Towards a sustainable rainwater harvesting in urban environments

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ABSTRACT
The SOSTAQUA project is a big R+D+i Spanish project on the technological developments for a self-sustainable urban water cycle. One of its lines of research, the results of which are presented in this paper, has been focused on rainwater harvesting, particularly on the potential uses of rainwater and on its requirements on catchment, storage, treatment, and distribution in urban environments. The core of this study has been an extensive characterization campaign of rainwater along the urban water cycle, which has helped to determine, on the one hand, the feasible urban uses for collected rainwater, and on the other hand, the treatment requirements to meet quality standards. This analysis has finally resulted in the development of recommendations on best practices and technologies for a self-sustainable water cycle.

KEYWORDS
Rainwater harvesting; rainwater quality; stormwater; sustainable urban drainage systems; urban rainwater cycle

INTRODUCTION
The recent drought and concerns about environmental matters, and in particular about climate change, have all highlighted the need to manage our water resources more sustainably. According to the United Nations, addressing water scarcity requires actions at local, national and river basin level, promoting the management of water resources maximizing economic and social benefit in an equitable manner without compromising the sustainability of ecosystems. Likewise, in 2007, a Communication from the Commission to the European Parliament and the Council (COM, 2007) estimated that 17% of the European territory was affected by water scarcity, giving priority to water-efficient economies. In this regard, unsustainable practices such as the fact that 50% of high quality water in urban areas (DEC, 2006) is currently used for lower quality purposes: garden irrigation, toilet flushing, etc., must be avoided, considering that these uses do not require such high quality and expensive water.

In this context, over recent years, rainwater harvesting (RWH), as the process of intercepting rainwater or stormwater runoff, has emerged as a new scheme for sustainable water management (see Figure 1), offering both an alternative water supply for non-drinking uses and a means to further reduce urban drainage problems linked to stormwater flows, such as the occurrence of combined sewer overflows or floodings.

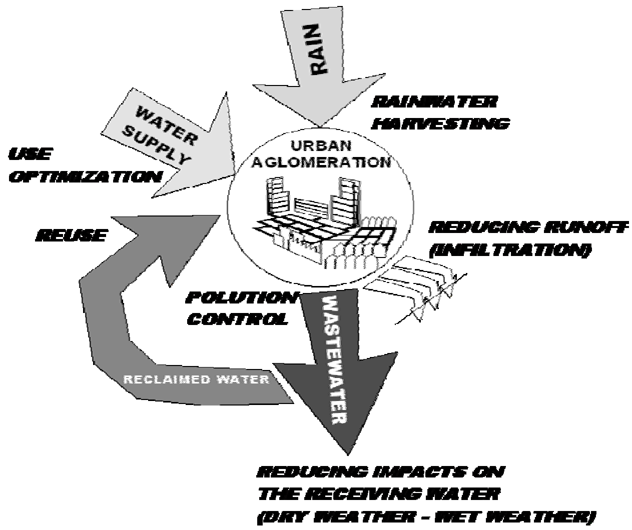

Figure 1. Example of a sustainable water cycle with the integration of rainwater harvesting

Rainwater harvesting schemes, including collection, treatment (if necessary) and storage of rainwater, can be implemented in existing urban areas or new developments, and integrated within the water cycle management plan or water savings plan of any community. Nevertheless, despite the potential and wide spread of RWH applications in countries such as Australia, USA, Japan, Germany or UK, compared to wastewater recycling and stormwater flow and quality management, there is a relatively little technical guidance and regulatory framework available for practitioners assessing the feasibility of RWH applications.

In this context, CLABSA (AGBAR group), the company in charge of the sewerage network management of Barcelona, with experience in stormwater management, and in collaboration with (GEAMA-UdC, Laboratorio AGBAR and EMUASA), has leaded the task on Sustainable Rainwater Management of the SOSTAQUA project (2007-2010), an R+D+i Spanish Project subsidized by the CDTI (Centro para el Desarrollo Tecnológico Industrial), on the analysis of technological developments aimed at a self-sustainable urban water cycle.

