for harvesting rainfall (Tam et al., 2010; Yaziz et al., 1989). This runoff would be accumulated in rainwater tanks for its consumption for non-potable uses. These tanks would be connected to a main back-up supply system in order to increase the reliability of this alternative water supply system. Street stormwater runoff reuse has not been considered, mostly because it is expected to be of lower quality (Göbel et al., 2007).

The proposed strategies differ on the spatial scale of construction of RWH infrastructures and on the time of construction. The spatial scale means differentiating between the construction of RWH infrastructures at either the building or the neighbourhood level. For the building level, the most common type of building in the neighbourhood has been considered: a 5-storey building (10 dwellings) with a projected roof area of 125 m². Thus, a strategy would be to install a rainwater conveyance, storage and distribution system in each building (strategies 1 and 2) and another one would be to build it up at the neighbourhood level, with a shared rainwater conveyance, storage and distribution system for all the buildings (strategies 3 and 4).

The time of construction differentiates between retrofit actions and new construction. Then, a strategy would be to install these infrastructures in the current neighbourhood, that is to say, as a retrofit operation (strategies 1 and 3), and another one would be in a greenfield development consisting of a new neighbourhood that would have the same characteristics as the case study (strategies 2 and 4).

2.2.2. Neighbourhood rainwater demand

The most publicly accepted non-potable applications for harvested rainwater are WC flushing, garden irrigation and use in washing machines (Roebuck et al., 2010). In this case study, the first of them was not considered since it was expected that greywater systems (from showers) would be in place to provide water for that purpose. The second use was also excluded since irrigation water demands were very small because xerogardening practices were in place.

For these reasons, it was considered that the most appropriate use for rainwater would be for laundry. Besides, the laundry water demand is higher than the RWH potential, which would reduce rainwater overflows from the tank. In addition, the laundry demand is regular throughout the year, which implies that a smaller rainwater tank is necessary (Ghisi et al., 2009) and maximizes the benefits (Rahman et al., 2010), especially when comparing it with a rainwater harvesting system designed to satisfy irrigation water demand, which is concentrated on dry periods when the availability of rainwater is limited. Secondly, using harvested rainwater for washing purposes has the additional benefit of reducing washing powder consumption, as rainwater is often softer than drinking water from the tap (Burkhard et al., 2000).

Table 2

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Spatial scale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Building</td>
</tr>
<tr>
<td>Temporal scale</td>
<td>1</td>
</tr>
<tr>
<td>Retrofit action</td>
<td>2</td>
</tr>
<tr>
<td>New construction</td>
<td>2</td>
</tr>
</tbody>
</table>
In strategy 1 (building level, retrofit action), water is distributed to each dwelling for consumption by individual washing machines. This water demand is assumed as high as 20% of the neighbourhood’s domestic water demand, based on general domestic water consumption facts (Mustow et al., 1997). Domestic water consumption, which has been accounted for through a monitoring control of water meters over a period of 1 year in a sample set of dwellings, is estimated at 57.231 m³/year, based on meter readings (281 L/dwelling per day). Thus, laundry water consumption is estimated at 20.5 m³/household per year.

In strategies 2 (building, new construction), 3 (neighbourhood, retrofit) and 4 (neighbourhood, retrofit), it is proposed that water be utilized in a public laundry room next to the storage rainwater tank. This assumption is made since it is believed that this is an advisable option for neighbourhoods with small apartments, such as is the case in this social housing neighbourhood, because it saves space in the apartments and the inhabitants do not need to purchase a washing machine. This option represents an important saving in terms of global environmental impact related to the space occupied by a washing machine in the dwelling and also the improvements related to the system’s use.

