Towards a Constructed-Wetland/Reservoir-Tank System for Rainwater Harvesting in an Experimental Catchment in Colombia[1]

Hacia un sistema humedal-construido/tanque-regulador para el aprovechamiento de aguas lluvias en una cuenca experimental de Colombia[2]

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Abstract

This paper presents the overview of the Pontificia Universidad Javeriana Bogotá (PUJB) RWH (rainwater harvesting) experience. In Colombia, few researches have developed projects for RWH; and no researches have considered SUDS (Sustainable Urban Drainage Systems) for RWH purposes. The PUJB's RWH project was a result of a research process that started within the campus in 2007, by the research group *Ciencia e Ingeniería del Agua y el Ambiente* (from the same university), within the framework of the PUJB Environmental Management Plan and the collaboration of the Physical Resources Office (PRO) of the University. The chosen technology, constructed-wetland/reservoir-tank (CWRT), collects stormwater runoff from a university parking building (3,776 m^2), the soccer field and the areas that surround the system (14,816 m^2). Recently, a monitoring program focused on the main changes of the stormwater quantity of the system was launched. The first results show that the CWRT fulfils its purpose in terms of peak and volume runoff attenuation. Additionally, the system can be seen as a full-scale laboratory to study the biodiversity and ecological impacts within the hydrological and hydraulic processes too.

Resumen

Este artículo presenta el panorama general del proyecto de aprovechamiento de aguas lluvias (AALL) de la Pontificia Universidad Javeriana Bogotá (PUJB). En Colombia se han desarrollado algunas investigaciones que contemplan el AALL, pero no se han desarrollado investigaciones que consideren sistemas urbanos de drenaje sostenible para este propósito. El proyecto de AALL de la PUJB es el resultado de un proceso de investigación desarrollado desde el 2007 por el grupo de investigación Ciencia e Ingeniería del Agua y el Ambiente, dentro del marco del proyecto de gestión ambiental de la PUJB y con el apoyo de Oficina de Recursos Físicos. La tecnología escogida, humedal-construido/tanque-regulador (HCTR), recoge la escorrentía de un edifificio de parqueaderos de la universidad (3776 m^2), de la cancha de fútbol y de las áreas alrededor del sistema (14 816 m^2). El HCTR cuenta con un programa de monitoreo encargado de registrar los cambios del agua en términos de cantidad. Los primeros resultados del comportamiento del HCTR muestran que el sistema cumple su propósito, en cuanto a atenuación del pico y del volumen de escorrentía. Adicionalmente, este sistema puede verse como un laboratorio a escala real para estudiar la biodiversidad y los impactos ecológicos dentro de procesos hidrológicos e hidráulicos.

Keywords

rainwater harvesting (RWH); sustainable urban drainage systems (SUDS); horizontal subsurface flow (HSSF) wetland

Palabras clave

aprovechamiento de aguas lluvias; sistemas urbanos de drenaje sostenible (SUDS); humedal horizontal de flujo subsuperficial

Introduction

Nowadays, there is an increasing attention on rainwater harvesting (RWH) as an alternative source of water [1] for non-potable uses that require lower quality: landscape irrigation, discharge of toilets, washing hard areas or building facades [2], [3]. The implementation of the RWH technique in urban areas is considered a multi beneficial strategy for urban flooding control [4]-[6], and for the reduction of potable water consumption [7]-[10]. It can also decrease the pressure on urban drainage systems during strong rain events [11], reduce and solve current water shortages, and the pollution of urban natural waterways [4]-[6]. RWH is additionally recognized as one of the specific adaptation strategies that the water sector should implement to deal with climate changes [12]-[14], and has more public acceptance than other techniques such as wastewater recycling, or reuse or desalination of seawater [9], [15].

Although there are positive results from many studies, there remains general avoidance to adopt RWH on a wider scale. One reason is the lack of information about the effectiveness of this technique [16]. This technique has been successfully implemented as an alternative water source in some countries (e.g. [10], [16]-[23]). However, its implementation depends on finding the answer of the following questions [24]: How much stormwater can be harvested? How reliable is this supply source? [25], and, how large a storage is required? [26].