OBJECTIVE AND METHODOLOGY

The present paper is aimed to show some of the most relevant issues, conclusions and final recommendations derived from the Sustainable Rainwater Management study within the SOSTAQUA's project. The study has been focused on the analysis of the potential uses of rainwater in urban environments, and which requirements on catchment, storage and treatment are necessary to meet the quantity and quality of water for each potential use, always guarantying human's and environment's health. This analysis has finally resulted in the development of practical guidelines to develop sustainable RWH applications. The study has been divided into 5 main tasks or topics of research, including:

- **T1. Rainwater harvesting framework.** State of the art on the experiences on RWH and the legal context covering that topic. For that purpose, a world-wide analysis of directives, national and local legislation or ordinances have been performed.
- **T2. Rainwater characterization.** This task includes the characterization campaigns for 60 rain episodes in the Spanish cities of Barcelona, Santiago de Compostela and A Coruña, with the purpose of detecting the presence of pollutants in those potential catchment locations of rainwater within the urban water cycle (see Figure 2). In such

study, more than 100 different parameters were analyzed, including among others: microbiological parameters, solids, nutrients, organic matter, salinity, heavy metals, volatile organic compounds (VOC), pharmaceutical drugs, pesticides, etc.

This task has helped to determine the quality of rainwater according to its source (sampling location), which will finally help to delimitate, on the one hand the feasible catchment locations and, on the other hand, the treatment requirements.

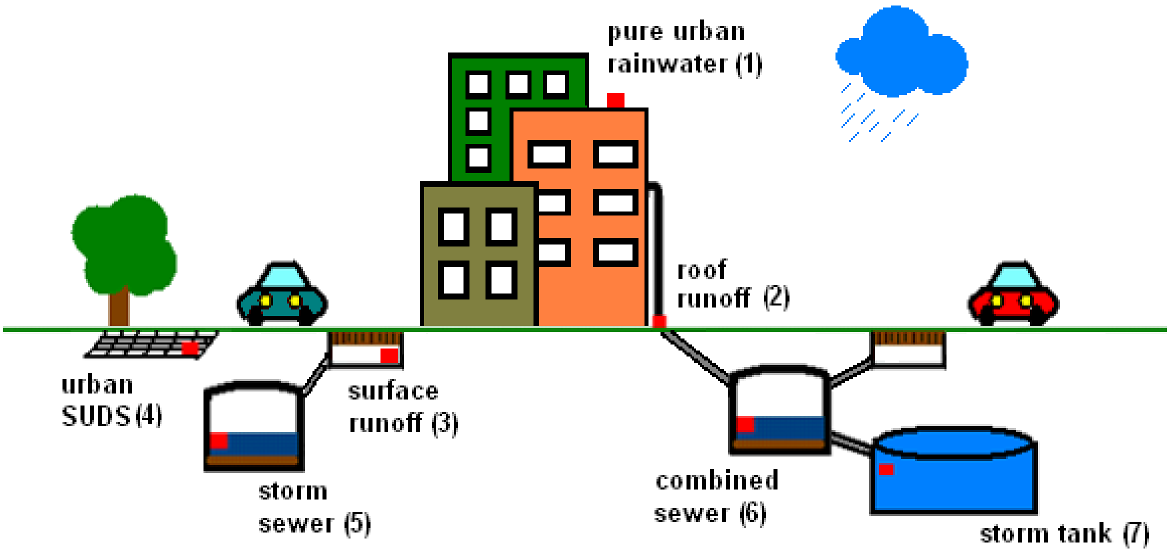

Figure 2. Potential catchment locations identified within an urban rainwater cycle

Detailed sampling protocols were established before starting the study. Special care was taken with regard to the definition of a significant rain event (involving sufficient intensity and minimum volume for a measurable runoff). Accordingly, rain gauges were installed in all the catchment points. Of equal importance was to gather a good representation of a wide variety of storms. This was accomplished by the analysis of several rainfalls (60 rain events were analysed in total), taking place at different seasons, of different intensities, with different lengths of preceding dry periods, and even with different surrounding urban area conditions (residential, commercial or industrial areas, different traffic intensities, different land uses, etc.).

