FEASIBILITY OF RAINWATER HARVESTING IN US

Jong-Jin Kim[1], William Laughner[1]
[1]Taubman College of Architecture, University of Michigan, Ann Arbor, Michigan
[2]College of Engineering, University of Michigan, Ann Arbor, Michigan

ABSTRACT: This paper assesses the climatic feasibility of water self-sufficiency of buildings that employ rainwater harvesting. The feasibilities of standard single-family residential buildings that employ rainwater harvesting in thirteen cities that represent a range of climatic regions across the continental U.S. were assessed. Using the water consumption data published by the United States Geological Survey (USGS) and the American Water Works Association (AWWA), the quantities of current water consumption in typical American households with the average population of 2.58 residents were analyzed. Using the NOAA 30-year average precipitation data, the volumes of rainwater that can be harvested from the rooftop catchment areas of standard two-story single-family homes in the test-bed cities were estimated. Comparing the volumes of water consumption and harvested rainwater, the water self-sufficiencies of the test homes were analyzed. Our analyses revealed that, with the current level of water consumption, rainwater harvesting can supply up to 33% of the total water demand and of typical homes in the Southeast subtropical region. In the arid Southwest, rainwater harvesting can meet less than 5% the domestic water demand even in rainy months. However, when rainwater is used for indoor uses only, rainwater harvesting can supply a higher fraction of residential water demands. Supplemented by rainwater harvesting, conservation through the incorporation of water efficient technology and change in resident behaviors is instrumental for enhancing buildings' water self-sufficiency.

KEYWORDS: Rainwater Collection, Water Self-Sufficiency, Water Conservation

INTRODUCTION

Rainwater collection provides multiple benefits: an alternative method to increase a building's water self-sufficiency, to reduce reliance on municipal treatment plants, and to reduce stormwater runoff. In recent years, rainwater harvesting has reemerged as an alternative onsite water procurement method. Many large commercial buildings are equipped with rainwater harvesting systems not only to lessen the reliance on municipal water but also to mitigate detrimental environmental harms associated storm-water runoffs. However, it is uncertain how significant a role rainwater harvesting can play in attaining a building's water self-sufficiency. What fraction of domestic water demands can be met by rainwater harvesting? How much the climates affect rainwater harvesting in various US regions? **What are architectural strategies for achieving zero or near-zero external water buildings?** This paper examines these questions pertaining to rainwater harvesting and strategies for water self-sufficient buildings.

1.0 RESEARCH OBJECTIVES

This study assesses the water-self-sufficiency of residential buildings that utilize rainwater harvesting in the US. One of the key research questions is how a region's climate affects its rainwater harvesting prospect. Specifically, how much rainwater harvesting can contribute to the water self-sufficiency of single-family homes across the United States.

1.1 Test Building and Climatic Regions

A typical American single-family residence is a two-story home with a total floor area of 2,000 ft2 (American Housing Survey, 2005). This study used a standard two-story residential building with 1,000 ft2 for each story. The home was assumed to be occupied by a population of 2.58 residents, which was the average population of American households (US Census Brief, 2010). The test building has a flat roof with no eaves or overhangs. The rainwater catchment area is 1,000 ft2. The collection efficiency of rainwater harvesting was assumed to be 30% that takes into account the various water losses in the process of harvesting. It was also assumed that the test homes were equipped with cisterns. All rainwater collected in rainy periods was assumed to be stored for consumption in dry periods. In order to evaluate the impact of the climatic variation on rainwater harvesting in the thirteen cities, each of them representing diverse climates of the continental U.S. including humid, dry, hot, cold, and various combinations, were selected.

2.0 RESEARCH METHOD

This paper defines water self-sufficiency of a building as the ratio of the volume of water collected on site to the volume of water consumption by its residents. The roof was assumed to be the sole catchment area of the building. The volume of rainwater harvested from a catchment area is a linear function of three factors: precipitation, horizontal footprint of catchment area, and the collection efficiency of rainwater harvesting systems. Harvested rainwater volume, thus can be estimated by the multiplication of precipitation, catchment area and collection efficiency.

2.1 Precipitation data
The volume of rainwater harvested was estimated based on the 30-year average annual and monthly precipitation data published by National Oceanic and Atmospheric Administration (NOAA, 2016). Among the thirteen test locations, Miami shows the highest precipitation of 160 cm per year, while Las Vegas was the lowest with a 10 cm of rain annually. Houston, New York, Chicago and Seattle are relatively wet cities, while Phoenix, Boise, Los Angeles and Denver are dry cities (See Figure 1).

