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Smart Rainwater Harvesting Service Design

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Abstract

Megacities expansion around the globe have significantly increased the demand for resources to the point of depleting available reservoirs and requiring importing resources from nearby locations sometimes implementing major infrastructure projects for guaranteeing access to resources. This is particularly true for one of the largest Megalopolis in the world, Mexico City, that imports 40% of its water supply from neighboring states. Despite of being a city holding important hydric resources, the lack of strategies, technological innovation, user-centered service design, consistent data acquiring, and optimization tools have led to a poor water management that maintains the metropolis with a constant scarcity of the resource. Therefore, the aim of the current paper is to present a conceptual service design for smart rainwater harvesting in urban settlements that provides an alternative source for citizens to reduce the local hydric stress, diminish aquifer overexploitation and increase water well recovery contributing to more sustainable cities.

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Keywords: Smart water; rainwater harvesting; resource optimization; aquifer recovery, smart service design.

1. Introduction

Current water availability, quality and access conditions around the world are worsening. Considering that water is used either directly or indirectly in every human activity and represents a pivotal resource for ensuring life, its management has not been consistent with its value. In 2015 approximately 2 billion people only had access to contaminated water and 485 thousand people died due to diarrhea caused by poor water quality access (UN Water,

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2015). Around 85% of natural wetland is lost and their natural hydrological services with them (UN, Water, 2023). Forecasts are not optimistic either, it is expected that by 2030 there will be an estimated deficit of 40% in global water (UN Water, 2020), it is also projected that some countries lose up to 6% of their GDP due to water scarcity and that 2.4 billion people, representing half of the worldwide urban population, face water scarcity in urban areas by 2050 (UN Water, 2023). Furthermore, groundwater overexploitation has increased 9 times in the last 100 years (UN Water, 2020). Considering that it is anticipated that an additional 2.5 billion people will be living in cities by 2050 and that global population will grow to 9.8 billion by that same year, higher amounts of resources will be required to fulfill just basic needs. Therefore, traditional methods, services, processes, and tools will not be enough to meet the future demands.

Although several programs and schemes have been designed and implemented successfully in Singapore, China, Australia and the United Kingdom, and technological innovations have enhanced efforts for guaranteeing hydric security, developing countries face additional challenges from problems' diagnosis to solution implementation.

As a result, the objective of the present paper is to propose a conceptual service design for Smart rainwater harvesting optimization in an urban settlement of a developing country, presenting the study case diagnosis and an optimization strategy to meet the needs from a User-Centered and Systemic perspective.

Nomenclature

d_{ij}	distance between nodes
x_{ij}	decision variable to indicate that a place was assigned to a well

2. Background

Megacities' demand for resources is increasing significantly due to the growth of population sometimes at a higher rate than urban planning or implementation of actions is. The hydric challenges that arise with the expansion of megacities specially in developing countries can only be tackled with strategies that focus on optimization of resources taking on account stakeholders' needs and the system's dynamics. Although some examples of success in this matter arise, such as Singapore's 4 National Taps program, Chinese Sponge Cities, Australian Water Sensitive Urban Design, and British Sustainable Urban Drainage Systems, it is required to implement further actions to optimize resources specially in high hydric stress places. Other initiatives have also transformed water management like Smart Water and technological advancements have also been of pivotal importance to bring innovative solutions.

2.1. The schemes

The Four National Taps program is a Singapore government's initiative to ensure water quality and availability in the country, where 60% of water supply comes from rainwater collected through special drainage systems, canals, rivers and stored in massive tanks, water is also imported from the Malaysian River Johor; nonetheless, the city relies on a special treatment process that fulfills its need during drought season, the final source is through the desalination of sea water, sometimes contributing to 25% of water supply (PUB, 2018).

Australian Water Sensitive Urban Design integrates bioinspired hydric systems with the objective of minimizing negative impacts in the water cycle while recovering natural ecosystems. Its rainwater harvesting system has been of great importance for water management in urban environments, given that this system treats rainwater on site and then delivers it where the resource is needed (Melbourne Water, 2013).

Sponge Cities was a scheme developed by China where multicriteria analysis, optimization techniques, and treatment models have been integrated for collecting the maximum amount of rain and stormwater, several systems have been developed and implemented including changes in infrastructure at large scale. This approach also models hydric administration around the interactions of the system elements, not only considering infrastructure and technology but also hydric vulnerability, climate change, economic feasibility among others (Nguyen, 2020), (Shun, 2020).