- **T3. Minimization techniques.** Analysis of the available minimization techniques that directly influence on the on-source quality of rainwater: the use of Sustainable Urban Drainage Systems (SUDS) and the implementation of good practices such as street and sewer's cleaning.
- **T4. Collection and storage techniques for rainwater.** Study of the available techniques to collect and store rainwater, in order to suggest the most feasible configuration capable of storing the most quantity of water without worsening its quality. Design criteria for these systems were also analyzed.
- **T5. Treatment techniques.** Analysis of those treatment techniques currently available to adapt quality of collected rainwater to the quality requirements of final uses. 51 different technologies were evaluated, considering treatment efficiency, energy consumption, operation and maintenance costs, land-take, etc.

RESULTS AND DISCUSSION

Rainwater harvesting framework

Many countries around the world are currently promoting the use of harvested rainwater for potable and non-potable uses. Examples of these countries are USA, Australia, Japan, the UK, France, Germany, India or sub-Saharan countries.

General advantages of RWH include: the reduction on the amount of freshwater needed for urban uses; the reduction on the water entering the sewers, with a reduction on combined sewer overflows and the risk of flooding; a cost saving with lower water, wastewater and stormwater charges; or a decrease on stormwater runoff pollution (Krishna, 2003). Nevertheless, it also involves a group of disadvantages that must be taken into account. For example, the dependence on the frequency and amount of rainfall, implying that in times of dry weather or prolonged drought, low storage capacities limit the availability of water, and increased storage capacities increase construction and operating costs; health risks derived from direct uses, or from potential cross connections with potable supplies and finally the potential reduction on revenues to public utilities.

Regarding the legal framework it can be concluded that different countries, regions and even cities do regulate RWH in a different way. Usually, the main legal problem is that there is no regulation for the use of rainwater. Then, rainwater is considered as recycled water, as an outflow of a tertiary treatment, although the chemical and biological characteristics of both resources are significantly different. The available approaches are mainly focused domestic uses of rainwater. Examples include: Décret du 2 juillet 2008 (France); British Standard 815 (The UK); Rainwater Harvesting Potential and Guidelines for Texas (USA) or Australian guidelines for water recycling, stormwater harvesting and reuse (Australia). In Spain, the reference approach generally used in local normative is the National Royal Decree (RD) 1620/2007, which establishes quality standards and possible uses for reclaimed water.

According to the available legislation, it can be stated that the characterization of rainwater, directly related to quality standards, is a key factor in any sustainable RWH approach.

Rainwater characterization

Some analytical results from the characterization campaigns, showing average concentration for main pollutants and for different sampling locations are presented in Figure 3. The analysis of these results illustrate how, as rainwater flows along the urban rainwater cycle, the concentration of most pollutants increase, due to the increase on the amount and types of polluting sources affecting the source of rainwater. Specifically:

- **Pure urban rainwater** (directly collected as it falls from clouds by means of rainfall) is almost free from all sorts of contaminants, except (in some occasions) from heavy metals, which strongly depends on the atmospheric pollution.
- **Roof runoff** (incorporating the pollution accumulated in roofs) presents some solids, although at low concentrations, and generally related to the first flush of the roof.
- **Surface runoff** (rainwater draining into the ground from roofs, roads, footpaths and other ground surfaces) sets from its significant concentration on solids, heavy metals, microbiological contaminants and organic matter.
- **Combined sewers and storm tanks** (stormwater runoff entering into the sewers). Apart from the pollutants present in surface runoff, it also incorporates all the pollutants related to wastewater and to the re-suspension of sediments found in the

network, resulting in high concentrations on solids, nutrients and pathogens, apart from some VOCs, HAPs and heavy metals. It must be also remarked the settling effect of the storm tank making solids and organic matter decrease significantly.

