Section 1

Basic Concepts

I. The importance of rainwater catchment systems

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I.1 History of rainwater catchment systems

Rainwater harvesting (RWH) has been present in cultures since ancient times, as a vital activity that required specific technical expertise and social organization. Harvesting rain for domestic or agriculture was a way of life. There are records that in the ancient city of Byblos in Lebanon approximately 4900 years ago, it had an efficient sewage system, storage, and catchment of rainwater (Fernández Pérez, 2009). By the year 1000 B.C. on the Arabian Peninsula, in the upper areas of Yemen, buildings and temples had courtyards and terraces that facilitated the catchment and storage of scarce rainwater (Ballen *et al*., 2006).

The Roman culture implemented functional rainwater harvesting systems in their houses (Fernández Pérez, 2009). In the early stages, the Romans used a pool close to the springs named *lacus*, when these pools where underground they were called cisterns. Later, in the *domus* or Roman house it was articulated around inner courtyards. The central *atrium* was open to the sky, where the rainwater from the roofs was guided to a central pool (*impluvium*) for use and storage in the house. As a result of urbanization and the growing population, the consumption of water increased. This led to the development of covered cisterns. These cisterns were

Editor(s): José Arturo Gleason Espíndola, César Augusto Casiano Flores, Raul Pacheco-Vega
and Margarita Rosa Pacheco Montes
doi: 10.2166/9781789060584_0003

built in the ground underneath the courts with two significant advantages: firstly, the amount of water which could be stored increased considerably and evaporation losses reduced; and secondly, the cisterns served as a protection against water pollution (Ballen *et al*., 2006).

The order of Caesar Justinian constructed one of the biggest cisterns of the world with a capacity of 80,000 cubic meters and measures of 140 by 70 meters. After the Roman Empire fell and with the arisal of new cultures like the Muslim culture, new ways of life and water management emerged.

In the arid regions of Iran, agricultural and permanent settlements were supported by the ancient *qanat* system of tapping alluvial aquifers at the heads of valleys and conducting water along underground tunnels by gravity, often over many kilometers (UNESCO, 2016).

Each qanat comprises an almost horizontal tunnel collecting water from an underground water source, usually an alluvial fan, into which a mother well is sunk to the appropriate level of the aquifer. Well shafts are sunk at regular intervals along the route of the tunnel to enable removal of spoil and allow ventilation. These appear as craters from above, following the line of the qanat from a water source to agricultural settlement. The water is transported along underground tunnels, called *koshkan*, utilizing gravity with the gentle slope of the tunnel to the exit (*mazhar*), from where channels distribute the water to the agricultural land of the shareholders (UNESCO, 2016).

In ancient Israel, the genius of human creativity is represented in Masada by its sophisticated water system. This system transformed a barren, isolated natural fortress set in an arid, dry climate (less than 50 mm yearly rainfall and without natural resources) into a lavish royal retreat with grand, classic bathhouse, two large swimming pools, and ample water supply. Masada's system utilized run-off water from one rainy day to sustain life for up 1,000 people for 2–3 years (UNESCO, 2000).

This water system was so accurately designed and executed to capture run-off water in such a desert climate. On the mountaintop, gutters and canals diverted water from roofs and unbuilt areas into small pools and grand cisterns. These cisterns also received run-off water from flash floods of riverbeds west of Masada.

Approximately 2000 years ago, an elaborate water harvesting system developed in the hinterland of the ancient capital Anuradhapura in Sri Lanka. This system allowed the collection, storage, and distribution of rainfall and run-off to supply a growing population with food under the semi-arid climatic conditions. The *Wewas* are reservoirs and the cornerstone of a highly sophisticated water harvesting system.

I.2 Rainwater harvesting in Mesoamerica

In Mesoamerica, water symbolized the generator of the development of local civilizations. The establishment of the first civilizations with seasonal agriculture made the cultures in Mesoamerica masters of irrigation techniques, including rain and stormwater irrigation systems, as is evidenced in various archeological investigations. The Mesoamerican cultures took advantage of the rainwater through natural or artificial ways, where they captured and retained water for the population.