Thus, water demand in strategy 1 is estimated at 14.3 m³/household per year. Water demand in strategies 2–4 is expected to be reduced by a 30% consumption reduction in mains supply charges. The NPV analysis requires a systematic approach that includes all the cost of the infrastructure facilities incurred over the analysis period (Sharma et al., 2009; Swamee and Sharma, 2008). Within the LCC approach, the calculation of the Net Present Value (NPV) and the payback period are conducted. The NPV analysis method is one of the most commonly used tools to determine the current value of future investments to compare alternative water supply options (Swamee and Sharma, 2008). The NPV provides a robust rationale for asset management as it considers the costs and performance over extended periods of time. In this analysis, the associated costs of RWH systems, such as capital, operational and maintenance expenses, are balanced against any benefits (such as reduction in mains supply charges). The NPV analysis requires a rate at which costs and benefits are reduced over time, known as the discount rate (MJA, 2007). The case study consists of a social neighbourhood promoted by local/regional governments. In general, public analysis is often conducted at discount rates lower than those required by private investment (Roebuck et al., 2010) to reflect the social time value of money rather than the investment value (MJA, 2007). For this reason, two possibilities have been considered: 0 and 3% discount rate. The choice of 3% is similar to the one proposed by Roebuck et al. (2010) and Tam et al. (2010). The selected discount period was 60 years, taking into account the lifespan of the proposed infrastructures (Rahman et al., 2010). Inflation has not been considered.

The payback period, which is the time that a project is expected to take in order to earn net revenue equal to the capital cost of the project, has also been calculated within the discount period. It is measured as the ratio between total capital costs and the difference between annual revenue and annual expenditures, taking into account the discount rate.

2.2.4. Economic assessment of the RWH infrastructures

The conceptual design and calculation of performance of indicators. The conducted conceptual design is the base for the estimation of the material usage, the energy requirements and the Life Cycle Costing (LCC). The LCC analysis is an economic analysis technique to estimate the total cost of a system over its life span. Thus, it is a systematic approach that includes all the cost of the infrastructure facilities incurred over the analysis period (Sharma et al., 2009; Swamee and Sharma, 2008).

Two performance indicators have been calculated as measures of the hydrological performance of the infrastructures: overall efficiency and water savings. The expected overall efficiency of the system is calculated as the ratio between the net amount of rainwater collected and delivered (Rd) and the volume of rainwater that potentially could have entered the system (WHP) (Chilton et al., 2000). Water savings have been calculated as the percentage of water demand in the laundry covered by rainwater.

2.2.2.3. Design of the RWH infrastructures

The conceptual design of infrastructures has been executed with the aid of expert companies in the field. For each strategy, the inventory of materials and works has been obtained and divided into three subsystems: harvesting, storage and distribution (Fig. 2). The sizing of piping systems (pipe diameters, valves, etc.) has followed well-known conventional procedures based on the most common hydraulic engineering principles. Pipe materials selected for the water supply system were based on the local water authority’s adopted practice.

The RW tank storage capacity (tank sizing) has been calculated according to the Water Balance Method using monthly demand and supply data (Texas Water Development Board, 2005). The results have been compared with those obtained on a daily basis with the software RainCycle (SUD Solutions, 2005), which is a computer-based modelling tool based on the yield after spillage algorithm in the form of a continuous simulation. For these methods, rainfall and demand time series need to be known. Average monthly rainfall data (665 mm/year) is obtained from meteorological records for a period over 30 years (Ninyerola et al., 2005), while daily rainfall data has been obtained for year 2008 based on data from the Catalan Meteorological Service in which rainfall was 687 mm. Therefore, the yearly distribution of rainfall has been taken into account in order to size tank storage capacity. The runoff coefficient (RC), which is the ratio of the volume of water that runs off a surface on its way to the storage tanks to the volume of rainfall that falls on the surface, has been assumed to be 0.9 (Vieissman and Lewis, 2003). The losses related to the filters are estimated at 5%.

The payback period, which is the time that a project is expected to take in order to earn net revenue equal to the capital cost of the project, has also been calculated within the discount period. It is measured as the ratio between total capital costs and the difference between annual revenue and annual expenditures, taking into account the discount rate.

2.2.4.1. Costs. Capital costs have been accounted for in 2009 with the Metabase ITeC (ITeC, 2010), a database from the Catalan Institute of Construction Technology that provides information on...
prices, technical details, companies and, certificates of generic building elements and products. The costs in this database both materials/equipment and installation costs (labour). Information from local RWH systems suppliers has been used to complement it.

While capital costs can be predicted with a fair degree of accuracy, long-term costs (operating and maintenance costs) are harder to forecast (Roebuck and Ashley, 2006). These long-term costs are accounted for under the following considerations:

- pumping electricity costs (16.84 c/KWh, based on the average domestic electricity price in Spain for the second semester 2009, which is very similar to the average price in EU-27 – 16.38 c/KWh, Eurostat, 2010);
- maintenance costs (150€ and 300€ every 2 years in strategies at the building and at the neighbourhood scale, respectively);
- pump replacement every 15 years;
- replacement of half of the filters every 15 years;
- pre-fabricated rainwater tank replacement every 30 years;
- the remaining infrastructures (concrete rainwater tank, piping . . . ) are assumed to have a life span equal to the discount period, that is to say, 60 years.