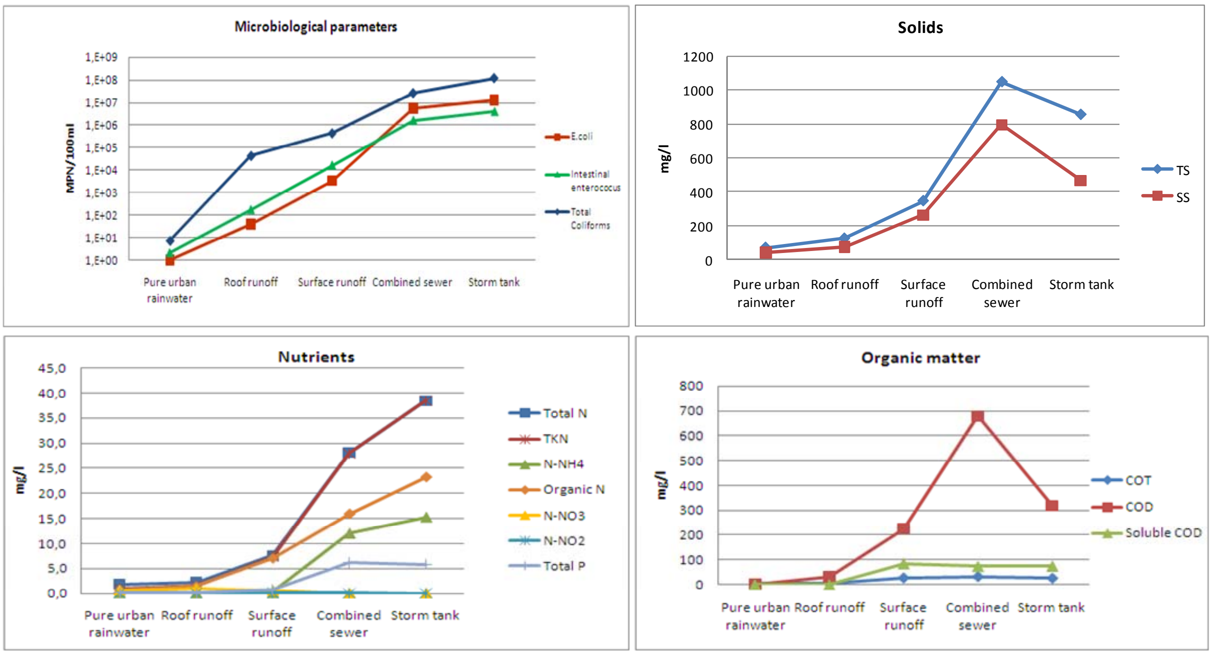

Figure 3. Average concentration for main pollutants at different sampling locations

Pure rainwater and roof runoff are the only source of water that directly meets reference quality standards. Nevertheless, when time between rainfalls was higher (high dry period), turbidity or suspended matter was in excess, exceeding the limits of water reuse for public uses. This may suggest a rejection of the first volumes of water to ensure good quality of water. For the rest of rainwater sources (surface runoff or stormwater in combined sewers), a minimization or treatment process will be always necessary before considering any use.

Minimization techniques

Minimization techniques, including Sustainable Urban Drainage Systems (SUDS) and street and sewer cleaning are key elements in any rainwater harvesting scheme involving urban catchments. 16 types of SUDS were analyzed as potential treatment units to minimize rainwater contamination (as on-source control or downstream treatment). Table 1 summarizes the treatment and reuse potential of different types of SUDS, from which, it can be generally concluded that:

- SUDS incorporating vegetation are the preferred option to minimize nutrients.
- SUDS with a high retention time (retention ponds, infiltration basins or trenches, sand filters, etc.) are the preferred option to minimize solids.
- Few SUDS technologies are capable of strictly remove microbiological pollutants, so, depending on final uses, disinfection treatments will be always necessary before use.

Furthermore, apart from the decontamination efficiency, additional factors such as land use, catchment characteristics, maintenance, cost-efficiency or community acceptability, must be additionally considered when selecting the most appropriate SUDS (CIRIA, 2007).