2.2 Household water consumption
The per capita domestic water consumptions in the 13 regions of the U.S. were calculated using two sets of county-by-county data: 1) domestic water consumption and 2) population data published by the United States Geological Survey (USGS, 2016). The annual county-by-county domestic water consumption data were divided by the corresponding population to obtain the annual per capita residential water consumption. The household water consumption was then calculated by using the per capita water consumption by the number of residents per household.
The domestic water consumptions of most cities analyzed in this study range from 200 liters (52.6 gal) per capita per day to 350 liters (92.1 gal), the average being approximately 300 liters (approximately 80 gallons), which is in conformity of data published US government agencies (USGS, 2010). Two distinct anomalies are Phoenix and Las Vegas, cities in the Southwest Desert, whose water consumptions are approximately 600 and 900 liters (158 and 237 gal)/persons/day respectively (See Figure 1). The water consumption in these desert cities are about two to three times of other cities. One might presume that residents in dry climates would spend water more parsimoniously, while those in wet regions would consume water more thriftlessly. However, the water consumption data shows that this is not the case. According to the residential water end use survey conducted by the American Water Works Association (Mayer, 1999), indoor water consumption is generally uniform regardless of climate. However, outdoor water use is highly variable with climate and the lifestyle of residents. This is due to residents in dry climatic regions using more water in landscape irrigation, swimming pools and decorative purposes (Inskeep 2014).

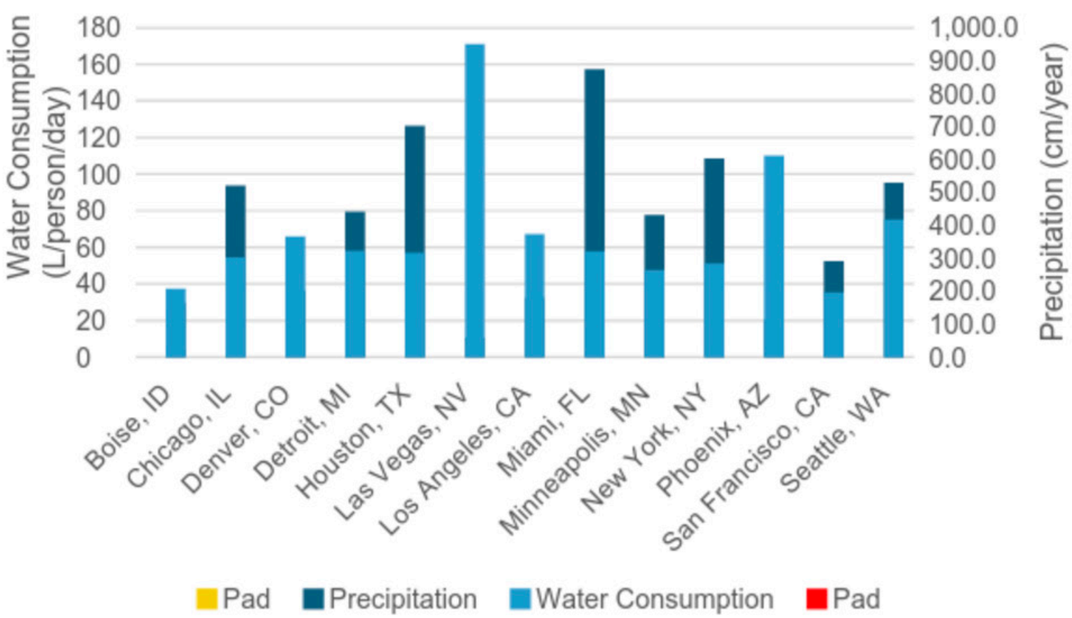

Figure 1: Daily per capita water consumption and precipitation of the 13 cities

3.0 ANNUAL WATER SELF-SUFFICIENCY
On an annual basis, rainwater harvested from the rooftops can meet only varying fractions of the total household water consumption (See Figure 2). In the rainiest region of Miami, rainwater harvesting provides 34% of annual household water consumption, followed by Houston with 27% and New York with 26%. In arid cities, rainwater harvesting supplies can meet a small fraction of household water demands: 5% in Los Angeles, 2% in Phoenix and 1% in Las Vegas. Note that the test-bed buildings in this analysis do not have any eaves or shading devices that are typically present in single-family homes. When the roof catchment area is enlarged by extending eaves, water self-sufficiencies of homes will certainly be higher.