In recent years it has been found that for the collection and storage of rainwater, designs focused on sustainable urban water drainage, Water Sensitive Urban Design (WSUD), generates opportunities for both RWH and gray water reuse systems [8]. The Sustainable Urban Drainage Systems (SUDS) are included in the WSUD concept. Initially, these systems were designed for flood control: collecting, storing, and treating stormwater; also to minimize the effects on the infrastructure (such as soil impermeabilization and increase of water demand) and the anthropic activity on the quality of water [27]. The application of SUDS is a current topic (except in Africa); around the world there are successful

SUDS experiences: USA [28], United Kindom [29], Chile [30], Malaysia [31], Australia [32], China [33], Korea [34], and Greece [35].

In Colombia some researches have been developed for RWH [36]-[41] and SUDS [42]-[47]; yet no research projects have taken into account SUDS for RWH purposes. Ballén *et al.* [40] concluded that the feasibility of RWH in Colombia depends on five variables: Precipitation, covered area of the house, water availability to supply, price per cubic meter of water, and the investment needed for the construction and maintenance of the systems. Additionally, it is necessary to include the capacity of the storage tank that is considered as a critical part of the design of such systems [48].

Hence, the Pontificia Universidad Javeriana Bogotá (PUJB) RWH project was the result of a research process that has been developed in the university since 2007 by the research group Ciencia e Ingeniería del Agua y el Ambiente (from the same university), within the framework of the PUJB Environmental Management Plan. The purpose of this paper is to present the procedures undertaken and the data used for the planning and the design of the constructed-wetland/reservoir-tank RWH system, as well as an overview of the whole experience until its construction. This case study is a demonstrative project that will be used to spread the understanding of RWH and the impacts on watershed hydrology.

1. Materials and Methods

For the development (planning and the design) of the RWH system in the campus of the PUJB (total campus area 18.4 ha) a series of projects were undertaken.

1.1. Rainwater Quantity and Quality Analysis

The first project was related with the assessment of the economic and technical feasibilities of RWH as an alternative for some uses. Three main aspects were developed in this project: (i) Assessment of the available rainwater volumes and the possible collection points; (ii) preliminary quality analysis of the collected rainwater; and (iii) assessment of the construction costs for the basic infrastructure required to collect rainwater and of the monetary savings obtained with the proposed solution [39].

Subsequently, a project was conducted to know the quality of the stormwater on the campus and to identify potential water uses. Measurement campaigns were carried out in March, June, September, and October 2009; February, April, August, September, and October 2010; May and October 2011; and October 2012. Ten sample points were chosen according to two criteria (Figure 1):

(i) Water quantity and quality and (ii) location and proximity to potential rainwater collection centers. The results of the raw stormwater analysis were compared to the limits set out by the Food and Agriculture Organization of the United Nations (FAO) [49], EPA [50], and standards from Colombia [51] and Japan [52]. The standards are for non-potable uses: landscape irrigation, environmental, and recreational uses. For each sample point, the runoff water quality for three storm events was assessed through 25 analytical tests used to quantify physical properties and chemical constituents.

Figure 1. Location of the ten sample points in the PUJB University

Source: authors' own elaboration

1.2. Inventory of Water Uses on the Campus

A study was developed to assess the inventory of water uses on the campus. This was done by means of a field study of the campus, using a site record form and the historical monthly mean drinking water consumption on campus (2003-2010) [53].

1.3. Decision Making: Analysis of RWH Scenarios

Subsequently, a Multi Criteria Decision Analysis (MCDA) tool (called CRIDE: multiCRIteria DEcision support tool) for supporting the decision-making process for RWH in the PUJB campus was developed. Six scenarios were proposed for RWH and eight criteria were suggested in order to evaluate each scenario. These scenarios emerged from an ideal scenario in which all the water harvested in the campus would be used (maximum supply volume) with drinking water quality (maximum quality water). The other scenarios were created by decreasing the quality of water (less possible uses) and/or the supply (less basins included), obtaining high, medium, and low water demands, and high, medium, and low water supplies. This allowed to establish the size of the SUDS considered and the pumping and treatment systems. The scenarios are described in Table 1.