Table 1. Removal of pollutants and reuse potential of stormwater for different SUDS (green: high removal; yellow: medium removal and red: insignificant removal)

SUDS / Pollutants removal/ Reuse potential	1.Retention ponds	2.Detention basins	3.Wetlands	4.Filter trenches	5.Infiltration basins	6.Soakaways	7.Permeable pavements	8.Modular pavements	9.Swales	10.Bioretention areas	11.Filter strips	12.Surface sand filters	13.Perimeter sand filters	14.Sub-surface sand filters	15.Organic filters	16.Green roofs
Sediments	Green	Green	Green	Green	Green	Green	Red	Red	Green	Green	Yellow	Green	Green	Green	Green	Green
Nutrients	Yellow	Red	Yellow	Green	Green	Green	Yellow	Yellow	Yellow	Yellow	Red	Red	Red	Red	Yellow	Yellow
Organic matter	Green	Yellow	Green	Green	Green	Green	Yellow	Yellow	Yellow	Green	Yellow	Green	Green	Green	Green	Yellow
Heavy metals	Yellow	Yellow	Yellow	Green	Green	Green	Yellow	Yellow	Yellow	Green	Yellow	Yellow	Yellow	Yellow	Green	Yellow
Hydrocarbons	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Red	Red	Yellow	Green	Yellow	Green	Green	Green	Green	Red
Bacteria	Yellow	Yellow	Yellow	Green	Green	Green	Yellow	Yellow	Red	Green	Red	Yellow	Yellow	Yellow	Yellow	Yellow
Micro-pollutants	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Red	Red	Yellow	Green	Yellow	Green	Green	Green	Green	Yellow
Reuse potential	Yellow	Red	Yellow	Red	Red	Red	Red	Red	Red	Green	Red	Yellow	Yellow	Yellow	Yellow	Green

On the other hand, the analysis of the influence of cleaning practices in the minimization of surface runoff and combined sewer contamination confirmed the necessity of these practices when surface runoff was considered.

Collection and storage techniques for rainwater

Collection and storage systems for rainwater can be as simple as the collection of rainwater running off a roof and conveyed to a storage tank, or as complex as bigger scale systems involving land surface and urbanized catchments. Regardless the complexity of the system, the main objective of the system must be to capture and store enough rainwater to meet the end-use volume requirements. Accordingly, the design of the collection and storage system must be considered as a key issue. For example, considering space limitations, the use of underground tanks (plastic or concrete tanks) would be preferred in urban areas, while the use of open storage (cheaper than underground tanks) would be specially recommended when integrated in recreational areas and when the risk of human contact was minimized.

Regarding design criteria, when calculating storage size, the amount of rainfall, catchment surface and efficiency of the system will determine the amount of rainwater that can be collected (supply). After that, a water balance must be performed, in order to compare the supply with the expected demand (which in turn depends on both the average daily water use and the number of days without rain, during which rainwater needs to be stored). This will finally determine the storage size. Finally, other factors such as water quality, maintenance, human health and safety risks must be also taken into account during the design phase.

Treatment techniques

Factors affecting the treatment requirements of RWH applications include: the initial quality of rainwater, the intended uses of rainwater and the existing regulations stating the quality standards for potential uses. Thus, the most sustainable RWH scheme would be the one strategically located to capture high-quality rainwater and designed to provide water to low quality demanding uses, so the system would not require a complex treatment unit.

Nevertheless, given the results of the characterization task, it seems that a degree of treatment will be usually required at least to guarantee a safe use of water. Accordingly, a review on potential treatment technologies was performed, although, given the inexistence of a wide market of technologies specially developed for rainwater treatment, the review has been based on those technologies in the field of wastewater reuse, including: screening devices, water diverters, settling, filtering and disinfection techniques. At this point, we must also consider the SUDS as alternative treatment technologies.

Taking into account the results of this exhaustive analysis, and considering, on the one hand, the main pollutants present in rainwater and on the other hand, the requirements of reference quality standards for urban uses (mainly solids, turbidity and pathogens), it seems that the optimal treatment system to be applied in RWH schemes, will be the one combining different treatment processes, known as treatment train, including:

- **Pre-treatment** (screening or filtering unit): to remove gross pollutants (with a higher concentration in final stages of the rainwater cycle). First flush removal must be also considered.
- **Primary treatment** (physic-chemical process or alternatively a SUDS): to remove most solids (and their related pollutants).
- **Advanced treatment and/or disinfection** (membrane filtration or disinfection): to adjust final quality, specially turbidity and pathogens removal. This step will depend on the exact quality requirements.