The Mayan culture was a great manager of its water through the use of *Chultuns* in all Mayan regions, and was able to capture and distribute rainwater for agricultural and human consumption. Chultuns were underground excavations waterproofed with gesso used since the pre-classic period (Ballén Suárez *et al.*, 2006).

In some cities of the Olmec culture can be found the oldest vestige of rain- and stormwater management in Mesoamerica: La Venta (now Tabasco, Mexico) used sewers and stone channels, and San Lorenzo (Veracruz, Mexico) used mud pipes and underground aqueducts of carved basaltic stone, joined with a mix of chapopote (Rojas, 2009).

On the other hand, the city of Tenochtitlan, founded in 1342, was not only the greatest achievement of Mesoamerican hydraulic engineering, but one of the greatest in the history of ancient man. The city constituted itself as a challenge of political and social organization, where the catchment of rainwater was vital for the operation of a higher self-sustainable city. Tenochtitlan was founded on a basin with a system composed of lakes, rivers, lagoons, and swamps, fed rain, permanent and semi-permanent rivers, as well as springs. Tenochtitlan was surrounded by water all the time. It required an overwhelming effort of hydraulic engineering and colossal construction work to sustain and maintain the necessary hydraulic infrastructure (Gutierrez, 2014). With the arrival of the Spanish conquerors, these techniques were complemented and in many cities replaced the traditional pre-Columbian rainwater harvesting systems.

The Spanish techniques introduced by the conquest allowed better excavation of cisterns and deeper wells with the use of the pulley, the wheel and the lathe. This resulted in a more efficient extraction of water. Colonial houses had pools as a means to contain the rainwater, while sanctuaries, convents and churches built reservoirs to store the water driven by pipes from the roofs (Rojas, 2009, p. 20 and 22).

Rainwater harvesting in barrels, pots, reservoirs, and wells was a typical system, which lasted in some places until the beginning of the 1970s, such as Merida, Zacatecas, and Guanajuato. However, in the current situation of worldwide water scarcity, it would be worth re-examining old techniques and taking advantage of what new water management and rainwater harvesting techniques bring to achieve sustainable communities and cities.

Throughout the Andes, the Incas built a series of dams that, by their location, are called Altoandinas, whose function was to store rainwater and then use it during the dry season. The Amunas is an ancestral practice to recharge aquifers. This practice consisted of a ritual that involved assemblies, cleaning of ditches, and, above all, reverence of water.

The system worked with open ditches that followed contours lines, allowing the rainwater to gather in cochas (pools), which were open, and then the water filtered into the mountain.

The water emerged downstream as puquios (underground aquaducts) months later and during the dry season, when sewage was more marked in the basin, they were used for agriculture. This kept the people provided with food (Ancajima, 2014).

I.3 Recent efforts of rainwater harvesting around the world

For thousands of years, collecting rainwater was a standard method for providing water. Over the last century, wells and municipal water supplies took over as primary water sources. However, in the past 40 years, there have been several attempts to create a new rainwater culture around the world. In the early 1980s, a pioneer in rainwater harvesting, Makoto Murase, designed a water recovery system. The system collects, filters, and stores rainwater in sizeable underground holding tanks, easing flooded sewers and providing a resource used for irrigation, toilets, washing, and drinking (Strauss, 2016).

Nowadays, over a thousand Tokyo buildings harvest and recycle rainwater, since the system installed in Tokyo's Sumo Stadium proved so successful that the city eventually required underground rainwater tanks for all new buildings.

In 1989, after the *4th International Rainwater Cistern Systems Conference* in Manila, the International Rainwater Catchment System (IRCSA) was founded. IRCSA aims to promote rainwater catchment systems planning, development, management, science, technology, research, and education worldwide and has established an international forum for scientists, engineers, educators, administrators, and those concerned in this field. IRCSA drafts international guidelines on this technology and updates and disseminates information, as well as collaborating with and supporting international programs (IRCSA, 2013).

After the formation of the international foundation, different countries started to create Rainwater Associations to promote sustainable rainwater harvesting practices, such as the American Rainwater Catchment Systems Association (ARCSA). ARCSA efforts include: creating a favorable regulatory atmosphere, creating a resource pool and educating professionals and the general public regarding safe drinking rainwater design, installation, and maintenance practices.