Table 1. Proposed rainwater harvesting scenarios

No.	Scenario Description
1	Runoff collection on twelve basins (maximum supply volume) with drinking water quality (maximum quality water).
2	Runoff collection on twelve basins for non-potables uses quality (floor cleaning, sanitary discharge and landscape irrigation).
3	Runoff collection on twelve basins for landscape irrigation use.
4	Runoff collection on nine basins with drinking water quality (maximum quality water).
5	Runoff collection on nine basins for non-potables uses quality (floor cleaning, sanitary discharge and landscape irrigation).
6	Runoff collection on nine basins for landscape irrigation use.

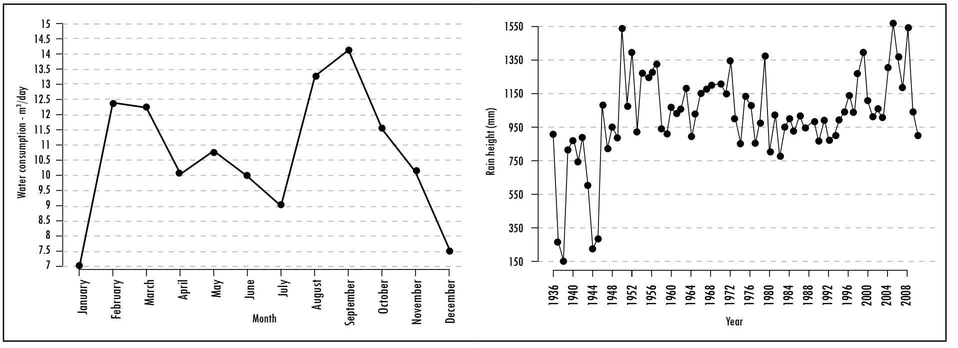
Source: authors' own elaboration

The criteria were defined based on the objectives for the Water Day project [54], which are those used in the French survey on SUDS [55]. These criteria were evaluated by the Physical Resources Office (PRO) of the University and the university researchers. Within the criteria set technical aspects were taken into account such as: hydraulic and environmental performance; management aspects such as: compatibility with the Development Plan of the University; and financial aspects such as: Net Present Value (NPV) of the investment. The weight of each criteria was defined by a survey conducted by four PRO leaders of the University and five experts on water management. The scenarios were evaluated with the set of criteria defined, in order to construct the decision matrix with minimum, average, and maximum assessments [56].

1.4. Sizing Method Proposed

A simplified method for RWH tank sizing using long day resolution rainfall time series and water demand was developed, following the recommendations of authors such as Campisano *et al*. [57]. The method was adapted to developing countries (low and medium hydrological data resolution). Also this method considers heterogeneous contributing catchments and water demand flow rates. In order to estimate the tank capacities it is proposed to take into account the probability to supply the water demand, as well as the most probable time step needed and their respective variabilities. The input data were 73 years of daily rainfall data between 1936 and 2010 (without years 1969 and 1988 with no data) (Figure 2 - right) and the monthly inventory of water uses of the university (demand). The rainfall data-set was collected from a daily rain gauge near the university campus (San Luis - type: Pluviograph station; latitude: 4°38'; longitude: 74°02'; elevation: 3000 m). The water demand was calculated from water bills (October 2003 - March 2010) delivered by PRO (Figure 2 - left). The contributing catchment has a surface of 22,026.20 m^2. It is composed by a sport center, a parking structure, a sport field, and green zones and roads, with a weighted runoff coefficient of 0.51 [58].

Figure 2. Monthly water uses in m^3/day for floor cleaning, sanitary discharge, and landscape irrigation in PUJB (left). Total amount of rain height per year for 73 years from San Luis Station (right)



Source: authors' own elaboration

2. Results

From the first project, related with the assessment of the economic and technical feasibilities of RWH as an alternative for some uses, results show the possibility of using rainwater for irrigation and washing hard areas and building facades of the PUJB, from the standpoint of the amount of water [39].

On the other hand, the results of the stormwater quality project on the PUJB campus showed that for the 25 raw stormwater parameters analyzed for each storm event, pH, turbidity, BOD, and a selection of metals exceeded the standard limits of EPA, Colombia, and Japan. Table 2 highlights the sample points (see Figure 1) that the pollutant levels exceeded the standard limits for at least one storm event.

