



Research on the Constructed-Wetland/Regulation-Tank System at Pontificia Universidad Javeriana's Bogotá Campus

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Abstract. The stormwater harvesting (SWH) project at Pontificia Universidad Javeriana (Bogotá) began in 2007, initiated by the Water and Environmental Engineering research group (Ciencia e Ingeniería del Agua y el Ambiente), as part of PUJB's Environmental Management Plan and in collaboration with the University's Office of Physical Resources. This process included assessments of water supply and demand, rainwater quality, and financial and construction considerations. The system—a constructed wetland/regulation tank (CWRT)—collects rainwater runoff from the university's parking building (3,776 m²), the soccer field, and surrounding areas (14,816 m²). Beyond its hydrological performance, especially during periods of water scarcity, the system also functions as a full-scale laboratory to study biodiversity and ecological impacts in hydrological and hydraulic processes. The monitoring program, focused on changes in rainwater quantity and quality, has inspired several master's and doctoral research projects. These studies explore critical topics in urban hydrology, including stormwater harvesting, urban sediment management, real-time decision-making systems, and environmental and human health. This paper outlines the development of the stormwater harvesting system, shares the main findings from research projects, and discusses ongoing projects.

Keyword:

Stormwater harvesting, multi-criteria decision analysis (MCDA), rainwater quality, constructed wetland, sustainable infrastructure, water quality improvement, hydraulic performance, rainwater collection, runoff retention, ultrasonic level sensor, Sustainable Urban Drainage Systems (SUDS), sedimentation tanks, regulating tank, non-potable uses.

1. Introduction

In recent years, stormwater harvesting (SWH) has emerged as a pivotal solution in the global quest for sustainable water management strategies. SWH involves the collection and utilization of rainwater runoff from urban areas for non-potable applications such as landscape irrigation, toilet flushing, and surface cleaning [1], [2], [3]. The growing interest in SWH is driven by its multifaceted benefits and its potential to address pressing water-related challenges in urban environments.

One of the primary advantages of SWH is its contribution to urban flood control [4]-[6]. By capturing and redirecting stormwater runoff, SWH systems help mitigate the risk of flooding in urban areas, enhancing community resilience to extreme weather events. Additionally, SWH reduces the reliance on conventional potable water sources [7]-[10], thereby alleviating pressure on municipal water supplies and promoting more sustainable water consumption practices.

Moreover, SWH systems play a crucial role in reducing the load on urban drainage infrastructure during heavy rainfall [11]. By capturing stormwater runoff for later use, these systems decrease the volume of water entering storm drains and sewers, thereby minimizing the risk of overflow and urban flooding. SWH also helps mitigate pollution of urban waterways by intercepting and treating runoff before it reaches natural water bodies [4]-[6], preserving water quality and protecting ecosystems.

SWH is increasingly recognized as a key adaptation measure for addressing climate change [12]-[14]. Climate projections indicate an increase in the frequency and intensity of extreme weather events, and SWH offers a sustainable solution for managing water resources under changing climate conditions. Its decentralized nature and reliance on local rainfall patterns make SWH systems resilient to climate variability, providing communities with a reliable water source, even in drought-prone regions.

Despite its potential benefits, the widespread adoption of SWH faces several challenges, including a lack of comprehensive information regarding its effectiveness [16]. Critical questions remain about the volume of stormwater that can be harvested, the reliability of supply sources, and the necessary storage capacity [25], [26]. Addressing these knowledge gaps is essential for promoting broader implementation of SWH and realizing its full potential as a sustainable water management strategy.

Recent advancements in Water Sensitive Urban Design (WSUD) have further enhanced the feasibility and effectiveness of SWH systems. WSUD integrates principles of sustainable urban water management and offers innovative solutions for rainwater collection and storage [8]. Sustainable Urban Drainage Systems (SUDS), a key component of WSUD, incorporate various elements such as permeable pavements, constructed wetlands, and bioretention gardens to manage stormwater runoff effectively [27]. Initially designed for flood control, SUDS now encompass the collection, storage, and treatment of stormwater, contributing to improved water quality and reduced environmental impacts in urban areas.