According to this basic scheme, the combination of technologies to be used can be variable. As a last resort, it should be the water manager who, using a cost-benefit or multicriteria analysis, evaluates which alternative better suits the objectives of RWH. To help in this process, the following implementation plan (Figure 4) is recommended.

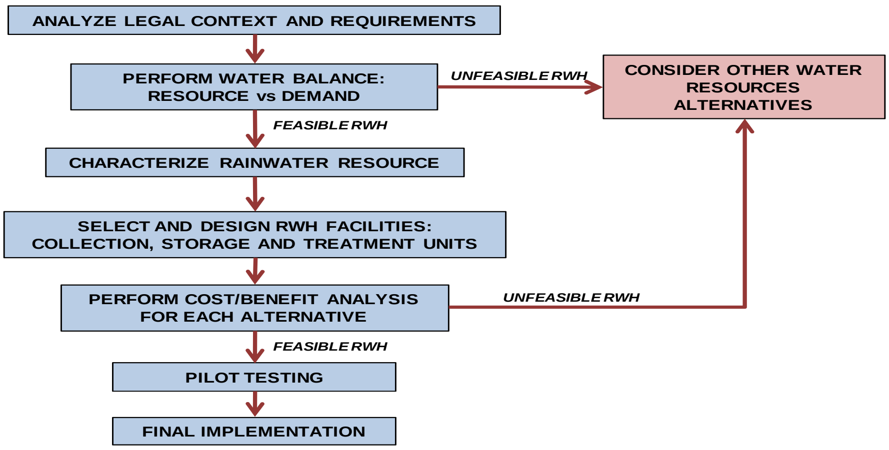

Figure 4. Recommended implementation plan for sustainable RWH applications

CONCLUSIONS

The research done within the SOSTAQUA project has allowed acquiring enough knowledge on how to approach sustainable rainwater harvesting applications in urban environments.

First of all, it can be stated that, together with reclaimed wastewater, there is a need to encourage planned and appropriate rainwater reclamation and reuse and to establish safe reuse practices. Nevertheless, the current lack of legal framework to develop RWH applications makes it primarily necessary to state national (or at least local) legislation specifically aimed to fix: quality standards, potential uses and treatment requirements for rainwater.

Besides the legal framework, quality of rainwater is a key factor to be taken into account when developing feasible RWH applications. Results from the characterization campaigns have provided exhaustive information about the quality of rainwater at the different collection points within the rainwater cycle. It has been confirmed that the last stages of the rainwater cycle will accumulate a higher volume of rainwater for potential use, but it will also imply a higher concentration of pollutants, making most necessary the use of minimization and/or treatment techniques (this information has a great practical use to fix both the treatment requirements and the potential uses of rainwater). Therefore, the most sustainable options for RWH applications in urban environments will involve those sampling locations where pollution is not so high: pure urban rainwater, roof runoff and stormwater runoff (before mixing with wastewater) and for that potential uses involving low quality requirements, which will minimize treatment costs: landscape irrigation (excluding crops irrigation), fire fighting, external cleaning (street and sewers cleaning and car washing), ornamental ponds and water features or groundwater recharge (by surface spreading).

Finally, in order to develop sustainable RWH applications, factors such as: the availability of the resource; the potential demand; and specially the evaluation of the benefits and drawbacks of using this alternative water source (rainwater) in front of conventional or alternative sources of water. In order to perform broader analysis, it is suggested that the decision maker took into account other benefits of the stormwater harvesting schemes, such as the reduction of downstream pollution loads and flows, which is an important issue to take into account for most local authorities and water managers.

Further research on the topic of RWH should be focused on the evaluation of the treatment efficiency of different treatment alternatives for rainwater and especially on the capital and operational costs (CAPEX and OPEX) related to these applications.

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