Every year communities all around the world are attempting to cope with water scarcity and floods. Therefore, to promote rainwater harvesting as an effective and sustainable solution for water shortages and to prevent natural hazards, including floods and droughts from weakening the resilience of communities and the ecosystems upon which they depend, in 2002, The International Rainwater Harvesting Alliance (IRHA) was established in Geneva. IRHA develops projects that reinforce the resilience of communities and restore ecosystems through better management of rainfall and run-off (IRHA, 2017).

Climate change projections raise concerns over changes in temperatures and rainfall patterns and, ultimately, over water supply to communities. Historically, following periods of drought or water shortage, rainwater is beneficial to provide drinking water to communities all around the world. In Australia, the Millennium drought left cities such as Melbourne a year away from running out of the water with extremely low dam levels. The drought was broken by a period of intense rainfall, where cities like Brisbane suffered major floods that caused billions of dollars worth of damage. Townsville suffered extreme monsoon conditions with dams reaching more than 200% capacity and triggering floodgates to open, causing flooding for thousands of residents. Therefore, Australia is transforming urban areas to ensure longterm liveability, sustainability, and resilience in the face of climate change and population growth through adaptative infrastructure, innovative and strong economies (Rogers & Hammer, 2019).

Urban Rainwater harvesting in those affected regions has dual benefits, supplementing municipal water supply and the potential to improve urban stream hydrology by capturing, consuming, and effectively removing excess urban run-off (Taylor & Brodie, 2016). Rainwater tanks are encouraged and being installed in urban areas, resulting in an increase resilience of cities to droughts and a reduction of mains water demand (van der Sterren *et al*., 2012).

Rainwater harvesting for domestic use is a prevalent practice in islands such as Thailand, the Caribbean, Hawaii, etc., particularly in areas not served by municipal water. In 2010, an estimated 30,000 to 60,000 people in Hawaii were dependent on rainwater catchment systems to satisfy their water needs (Donohue *et al*., 2017).

II. FUNDAMENTALS OF RAINWATER CATCHMENT SYSTEM

Rainwater harvesting is a technique of collection and storage of rainwater into natural reservoirs or tanks, or the infiltration of surface water into subsurface aquifers (before it is lost as surface runoff). One method of rainwater harvesting is rooftop harvesting. With rooftop harvesting, almost any surface (tiles, metal sheets, plastics, but not grass or palm leaf) can be used to catch the flow of rainwater and provide a household with high-quality drinking water all year-round. Other uses include water for gardens, livestock, irrigation, and industrial supply.

A rainwater harvesting/catchment system consists of seven phases for proper functioning (See Figure S1.1):

(1) Catchment area

The catchment area is generally roofs, patios, garages, asphalted roads, or any non-permeable surface where rainwater flows and collection is feasible. Catchment areas need to have a slope that allows the water to flow directly to the gutters or downspouts for its conveyance.