In Colombia, while research on SWH [28]-[33] and SUDS [34]-[39] exists, further exploration is needed to integrate SUDS for SWH purposes. Additionally, comprehensive scientific investigations analyzing resource quality, flow rates, and storage options are lacking in the Colombian context. The SWH project at Pontificia Universidad Javeriana Bogotá (PUJB) represents a pioneering initiative aimed at addressing these knowledge gaps. Initiated in 2007 by the research group "Ciencia e Ingeniería del Agua y el Ambiente," this project, embedded within the PUJB Environmental Management Plan, seeks to promote rainwater use for various non-potable purposes across the institutional campus. By

implementing low-impact drainage systems and adopting a holistic approach to water management, the project aims to redefine the concept of a sustainable campus and serve as a model for other institutions and communities. This paper provides insights into the development of the stormwater harvesting system at PUJB, shares key findings from ongoing research endeavors, and facilitates discussions on future projects and collaborations.

2. Materials and Methods

A comprehensive study was undertaken to assess the water usage inventory on the campus of Pontificia Universidad Javeriana Bogotá (PUJB). This involved conducting a detailed field survey of the campus, utilizing site record forms and analyzing historical monthly average drinking water consumption data from 2003 to 2010 [40]. Simultaneously, a project was initiated to evaluate water resource availability by analyzing pluviograph records from the surrounding area.

Subsequently, a project was launched to investigate the quality of stormwater on the campus and identify potential water reuse opportunities. Measurement campaigns were conducted from March 2009 to October 2012, during which stormwater quality was assessed for three storm events at various sampling points. A total of 25 analytical tests were performed to quantify the physical properties and chemical constituents of the runoff.

To support the decision-making process for rainwater harvesting (RWH) at the PUJB campus, a Multi-Criteria Decision Analysis (MCDA) tool, CRIDE (multiCRiteria DEcision support tool), was developed. This tool facilitated the determination of the appropriate size for Sustainable Urban Drainage Systems (SUDS) and aided in the design of pumping and treatment systems. Decision-making criteria were collaboratively defined and weighted by the research group and the Physical Resources Office (PRO) of the University. These criteria encompassed technical aspects such as hydraulic and environmental performance, managerial considerations aligned with the University's Development Plan, and financial factors, including the Net Present Value (NPV) of the investments [41].

Additionally, a simplified method for sizing SWH tanks was devised using long-term, high-resolution rainfall time series data and water demand assessments. Following the recommendations of authors such as Campisano et al. [42], this method was tailored for application in developing countries with limited hydrological data resolution. The method accounted for heterogeneous contributing catchments and variable water demand flow rates, incorporating probabilities for meeting water demand and the most probable time steps along with their respective variabilities. Input data included 73 years of daily rainfall records (1936–2010) from the San Luis rain gauge station and the monthly water usage inventory at the university from October 2003 to March 2010. The contributing catchment area covered 22,026.20 m², comprising sports facilities, parking structures, sports fields, green spaces, and roads, with a weighted runoff coefficient of 0.51 [43].

Following the construction of the SWH facility, known as the Constructed Wetland/Regulation Tank (CWRT) system, in 2013, several research projects were initiated, including two PhD theses. These projects focused on developing real-time decision-making systems for rainwater harvesting and on the management and utilization of urban runoff sediments.

In 2024, a research project was launched between the Bogotá and Cali campuses of Pontificia Universidad Javeriana to identify adaptation measures for SUDS to mitigate the effects of climate change on runoff quantity and quality regulation. This project includes the

CWRT system in Bogotá and reflects the university's commitment to sustainability and innovation in water management practices.

The following figure presents a diagram illustrating the timeline of the six phases that comprise the previously presented methodology.