Sustainable Urban Drainage Systems focus on stormwater control by balancing infiltration, evapotranspiration, rainwater harvesting and storm water reuse mainly in urban settlements, through Nature Based Solutions and Best Practices with the aim of restoring the natural flow of water and important hydrological processes in cities. Also, this scheme has the target to set the runoff, infiltration conditions to pre-urbanization levels by building the necessary infrastructure for more efficient infiltration and evapotranspiration. Some of the systems that are implemented for this are permeable pavements, swales, rain gardens, soak ways, infiltration trenches, infiltration basins, green roofs, retention basins, wetlands and traditional rainwater harvesting systems (Raimondi, 2023).

2.2. Smart Water and technological innovations

It is of pivotal importance to use Smart tools for creating Sustainable Cities and implementing Smart Processes for a Sustainable future. That is how Smart Water comes with the aim of improving scenario planning, increase available data, enhance an efficient water use to guarantee hydric security through the application of strategies supported by technology, using tools such as the ones of Internet of Things (IoT), Data Mining, Artificial Intelligence, Complex Networks, among others. Supporting the process of decision-making with data-driven approaches that consider climatic and economic scenarios, structures, levels of influence, measuring systems among others (Raffensberger, 2017) (BSW, n.a.).

Other programs have given important support for the advancement of solutions, like the Copernicus one providing satellite information in climate status, land, surface waters, among others. Also, the Mackenzie DataStream platform shares data to allow scientists, governments, and citizens to make informed decisions according to the state of the basins (IISD, 2018).

Technological innovations have supported rainwater harvesting around the world, like the photovoltaic rainwater collection system (Guo, 2020), a self-priming root for rainwater harvesting that collects leakage and moisture in trees (Hai, 2020), a wall that collect humidity and rainwater, storing liquid at the same time (Zhu, 2019), an antibacterial nano-sponge with a strong coefficient of water absorption (Zhuang, 2021), (Trotta, 2019) and other important innovations have been pivotal for the improvement of water management.

2.3. The gap

Vast solutions have been developed worldwide in this matter; however, additional actions are required to reach the intended objectives and mitigate the effects of the hydric global crisis. While the presented solutions above have had significant results, they have been implemented mostly in developed countries and further conditions have not been taken on account for developing countries where complexity arises alongside hydric stress. At a residential and municipal level, the logistic, methodological, and technological tools are not always at the reach of stakeholders for many actions are limited. Furthermore, the adoption of Industry 4.0 tools that could bring an enhancement to water management are not yet considered in growing economies for it constitutes additional costs and implementations that are not feasible for the conditions. Optimization techniques are required to implement these smart tools strategically, reducing costs and properly monitoring the systems. As a result, this paper proposes to fill a gap through a smart rainwater harvesting service design to bring solutions to the residential sector in a developing country giving alternatives for a better resource management and optimization through an adaptative system.

3. Study case

Mexico City and its Metropolitan Zone face the titanic task to supply water to over 21 million people and several industries at the same time. The hydric needs are by far only comparable with great megalopolis as Shanghai, Beijing, New York, Tokyo, and other cities. In Mexico City different aspects convey in water management that require to be visualized from a systemic point of view to understand the magnitude of the problems and challenges that faces daily. The first aspect to take into consideration is its water importing system, while the city extracts 60% of its water from groundwater, 40% comes from the Lerma-Cutzamala System and other sources like the Barrientos Risco, Southern Waters and Chiconautla (SRM, 2013). Although the metropolis holds 13 rivers, 6 canals, 2 dams, a natural lake, various water springs, over 580 water wells with depths of 165 meters to 1 kilometer, and an average of 900 mm of rainwater per year (CONAGUA, 2018), the constant pollution of water bodies, the poor management of aquifers, the hydric demand, the lack of treatment, the cross-contamination, the deficiency of real time data and optimization tools make this city face constant scarcity despite of the available hydric resources.

Given the demographic expansion of Mexico City over the years, 25% of its population lives in a set of buildings called habitational units, where water administration can be presented in several ways. While the government regulates certain aspects, inside the habitational units the hydric resources management is in many cases performed by a neighbor committee. One location of Mexico City where a group of habitational units and an approximate of 40 thousand families live was selected due to the similar conditions that can be found for a quarter of the population of the metropolis, furthermore this complex is supplied by 4 different water wells. In this location water scarcity is a familiar subject, according to a diagnosis performed by the authors through a simulation and other methods, during the year the study case presented water cuts of 4 to 36 hours, having a yearly consumption of almost 4 million cubic meters (Ramos, 2022). The causes for which these water cuts were present is shown in Figure 1, where water scarcity in the wells, leakages and energy fails could represent important reasons for cutting off the supply. In this case several problems are visible such as the high vulnerability of the system due to its unique water source, the resource management biased by lack of information and real-time data, technological tools, knowledge, and optimization techniques, also the amount of water consumed and extracted from a single source (the water wells), the aging piping system originally constructed in the decade of 1970, the leakages and other major problems.