Table 2. Summary of the sample points that overpass the standards limits

Analysis	Units	Landscape irrigation		Environmental and recreational uses	
		Sample Points that exceeded the limits	Standard limits	Sample Points that exceeded the limits	Standard limits
pH	-	1, 3 and 9	4.5 (Colombia)-8.0 (FAO)	1 and 9	5.8-8.6 (Japan)
Turbidity	NTU		NS	1-10	2 (Japan)
BOD	mg/L	NS	-	1-10	10 (EPA)
Cd	mg/L	1, 3, 4, 5, 7, 9 and 10	0.01	NS	
Hg	mg/L	1, 3, 4, 5 and 10	0.01 (Colombia)	NS	-
Mn	mg/L	3 and 7	0.2	NS	-
Pb	mg/L	4 and 10	5	NS	-

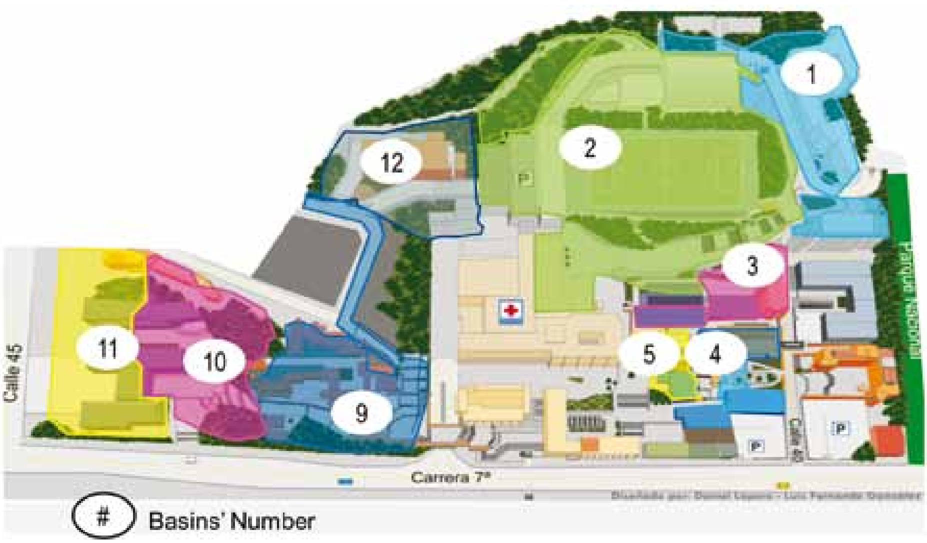
NS: not specified by standard.
Source: authors' own elaboration

Another result was the identification and quantification of the water that the PUJB uses: 41% for floor cleaning, 22% for drinking water, 21% for landscape irrigation, 16% for sanitary discharge. According to these results, 78% of the water has been used for non-potable uses (2003-2010) and only 22% for drinking water.

With the application of CRIDE, the best scenario (first in the ranking) was the scenario number five. This scenario consists of the runoff collection on nine basins (Figure 3) (basins number 1, 2, 3, 4, 5, 9, 10, 11 and 12) with quality for non-potables uses (floor cleaning, sanitary discharge, and landscape irrigation) using SUDS such as: basins, bioretention gardens, permeable paving, and constructed wetlands [59] for the collection and treatment of rainwater [56]. The results were reported to the PRO of the University, and they decided to design and construct scenario number five, beginning with the RWH of one of the nine basins (basin number 2). This basin represents 15% (2.73 ha) of the total campus area, with a contributing catchment of 2.20 ha and with a weighted runoff coefficient of 0.51.

Taking into account the results described above, the execution phase of the PUJB RWH began. This was carried out with a participatory work between the PRO of the University, university researchers and an expert designer, in the making of the engineering design for scenario number five. First, the location of the RWH system was chosen and also the treatment option to meet the requirements for non-potable uses. The criteria take into account for this decision was: (i) The quality of the stormwater (according to the quality campaigns heavy metals were found in the parking building –sample point 4– see Table 2) and (ii) the location of the existing stormwater drainage system. The chosen place is near to sample points four and five (figure 1). In this place it was projected the collection of stormwater runoff from the parking building (3,776 m^2), the soccer field, and the areas that surround it (14,816 m^2).