2.2.4.2. Benefits. The primary financial benefit will be a reduction in the annual water bill from local water authorities. This annual revenue is calculated as the savings related to the substitution of mains water for rainwater. Thus, the price of pipe water supply and the amount of rainwater delivered (Rd) are considered. It needs to be highlighted that only the costs related to water supply (but not to the sewage system) are considered, since once the water is used it will also end up to the sewage system (independent of the original supply source).

With respect to the pipe water price, two scenarios are considered:

- Scenario 1. It considers the current domestic average water price of water supply in the region: 1.12 €/m³. This figure is provided by AEAS (2010), the Spanish Association of Water Supply and Sewage, who carries out a rigorous yearly survey on water prices based on three different levels of water consumption.
- Scenario 2. It considers that water supply prices in the case study region will achieve the arbitrary price of 4 €/m³ in the coming years, particularly because of water scarcity and increasing water costs related to more expensive water sources (i.e. desalination). The adoption of the current average cost of mains water as an indicator of savings is an underestimate, given the ‘full cost’ of water is likely to be higher than currently priced (Mitchell et al., 2005). Actually, prices of water in Spain have increased along the past years at a annual rate over 5% (AEAS, 2010) and it is expected that these prices will go on increasing. This is mostly explained because water prices will have to move to full-price water recovery under European Union (EU) Water Framework Directive of which Spain is a signatory (Downward and Taylor, 2007). As a consequence, there will be some sort of homogenisation of prices throughout Europe, where there is currently a big disparity among countries (current water supply prices in some European cities ascend to as much as 3.68 €/m³ in Copenhagen, 2.89 €/m³ in Brussels or 2.41 €/m³ in Luxembourg for a monthly consumption of 16 m³/household, Global Water Intelligence, 2010).

3. Results

Table 3 shows the size of the tank for each strategy, as well as the water savings and the overall efficiency, according to the water balance on a daily basis.

Table 4 shows the inventory of elements for the RWH infrastructures. The main difference between strategies 1 and 2 lies in the distribution of water (in new construction water is used in a common laundry room, so fewer pipes, bypasses and valves are necessary). The difference between strategies 3 and 4 lies in the demolition and repositioning of paving.

Table 5 shows the capital costs related to the main items of the inventory. The costs are concentrated in the storage subsystem for strategies at the building scale, while they are largely attributed to the harvesting subsystem for the strategies at the neighbourhood scale. The capital costs per household are within the range of 648–650 € for strategies in new construction and between 759 and 790 € for retrofit actions.

Table 6 shows the NPV of each strategy considering the two variables: pipe water price (scenarios 1 and 2) and discount rate (r = 0% and 3%). The payback period is shown in the cases that it falls within the discount period (r = 60 years). A positive value of the NPV is an indication of benefits outweighing costs. The NPV values for strategies at a different spatial scale (building level – 1 and 2 – and neighbourhood level – 3 and 4) are not directly comparable, precisely due to reasons of scale. To aid comparison, the metrics have been scaled for strategies 1 and 2 (RWH at building level), so that they are applicable to the whole neighbourhood. Thus, the NPV of strategies 1 and 2 are also expressed at the neighbourhood scale, that is to say, considering the RWH system at the building level reproduced in each building (Table 6).

Fig. 3 represents the dependence of the NPV on the price of pipe water for the whole set of strategies, considering two interest rates (0 and 3%). From these functions, the price of mains water that results in a NPV=0 is obtained (Fig. 3). Prices of main water higher than this will entail cost-efficient RWH strategies.