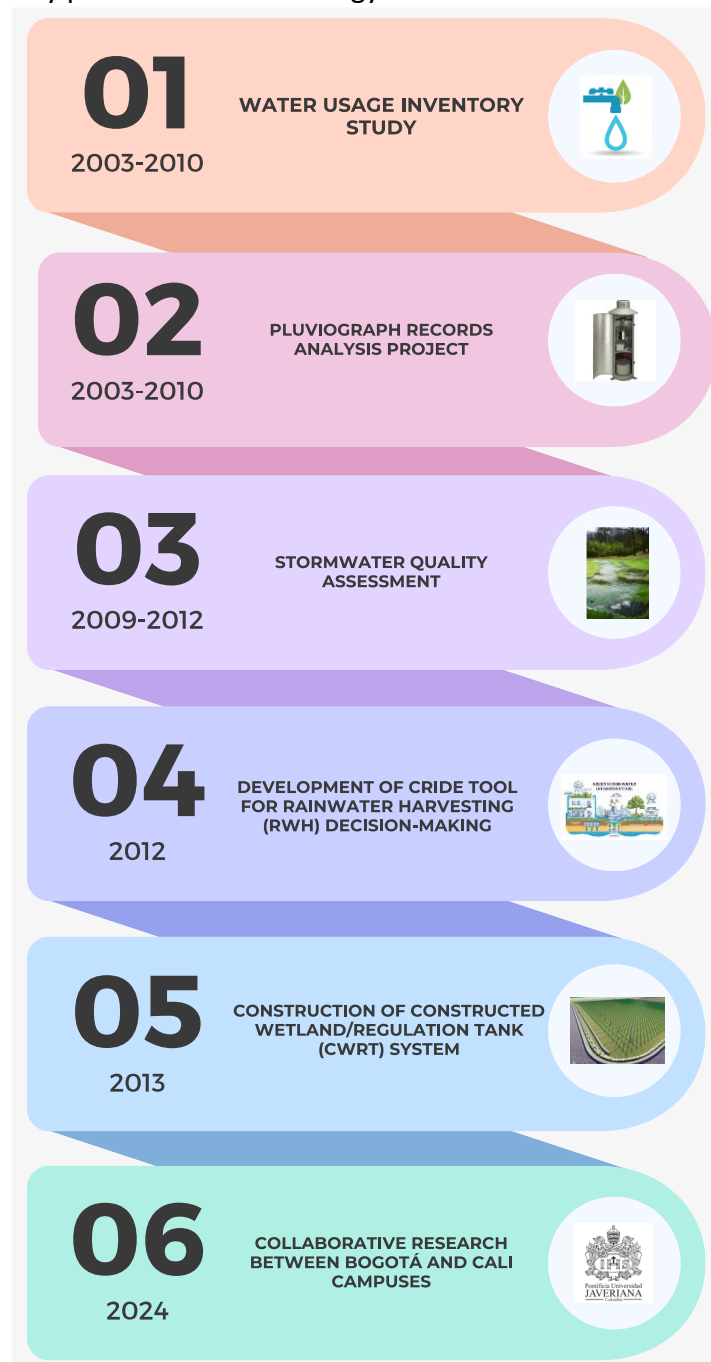


Figure 1. Timeline of the Six Phases of the Presented Methodology

3. Results

The assessment of water usage at PUJB provided valuable insights into the campus's consumption patterns. PUJB consumes approximately 16,651 m³ of water monthly and 199,807 m³ annually. Significant variation was observed among buildings, with daily water consumption ranging from 134 L to 111,751 L. Some buildings demonstrated high water usage, ranging from 14,971 L/day to 78,051 L/day, while others had lower demands,

between 219 L/day and 1,978 L/day.

The analysis identified activities responsible for the highest water demands, such as floor cleaning, garden irrigation, toilet discharges, and surface cleaning, which collectively accounted for 72% of total water usage. Essential activities relying on potable water, including handwashing, laboratory work, drinking, showers, and dishwashing, made up only 20% of the total usage. These results emphasize the need for optimizing water usage and implementing sustainable management practices to enhance resource efficiency on campus.

The findings from the stormwater quality project at PUJB revealed elevated pollutant levels in runoff. Analysis of 25 stormwater parameters across three storm events showed that pH, turbidity, BOD, and several metals, including Cd, Hg, Mn, and Pb, exceeded regulatory limits set by the EPA, Colombia, and Japan. These levels highlight potential environmental risks, stressing the importance of effective stormwater management practices to mitigate contamination and protect urban water quality. Continued research and monitoring are needed to assess the long-term impacts of stormwater pollution and develop sustainable management strategies at PUJB.

Following the implementation of CRIDE, scenario five emerged as the optimal solution, ranking highest among the evaluated options. This scenario involves collecting runoff from nine designated basins for non-potable uses such as floor cleaning, sanitary discharge, and landscape irrigation. Sustainable Urban Drainage Systems (SUDS), including basins, bioretention gardens, permeable paving, and constructed wetlands, were integrated for rainwater collection and treatment [44], [41]. Upon assessment completion, the results were presented to the Physical Resources Office (PRO) of the University for review and decision-making.

The PRO opted to proceed with scenario five, starting the construction of a stormwater harvesting (SWH) system for one of the nine designated basins. This basin, covering approximately 2.73 hectares, represents 15% of the total campus area and has a contributing catchment of 2.20 hectares with a weighted runoff coefficient of 0.51. The selection of this basin reflects its suitability for rainwater collection and its significant contribution to overall water management on campus.