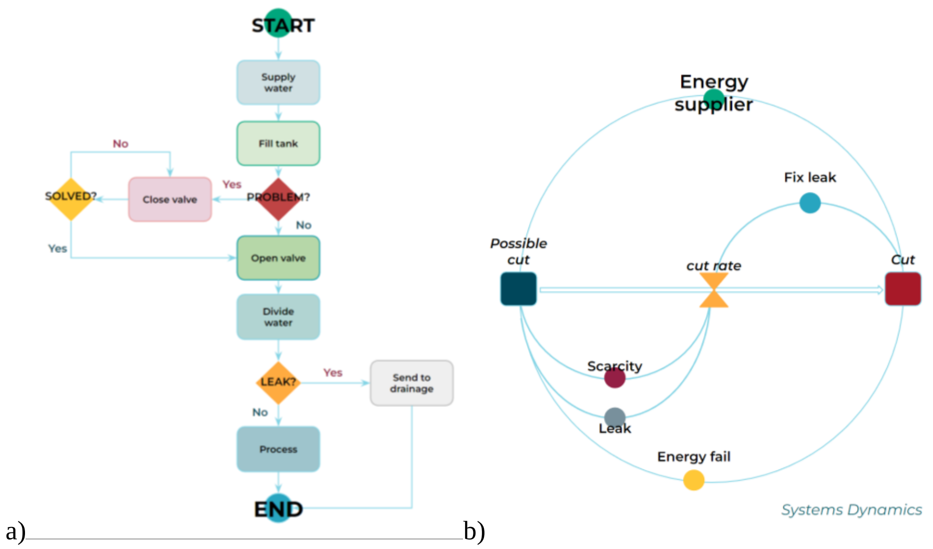

Fig. 1. (a) Process without rainwater harvesting; (b) Systems dynamics of the process without rainwater harvesting.

4. Proposal

The Mexican Institute for Competitivity assures that a house with a roof of 120 square meters in a high precipitation zone such as the one of the study case, could collect an approximate of 128 thousand liters per year (IMCO, 2017). Given that the roofs considered for this study have an area of 400 square meters for water harvesting, one system could collect approximately 426 thousand liters, that without receiving any special treatment could supply water for activities such as car washing, green areas irrigation, WC discharge, and other actions that wouldn´t require a specific water quality. According to the Environmental Protection Agency in the U.S. WC discharges represent 30% of water consumption at a residential level (EPA, 2015), for the implementation of a rainwater harvesting system just for the purposes highlighted before could represent a significant improvement in lowering the water well stress of the zone.

Considering the circumstances and potential of the study case a concept of a rainwater harvesting service was designed, using optimization techniques and methods to gather data for an effective rainwater collection, treatment, storage, and distribution. The aim of the proposal is to provide alternatives for different scenarios of precipitation and water usage setting strategic places for installing collection and monitoring devices for adaptative smart rainwater harvesting systems with the possibility of fulfilling residential hydric needs and to recover water wells.

The proposal for this study case is designed to meet the demands of 8 different sections of the residential complex that considers 160 buildings, 20 in every section as potential place through Greenfield Analysis (Ivanov, 2021), as shown in Figure 3, to locate rainwater collection systems. It is important to highlight the most relevant aspects for the conceptual proposal which are collection, storage, treatment, management, and smart components.

1. Collection: Rainwater is collected through different methods, from traditional water systems to some others regarding nanomembranes and non-traditional configurations.
2. Storage: Depending on the needs of the stakeholders, water could be stored in on site traditional tanks, the main cistern, or directed to recover the nearest water well, depending on the amount of water collected.
3. Treatment: According to the desired use of water, the level of treatment would be recommended, for this particular proposal, it was considered a light treatment for on site storages and a non-potable requiring activities, for general use of water, a treatment plant would be built next to the principal cistern depicted by a star in Figure 3, another alternative would be having a treatment facility in every collecting system in order to use the water for general matters within every section.
4. Management: Rainwater storage and treatment would also depend on the type of management and use of the resource, whether it is used for community purposes or to meet just the building needs.
5. Smart components: Once knowing the ideal sites to harvest, store and treat water and all the possible configurations that could be set according to the aspects highlighted, sensors and controllers would be set in those places to fix the desired configuration or a configuration according to the needs, whether the capacity of the storage or treatment systems would be surpassed and the water would need to be directed towards the water wells, or the main cistern instead of supplying to one section. A whole control system would be required to automate the configurations and the process of water collection. Also, the data collected would be of great importance to determine water usage and create simulation scenarios based on real-time information.