Table 3

<table>
<thead>
<tr>
<th>Strategy</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank capacity (m³)</td>
<td>8</td>
<td>6</td>
<td>275</td>
<td>275</td>
</tr>
<tr>
<td>Demand (m³/year)</td>
<td>205</td>
<td>143</td>
<td>8030</td>
<td>8030</td>
</tr>
<tr>
<td>Water savings (%)</td>
<td>35.7</td>
<td>43.9</td>
<td>43.4</td>
<td>43.4</td>
</tr>
<tr>
<td>Overall efficiency (%)</td>
<td>100</td>
<td>86</td>
<td>78</td>
<td>78</td>
</tr>
<tr>
<td>Overflows (% of water entering the tank)</td>
<td>0</td>
<td>14</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Tank empty (days/year)</td>
<td>256</td>
<td>223</td>
<td>226</td>
<td>226</td>
</tr>
</tbody>
</table>

Table 4

<table>
<thead>
<tr>
<th>Strategy (r)</th>
<th>0%</th>
<th>3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water price (€/m³)</td>
<td>4.66</td>
<td>4.44</td>
</tr>
<tr>
<td>Water price (€/m³)</td>
<td>6.42</td>
<td>8.42</td>
</tr>
</tbody>
</table>

Fig. 3. NPV (Net Present Value) function depending on the pipe water price. The minimum water price that entails positive NPV is shown.
Table 4
Elements included in the design of the infrastructures for RWH. The dash indicates that this item does not apply for the strategy. D stands for diameter (in mm).

<table>
<thead>
<tr>
<th>Item [units of measurement in brackets]</th>
<th>Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Harvesting</td>
<td></td>
</tr>
<tr>
<td>Trench works</td>
<td></td>
</tr>
<tr>
<td>Trenching [m³]</td>
<td>20</td>
</tr>
<tr>
<td>Filling with sand and excavation materials [m³]</td>
<td>19.8</td>
</tr>
<tr>
<td>Storm sewers</td>
<td></td>
</tr>
<tr>
<td>PVC building derivations [m]</td>
<td>20 (D125)</td>
</tr>
<tr>
<td>PVC general storm sewer [m]</td>
<td>–</td>
</tr>
<tr>
<td>Manholes</td>
<td></td>
</tr>
<tr>
<td>Downpipe drain (non-syphonic) [u]</td>
<td>2</td>
</tr>
<tr>
<td>Inspection chamber [u]</td>
<td>3</td>
</tr>
<tr>
<td>Pavement works</td>
<td></td>
</tr>
<tr>
<td>Bituminous pavement demolition [m²]</td>
<td>–</td>
</tr>
<tr>
<td>Pavement reposition (40 cm aggregates, 8 cm bitumen weighting, 1kg/m² prime coat) [m²]</td>
<td>–</td>
</tr>
<tr>
<td>Filter</td>
<td></td>
</tr>
<tr>
<td>Filter [u]</td>
<td>–</td>
</tr>
<tr>
<td>Storage</td>
<td></td>
</tr>
<tr>
<td>Earth movements</td>
<td></td>
</tr>
<tr>
<td>Excavation [m³]</td>
<td>–</td>
</tr>
<tr>
<td>Earth transportation to landfill [m³]</td>
<td>–</td>
</tr>
<tr>
<td>Rainwater tank (built in situ)</td>
<td></td>
</tr>
<tr>
<td>Cleaning and ground levelling with concrete HL-150/P/20 (0.2 m thickness) [m²]</td>
<td>–</td>
</tr>
<tr>
<td>Floor and ceiling slabs of concrete HA-30/B/20/11b (0.5 m thick) [m³]</td>
<td>–</td>
</tr>
<tr>
<td>Floor slab reinforcements with corrugated rod steel B500S (50kg/m²) [kg]</td>
<td>–</td>
</tr>
<tr>
<td>Ceiling slab reinforcements with corrugated rod steel B500S (120kg/m³) [kg]</td>
<td>–</td>
</tr>
<tr>
<td>Floor slab shattering with pine wood boards [m²]</td>
<td>–</td>
</tr>
<tr>
<td>Ceiling slabs shattering over scaffold [m²]</td>
<td>–</td>
</tr>
<tr>
<td>Walls made of concrete HA-30/8/B/20/1la (0.5 m thickness) with repellent additive [m³]</td>
<td>–</td>
</tr>
<tr>
<td>Wall reinforcement with corrugated rod steel B500S (80kg/m²) [kg]</td>
<td>–</td>
</tr>
<tr>
<td>Wall shattering with pine wood [m²]</td>
<td>–</td>
</tr>
<tr>
<td>Sealing with polymer in aqueous dispersion for waterproofing (1.3 kg/m²) [m³]</td>
<td>–</td>
</tr>
<tr>
<td>Pre-fabricated tank</td>
<td></td>
</tr>
<tr>
<td>Polyester tank with filter (including excavation) [m³]</td>
<td>1 (8 m³)</td>
</tr>
<tr>
<td>Distribution</td>
<td></td>
</tr>
<tr>
<td>Pumping station</td>
<td></td>
</tr>
<tr>
<td>Submersible pump (2.2 kW) [u]</td>
<td>1</td>
</tr>
<tr>
<td>Distribution system</td>
<td></td>
</tr>
<tr>
<td>Polypropylene bypass (D20) [m]</td>
<td>110</td>
</tr>
<tr>
<td>Polypropylene copolymer PP-R pressure pipe [m]</td>
<td>52 (D20/25)</td>
</tr>
<tr>
<td>Ball stopcock (polypropylene copolymer PP-R), (D20)</td>
<td>14</td>
</tr>
<tr>
<td>Solitude manual valve tap with screw type [u]</td>
<td>4 (D19)</td>
</tr>
<tr>
<td>Retention valve [u]</td>
<td>4 (D20)</td>
</tr>
<tr>
<td>Reducing valve [u]</td>
<td>1 (D19)</td>
</tr>
<tr>
<td>Gate valve with manual clamps, 16 bar [u]</td>
<td>1 (D25)</td>
</tr>
<tr>
<td>Manhole of prefabricated concrete placed on a concrete sill HM-20/P/40/15 cm thick [u]</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5
Capital costs of the infrastructures for RWH. The dash indicates that this item does not apply for the strategy. In parentheses, the relative contribution of each subsystem to the total cost of each strategy.