Figure 3. PUJB campus basins defined for scenario 5



Source: [56].

Hence, it was proposed a constructed-wetland/reservoir-tank system for the PUJB RWH. The system was built from 2012 to 2013. The system receives runoff from the parking lot, soccer field, and green areas. The constructed-wetland is a horizontal subsurface flow (HSSF) wetland (Figure 4), and the underlying gravel bed was built with different gravel sizes to minimize possible clogging. It was specifically designed to enhance the quality of runoff from the parking lot. The HSSF is divided in three zones and the gravel are strictly organized according to a decreasing size: the first zone will have a gravel size of 1 in; the second zone will have a gravel size of ¾ in; and the third zone will have ½ in. The CWRT system has two settling tanks: one before the constructed wetland and the other that receives the stormwater runoff from the soccer field.

Pertaining to the reservoir tank sizing, the simplified method described in section 1.4 was used: 211 m^3 of stormwater storage, taking into account the last ten years of the rainfall data-set and 15 days of storage time with a 75% probability to supply the water demand. This design aims to store the treated water coming from the constructed wetland as well as untreated stormwater runoff from the soccer field and green areas. Likewise, the tank is located beneath the constructed-wetland given a lack of available space.

To gauge the performance of the system (its hydraulic attenuation), it is monitored by means of two triangular sharp-crested weirs, a series of piezometers, and ultrasonic level sensors. The locations of the weirs are: the entrance of settling tank (Input Figure 4 left) and the exit of the constructed-wetland (Output Figure 4 left). The piezometers are spaced throughout the constructed-wetland. For the ultrasonic levels, two were placed in front of each weir, three in the constructed-wetland, and one in the reservoir tank (White dots Figure 4 left).

Figure 4. Constructed-wetland/reservoir-tank system (reservoir-tank volume = ±145 m^3; superficial area of the wetland = 85.12 m^2) and ultrasonic-level measuring device (white dots)

Source: authors' own elaboration

During 2013, 14 rain events were recorded and processed (three in October, ten in November, and one in December). However, only five events could be analysed, due to problems with three of the five ultra-sonic measurement devices in the wetland. Nonetheless, these results still allow us to establish a preliminary behavioral pattern for the system.

Initial results show that the constructed-wetland delays runoff hydrographs between 11 and 53 min, with this variation being mainly a function of the total duration of the rainfall. In addition, outflow runoff peaks vary between 37% and 78% of those observed for inflow, while the constructed-wetland retains up to 46% of the total rainfall volume.

Conclusions

This paper summarizes the procedures undertaken and the data used for the planning and design of the specific PUJB RWH system (constructed-wetland/reservoir-tank), as well as an overview of the whole experience until its construction.

The first project gives us the feasibility for RWH at the campus from the standpoint of quantity. According to the quality campaigns, quality enhancement is required using low cost treatment options. The inventory of the PUJB water uses showed us that the main PUJB water use is for non-potable purposes. This led us to propose a series of RWH scenarios, and the best scenario was chosen according to a MCDA tool specially developed for this purpose (non-potable uses, nine basins out of twelve, using SUDS for collection, storage, and treatment). As part of the RWH scenario chosen, a constructed-wetland/reservoir-tank was sized following a simplified method specially developed for the reservoir tank. This method takes into account the failure probability of the system (the probability of having no water), considers all the years of the hydrological data resolution, and the effects of climate change (the last 10 and 5 years, and the last year), instead of conventional SUDS designs that consider extreme events. Also, this failure probability will be a reference value to evaluate the performance of the design method proposed.

The implication of having a constructed-wetland/reservoir-tank will be that the performance (its hydraulic attenuation and the quality performance) at a real scale can be studied. The first results show that the constructed-wetland fulfils its purpose in terms of peak and volume runoff attenuation. As far as the present study is concerned, technical difficulties were also encountered. At the present moment, we are trying to resolve this issue by improving the ultra-sonic measurement installation and its calibration. The next monitoring phase will consist of installing quality sensors (online turbidity and pH sensors).

Also, the system can be seen as a full-scale laboratory to study the biodiversity and the ecological impacts within the hydrological and hydraulic processes. It is expected that this system would be an example for future RWH projects and to be a tool for future researchers.

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