The service concept takes on account these aspects, bringing a solution according to the volume of precipitation, usage, or hydric demand, where the system selects the type of collection, treatment, storage, and distribution. The sensors supply real time information for choosing the configuration that will utilize resources more efficiently, reducing waste and lowering stress to groundwater. As shown in Figure 2, it is possible to select from individual collection or community harvesting. The first arrangement treats, stores, and distributes on site, for meeting the building hydric needs, the treatment can be configured in light or heavy mode for different usage purposes such as WC discharges, cleaning, car-washing for a light treatment or heavy for usages that require a higher water quality, this can be selected by the user or be set in automatic from a smart integrated system.

The second arrangement is for community harvesting where a single building can collect rainwater for other buildings, treating on site and directly distributing to other buildings such as depicted in Figure 3, also serving these collecting buildings as ideal places for monitoring systems to operate. The same arrangement can select another configuration for high volumes of water where every building can serve as a collector and pump the harvested water to a distribution building that connects with the principal cistern that gives service to the 8 sections and 160 buildings, as shown in Figure 4, every section has 2 main edifices connected to the principal tank. The treatment could be effectuated either in wetlands or in a treatment plant located near the main cistern so the rainwater can meet the required quality for all-purpose usage and be integrated to the main hydric network, consequently reducing groundwater exploitation.

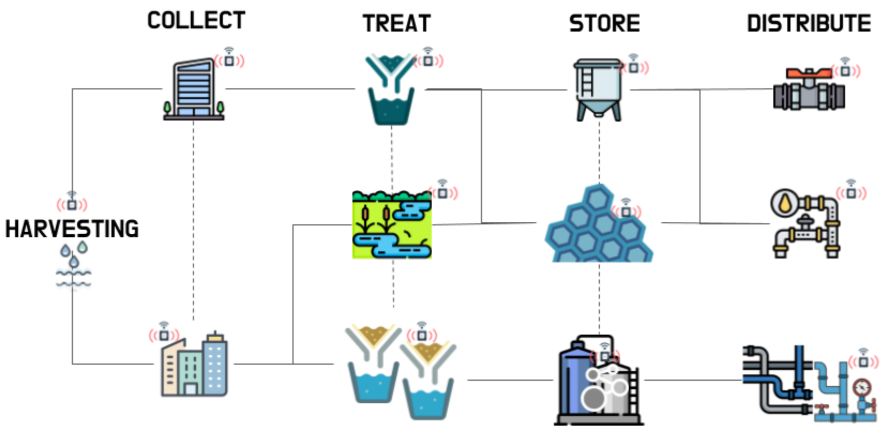

Fig. 2. Proposal scheme.

Given that in occasions the precipitation volume goes beyond the available storage and the capacity of the treatment facilities, an alternative is described in Figure 5 where three strategic buildings would pump the collected water to infiltration or absorption wells symbolized by letter P, to recover groundwater, treatment being naturally effectuated through the soil.

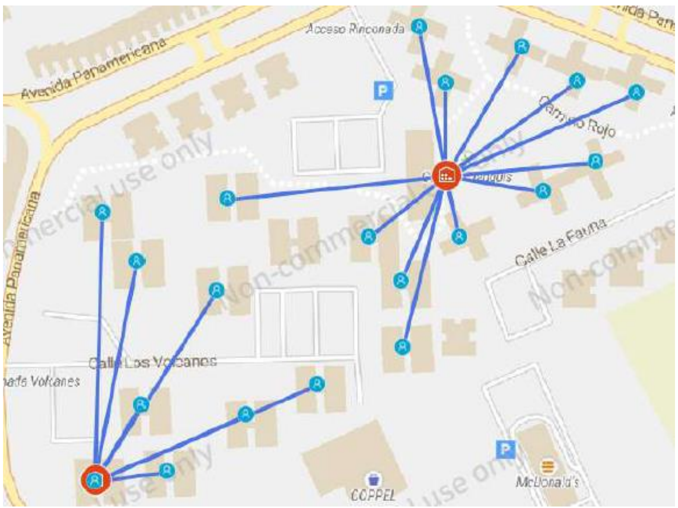

Fig. 3. Greenfield Analysis to determine the buildings where collection and monitoring systems would be set in one of the sections.