<table>
<thead>
<tr>
<th>Item [costs expressed in €]</th>
<th>Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Harvesting</td>
<td></td>
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<tr>
<td>Trench works</td>
<td>600</td>
</tr>
<tr>
<td>Storm sewers</td>
<td>627</td>
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<tr>
<td>Manholes</td>
<td>820</td>
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<tr>
<td>Pavement works</td>
<td>–</td>
</tr>
<tr>
<td>Filter</td>
<td>–</td>
</tr>
<tr>
<td>Total (relative contribution in parentheses)</td>
<td>2047</td>
</tr>
<tr>
<td></td>
<td>(25.9%)</td>
</tr>
<tr>
<td>Storage</td>
<td></td>
</tr>
<tr>
<td>Earth movements</td>
<td>–</td>
</tr>
<tr>
<td>Rainwater tank structures (made-to-measure)</td>
<td>–</td>
</tr>
<tr>
<td>Pre-fabricated tank</td>
<td>3650</td>
</tr>
<tr>
<td>Total (relative contribution in parentheses)</td>
<td>3650</td>
</tr>
<tr>
<td></td>
<td>(46.2%)</td>
</tr>
<tr>
<td>Distribution</td>
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<td>Pumping station</td>
<td>1006</td>
</tr>
<tr>
<td>Distribution system</td>
<td>1200</td>
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<tr>
<td>Total (relative contribution in parentheses)</td>
<td>2206</td>
</tr>
<tr>
<td></td>
<td>(27.9%)</td>
</tr>
<tr>
<td>Total infrastructures</td>
<td>7903</td>
</tr>
</tbody>
</table>
4. Discussion

In general, no strategy is cost-efficient if average domestic regional water prices are considered (scenario 1). This is consistent with most previous studies, which have found RWH systems to be financially unrewarding under the current water price regime where water is supplied to urban residents at a subsidized rate (Rahman et al., 2010). The economic performance of RWH strategies is the least interesting at the building scale, where revenues never compensate costs (no payback period available: negative NPV) independent of the water price (within the considered scenarios) (Table 6). The differences in the financial performance of strategies at the two spatial scales are evident if the NPV is extended to the whole neighbourhood. This results agree with other authors (Roebuck et al., 2010), who state that domestic RWH ‘at the building scale’ is unlikely to be cost effective for all reasonably foreseeable scenarios.