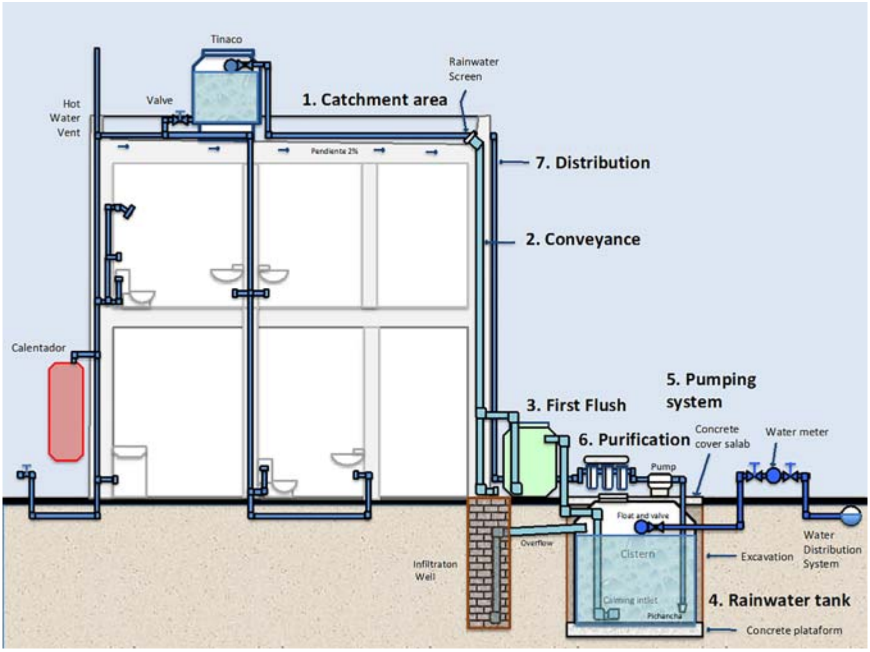

Figure S1.1 Rainwater Catchment Systems Components. *Source*: Authors.

The catchment area can be composed of many materials such as cement, metal, fiberglass, plastic, roof tiles, etc. Some elements can generate water losses or release toxins, so it is noteworthy to consider the material for the catchment area.

(2) Conveyance system

The conveyance system includes the set of gutters or pipes that drive rainwater from the catchment area to the storage system. Gutters and downspouts must be in accordance with the requirements of the system and the characteristics of the building. The roof, gutters, and downspouts should be durable, sized correctly, and accurately placed in the building where they will be used (Kniffen, 2012).

(3) First flush

The first flush diverter is designed to hold the water from the first rains of the season. The first flush diverter keeps the first flow of poor quality roof runoff from entering the tank. Diverters must have a drainage outlet for emptying standing water and be emptied as needed. This device is especially needed when trees and birds are close to the catchment area and depends on the catchment area size.

Additionally, to keep the water clean, prevent clogging, and sediment build-up, basic filtration is required. Before the water goes to the storage tank, it is necessary for a leaf screen, so the water inside the tank is as clean as possible.

(4) Water storage tank

The water storage is the equipment that stores and protects the water. A water tank needs to consider price, size, aesthetics, and/or water use. The tank capacity is determined by supply and demand.

Rainwater tanks need at least three connections: (a) a water inlet with optional turbulence calming device to prevent remixing of sediment; (b) an overflow inlet located below the water entrance level; (c) pipe to the pump and pressure tank; and optionally a connection to municipal water/make up water.

Considerations for rainwater tanks should include the following: above ground-tanks should be UV resistant to prevent sun damage; mosquito and animal-proof tank-access points – microbial insecticide specific to mosquito larvae can be used; overflow should be directed to a useful area, away from tank foundations, buildings, and toward plants or another tank; and any tank used for underground storage must be rated for this use.

(5) Pump system

The pumping system distributes the water from the storage tank to the places of use. It should be noted that the suction pipe of the pump must be at least 50 cm above the bottom of the tank to prevent sediments (Palacios, 2010). The pump needs to have enough power to send water through the filters and to the place of use.

(6) Filtration

This is the purification process to which rainwater is subjected to guarantee a certain quality, so it meets the necessary conditions for its use. The purification process depends on water use. When rainwater is used for human consumption, three filters are required: polypropylene, carbon block, and UV light.

(7) Distribution

Once the rainwater has the quality needed for its required use, it can be distributed to where it is needed. Commonly, the rainwater distribution system is separated from the municipal water supply system. Therefore, there will be two distribution networks. Usually, the rainwater distribution pipes are painted purple in color to differentiate between networks. The rainwater is consumed for different purposes, mainly human, domestic, industrial or agricultural uses.

This book aims to present different experiences of systems installed at homes, buildings, and roofs. To learn more about other forms of rainwater harvesting and use, the following are recommended reading.

- *Harvest the Rain. How to enrich your life by seeing every storm as a resource*, Nate Downey (Ed) (2010) Sunstone Press, Santa Fe, New Mexico.

- *Rainwater Harvesting Manual* 1st edition, Ann Audrey (Ed) (2015) ARCSA, Tempe, Arizona.
- *Rainwater Tank Systems for Urban Water Supply. Design, yield, energy, health risks, economics, and social perception*, Ashok K. Sharma, Donald Begbie & Ted Gardner (2015) IWA, London, UK.
- *Designing Rainwater Harvesting Systems. Integrating rainwater into building systems*. Celeste Allen Novak, Edward Van Giesen & Kathy M. DeBusk (2014) Wiley, New York.

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