Optimization tools were implemented to determine the ideal sites according to the amount of people or buildings it would serve. Also minimizing the distance among buildings Equation 1, and the ideal paths for delivering harvested water to the main cistern where water would be treated and delivered through the existing piping system, as shown in Figure 3. Equation 1 has the objective of minimizing the distance between nodes d_{ij} and x_{ij} the designated well that would be recovered according to the distance from the collection site to the nearest well as depicted in Figure 4.

$$Min\ Z = \sum_{i\epsilon I, j\epsilon J} d_{ij} \cdot x_{ij} \quad (1)$$

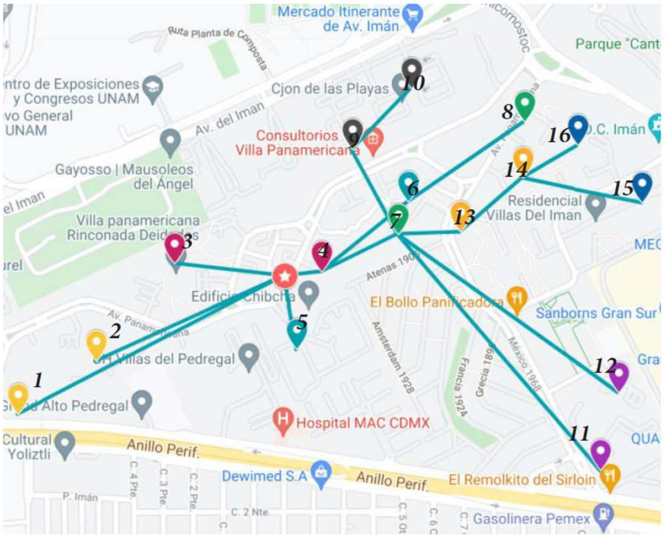

Fig. 4. Ideal sites to catch and deliver rainwater from every section to main cistern.

A pivotal part of the proposal is to recover existing water wells through infiltration wells and canals that would be built near the extraction wells, given the natural treatment that rainwater would receive through the soil and the infinite storage that the soil represents, this would constitute a possible solution to diminish hydric stress in the zone. It is important to note that according to the measurements.

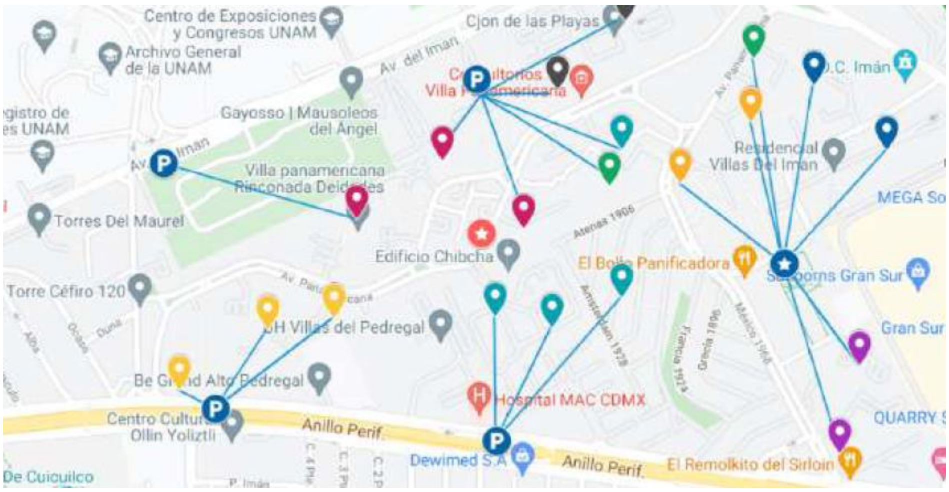

Fig. 5. Ideal sites to catch and deliver rainwater from every section to the nearest water well.

Finally, it is of great importance to highlight that the conceptual service proposal is adaptative and individual or community harvesting can be performed at the same time according to the needs, circumstances and conditions of the system.

4. Conclusions

The present paper proposes a conceptual service design for smart water harvesting, through an adaptative system that optimizes distances and resources according to the volume of precipitation, water usage, demand and needs. By locating collection and monitoring systems in strategic sites it is possible to collect, treat, store, and distribute water more efficiently. Not only does the strategic location represents an operational advantage but it is of great importance for managing information and making data-based decisions.

This rainwater collection service has the intention to reduce aquifer overexploitation and mitigate the effects of the existing crisis, providing an additional source for urban settlements in Mexico City. Although the conceptual service was designed for a particular place of Mexico City, this solution could be used in different megacities of developing countries around the world.

Given the urgent need to diminish surface and underground water overexploitation, additional sources of water are required, and the objectives can only be met through the correct implementation of smart tools, services, and technology accompanied by optimization techniques and algorithms to solve problems. Smart adaptative solutions are urgent to face the challenges caused by the global hydric crisis.

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