Nevertheless, the strategies at the neighbourhood level seem to be more favourable, in particular in scenario 2 (increase in local water prices). This is consistent with the findings from (Fletcher et al., 2008; Mitchell et al., 2005), who estimate that costs of RWH are inversely related to their scale. The most cost-efficient strategy is the one at the neighbourhood level and under new construction (strategy 4). In this case, the payback period is reduced to 27 years, which might be acceptable from the point of view of the Public Administration because of its wider time horizon reference compared to private companies. Therefore, strategies at the neighbourhood level should be preferable, although it has to be kept in mind that distributed RWH infrastructures are relatively untried and unproven (Makropoulos and Butler, 2010). Furthermore, the retrofit of RWH into existing urban areas is proving to be a challenge (Fletcher et al., 2008).

The RWH economic feasibility in the case of the neighbourhood studied is strongly conditioned by the small catchment area per dwelling. This residential neighbourhood presents a high urban density although only 29% of its land is occupied by buildings. Consequently, a small portion of catchment area (less than 14 m² of roof per dwelling) corresponds to each household, and, therefore, the ratio ‘rainfall per inhabitant’ is small. This contrasts with the catchment area availability per dwelling in other parts of the city of Granollers (i.e. if we consider a neighbourhood with semi-detached houses, each household has around 80 m² of roof) or the ones considered in other studies (Mitchell et al., 2005). Tam et al. (2010) indicated that a factor that may limit the appropriateness of RW catchment systems is the shortage of space and high cost of land, which is generally the case for dense urban areas. Furthermore, not only is the neighbourhood located in an area with limited rainfall, but also regional water prices are lower than average European prices (Global Water Intelligence, 2010). For all these reasons, water savings (benefits) from the projected rainwater systems in this dense Mediterranean neighbourhood are limited. The economic performance of rainwater harvesting schemes in other areas or regions would depend mostly on urban density, rainfall pattern and water supply prices, therefore differing to greater or smaller extent with the results presented here.

In order to enhance RWH strategies – at any spatial scale – it would be necessary to consider interest rates being as low as possible (Table 6, Fig. 3). As an example, strategy 3 is only profitable for a 0% interest rate – which takes place in scenario 2. At the same time, increased water pricing regimes are necessary to foster RWH, which is incidentally a feasible trend taking into account the implementation of the Water Framework Directive, as well as the increase in water demand. The water prices that should be achieved so that RWH would be cost-efficient largely differ between the strategies – from 1.86 €/m³ for strategy 4 (r = 0%) to 6.42 €/m³ for strategy 2 (r = 3%) (Fig. 3). Therefore, it seems realistic that the neighbourhood strategies will be cost-efficient in the short term, but it is more difficult to expect that strategies at the building level to show favourable economic performances.

Another consideration is that water companies already price water based on block tariffs, with rising prices as the consumption of water increases. Thus, the considered water prices so far correspond to average water prices. However, the main water that would be first substituted by rainwater would correspond to the highest block tariff, that is to say, the one with the most expensive water. Consequently, the substituted water price is higher than the average one, which would result in increased benefits and a better economic performance for all considered RWH systems.

In any case, however, the decision of rejecting RWH infrastructures should not be based only on economic criteria. Taking into account the scarcity of water resources, together with the expected increase in water demand; and considering that capital costs are less than 800 €/dwelling, it would not be acceptable that public policies underutilize or overlook rainwater resources. RWH systems, even in dense areas such as the case study neighbourhood and in Mediterranean conditions, can satisfy between 35.7 and 43.9% of the laundry demand (Table 3), which represents about 6–7% of the total domestic water demand. This would be enough to defer the need of new supply infrastructures to satisfy growing water demands.

These results need to be considered as a first step in the financial assessment of the infrastructures for RWH and use in urban areas, since a major shortcoming of the cost–benefit analysis is that, by definition, it ignores non-monetised impacts. The analysis of financial benefits purely in terms of potable water savings provides an incomplete picture because it excludes externalities (Coombes et al., 2002), because of the difficulties in their quantification (Fletcher et al., 2008). However, it is evident that the

### Table 6

Financial results for the RWH strategies. The shadowed cells show the positive NPV. Abbreviations: r stands for ‘interest rate’, n.a.’ stands for ‘not available’.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Strategy</th>
<th>NPV at r = 0% (€)</th>
<th>Payback period (years)</th>
<th>NPV at r = 3% (€)</th>
<th>Payback period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Current water price (1.12 €/m³)</td>
<td>1</td>
<td>–15,561</td>
<td>n.a.</td>
<td>–10,909</td>
<td>n.a.</td>
</tr>
<tr>
<td>Payback period (years)</td>
<td>n.a.</td>
<td></td>
<td></td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>(2) Future water price (4 €/m³)</td>
<td>2</td>
<td>–2,922</td>
<td>n.a.</td>
<td>–4905</td>
<td>n.a.</td>
</tr>
<tr>
<td>Payback period (years)</td>
<td>n.a.</td>
<td></td>
<td></td>
<td>n.a.</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: $r$ stands for ‘interest rate’, ‘n.a.’ stands for ‘not available’.
inclusion of environmental and social aspects in financial analysis would present an improved economic performance (Ouessar et al., 2004).