The decision to prioritize scenario five demonstrates the university's commitment to sustainable water management and the adoption of innovative solutions to address water-related challenges. By leveraging SUDS techniques and targeted interventions, the university aims to enhance water efficiency, reduce dependence on conventional water sources, and promote environmental stewardship. The successful implementation of scenario five will serve as a model for future sustainability initiatives, fostering resilience and positive change on campus.

Following the assessment, the SWH project implementation phase commenced, involving collaboration between the PRO, university researchers, and an expert designer. This participatory approach ensured the development of an effective engineering design for the SWH system, with key criteria including stormwater quality and the location of existing drainage systems guiding the decision-making process.

Ultimately, the project selected a location for the SWH system that collects stormwater runoff from various campus areas, including a parking structure (3,776 m²) and the soccer field and surrounding areas (14,816 m²). By strategically selecting these areas, the project maximized water capture efficiency and minimized environmental impact.

The collaborative effort ensured that critical factors, such as water quality and system integration, were considered during planning. Through multidisciplinary expertise and

stakeholder engagement, the SWH project developed a sustainable and resilient water management solution tailored to PUJB's specific needs and conditions.

The CWRT system, constructed between 2012 and 2013, includes two settling tanks, a horizontal subsurface flow (HSSF) wetland, and a reservoir tank with a 211 m³ capacity for storing stormwater. The system's design allows for a 15-day storage time, with a 75% probability of meeting water demand. Continuous monitoring of the system's hydraulic performance, using triangular sharp-crested weirs at the wetland's inlet and outlet, facilitates ongoing assessment of its efficiency.

Preliminary results indicate the constructed wetland delays runoff hydrographs by 11 to 53 minutes and attenuates peak outflow to 37%–78% of inflow peaks, retaining up to 46% of total rainfall volume. These outcomes highlight the wetland's effectiveness in reducing peak flows and retaining stormwater, contributing to sustainable stormwater management on the PUJB campus. Continued monitoring will provide further insights into its long-term performance.

Rainwater characterization during three storm events revealed high turbidity and Total Suspended Solids (TSS) in the effluent, making it unsuitable for uses like showers and toilets but viable for irrigation and landscaping. Microbiological analysis detected 15 MPN/100 mL, further limiting the use of this water for certain applications. Chloride and Total Dissolved Solids (TDS) remained stable at the constructed wetland outlet but increased at the CWRT system outlet during all three events. Continued research is required to improve treatment processes and ensure rainwater quality for various uses.

An online water quality monitoring system, utilizing UV-Vis spectrometers, was implemented for real-time analysis, supported by Arima-based predictions. The system demonstrated robust forecasting accuracy, with prediction errors remaining under 15% across all datasets. This monitoring approach enables stakeholders to proactively manage water quality and optimize treatment processes, enhancing decision-making and supporting sustainable water resource management.

4. Conclusions

This paper outlines the methodologies employed and data used during the planning and design phases of the PUJB SWH system, which consists of a constructed wetland/reservoir tank. It also provides an overview of the entire pre-construction process.

The water use inventory at PUJB revealed that the majority of demand is for non-potable purposes, leading to the proposal of several SWH scenarios. The optimal scenario was selected using a custom Multi-Criteria Decision Analysis (MCDA) tool. This scenario integrates non-potable uses across nine basins, utilizing Sustainable Urban Drainage Systems (SUDS) for water collection, storage, and treatment. The sizing of the constructed wetland/reservoir tank in this scenario was determined using a simplified method specific to the reservoir tank.

Preliminary findings suggest that the constructed wetland effectively reduces peak runoff and overall runoff volume, while also serving as a research platform to study biodiversity and ecological impacts on hydrological and hydraulic processes.

The developed methodologies have the potential for integration into real-time control systems, such as those used for managing sewer systems and stormwater basins. These approaches could reduce the need for extensive monitoring equipment, thereby lowering the requirements for specialized training and reducing operational costs.

Sediments collected from the CWRT system's sand traps are deemed suitable for soil remediation and revegetation on non-agricultural land, provided that the receiving soil has inferior characteristics compared to the sediments. However, due to the high concentrations of Total Organic Carbon (TOC), the use of these sediments should be limited to filling material for concrete structures and culverts in core or foundation areas. Additionally, the elevated levels of heavy metals (HM) found in the sediments make them unsuitable for agricultural use.

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