This cost–benefit analysis considers the savings of mains water as the only benefit of RWH systems. However, it is well-known that there are many other benefits of RWH in urban areas (environmental, social and financial). Among these we highlight, due to their financial and environmental repercussions, the reduction (or deferring the need) of the following water infrastructures:

- downstream storm water conveyance and treatment systems,
- alternative water supply infrastructures (such as new dams, desalination plants or water transfers), as well as a reduction in the water supply infrastructures in new neighbourhoods;
- flood-prevention infrastructures.

In addition, there are other less tangible benefits which can also be relevant, such as the value that households may attach to the added insurance that rainwater tanks provide against impacts of water restrictions (Tam et al., 2010) or the improved environmental outcomes for surrounding rivers and streams (MJA, 2007).

If all these multiple benefits were taken into account, the financial benefits would increase and, consequently, the payback period would be reduced. Some steps into this direction are being taken. Many countries, such as Germany, the UK and Australia, are charging households a rainwater fee (also named surface water charge) for the buildings whose stormwater runoff is connected to the sewerage system (Nolde et al., 2007; Ofwat, 2010). However, if no connection to the sewer exists because there is a RWH system, the house owner may be entitled to a rebate on the bill from the sewerage company. In addition, some state governments and local councils have offered cash rebates to support the installation of rainwater tanks in households (Tam et al., 2010). Therefore, some financial mechanisms which take into account the externalities of RWH strategies are being developed, which may eventually foster the development of RWH systems.

5. Conclusions

This research evaluates which is the most cost-efficient rainwater harvesting (RWH) strategy in a dense urban neighbourhood in Mediterranean conditions in Spain. Based on the economic analysis, the cost-efficiency of the presented RWH strategies may be put in doubt in dry areas in Spain, as in many other countries, if current local water prices are still so low. However, the application of the EU Framework Water Directive will increase local water prices so as to include the real costs of supplying water. As a consequence, this may foster the interest on RWH strategies from an economic point of view.

Despite some strategies seeming not to be economically cost-efficient, the small capital costs (<800 €/dwelling) and the expected decrease in water availability (which will result in increasing reticulated water supply costs) make it advisable to promote RWH infrastructures.

The results of this research indicate that RWH strategies should be preferably installed at the neighbourhood level, since it enables economies of scale, and that they should take place at the moment of the settlement construction. Considering a 0% interest rate, a water price of 1.86 €/m³ would be enough to make RWH cost-efficient for this option. On the other hand, considering an increase in the local water price (up to 4 €/m³) and a discount rate of 3%, the payback period would be 51 years. If no discount rate were considered, the payback period would be reduced to 27 years. Therefore, this strategy is more cost-efficient than the one at the building level.

Future research will focus on the one hand, on the expansion of the economic analysis in order to include the externalities caused by RWH. On the other hand, it will focus on the environmental analysis of the proposed infrastructures, through a Life Cycle Assessment – as our research group has been doing in the analysis of several urban infrastructures (Olivier-Solá et al., 2009a,b,c). These analyses should be compared with current conventional water supply systems and with alternative ones, specially in the current context of breakdown of the water supply model (desalination, reclaimed waters). Finally, it will be necessary to study the administrative obstacles that will arise so as to promote RWH at the neighbourhood level, as well as to study planning procedures and new legal frameworks in order to incorporate RWH into current and future urbanisation schemes.

Acknowledgements

The authors wish to thank Adigsa and Consma for their collaboration on this project and also the Catalan Government and the European Social Fund for the FI scholarship enjoyed by Farrery R. With the financial support of the Spanish Ministry for Science and Innovation through the project ‘Análisis ambiental del aprovechamiento de las aguas pluviales’ (ref. CTM 2010-17365).

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