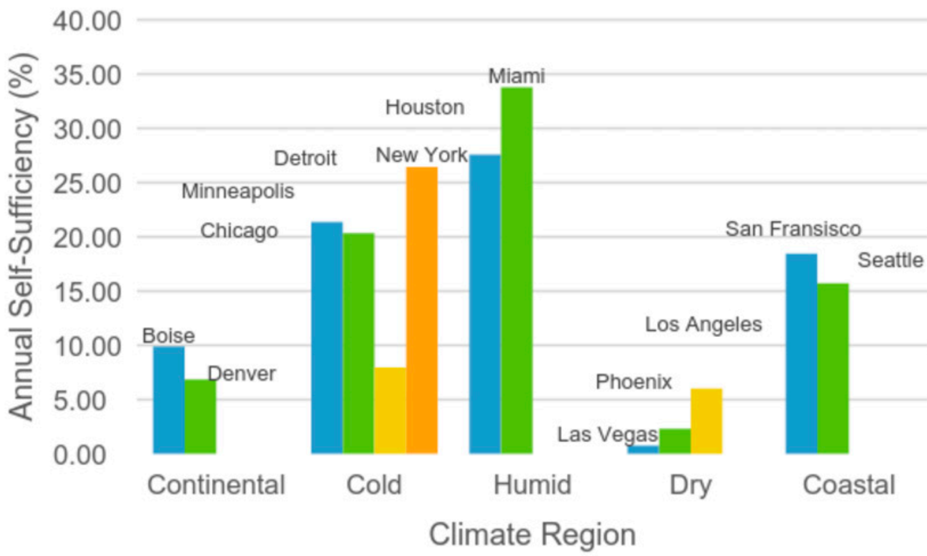

Figure 2: Annual water self-sufficiency of single-family homes in 13 US cities

4.0 MONTHLY WATER SELF-SUFFICIENCY

In most regions of the world, precipitation fluctuates during the course of a year. Some regions have rainy months in summer, while others experience more precipitation in winter. Thus, the seasonal water self-sufficiency of homes that utilize rainwater harvesting varies during the course of a year, and depends largely on the particular climatic patterns.

4.1 Southeast and South Central Regions

The Southeast and South Central regions from Houston to Miami are the most rainy regions in the US, and rainwater harvesting is most feasible in this region. In Miami, a distinctive seasonal disparity of water self-sufficiency exists. During the summer from May through October, the water self-sufficiency ranges from 35% to 65%, while in wintery months, November to April, the water self-sufficiency varies from 10% to 20%. In Houston, with the exception of June and October, the monthly water self-sufficiency is relatively monotonous in the range of 20% to 30%. This uniformity is advantageous in cistern sizing, i.e., a smaller cistern can be utilized throughout the year. While in Miami, a large cistern that is required to harvest high volume of rainwater in summer that is underutilized in winter (See Figure 3).

4.2 Pacific Northwest and Northern California Regions

In the Pacific Northwest and Northern California regions, rainwater harvesting is highly variable with season (See Figure 4). Precipitations are high in winter months from November to March, with little or no precipitation in the summer months. In San Francisco, rainwater harvesting provides over 40% of the total water demand in December through February, while in May through September the water self-sufficiency is less than 10%. In particular, during June through September, rainwater harvesting can meet the total water demands of homes in San Francisco less than 5%. Seattle shows a similar pattern of seasonal disparity in water self-sufficiency, but in a lesser degree. From October through March, water self-sufficiency of homes in Seattle's is over 20%, while in May through September, it is less than 10%. In order to mitigate rainwater shortage in summer, maximum amount of rainwater should be harvested and stored in winter. And water conservation strategies to reduce water demands in summer must be developed.

4.3 Mountain regions

In the Mountain regions as representative in Denver and Boise, water self-sufficiencies of the test homes are less than 15% throughout the year. In Boise, Similar to Seattle, precipitation is high in wintery months and low in summer. On the other hand, in Denver water self-sufficiency is high in summer and low in winter. In Boise, during November through May, water self-sufficiency is approximately 15%, while In June through September it ranges from 2% to 8% (See Figure 5).

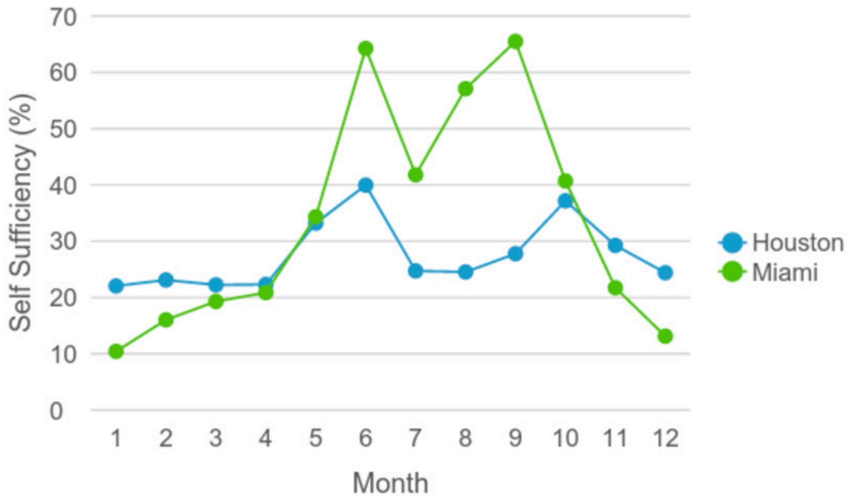

Figure 3: Monthly water self-sufficiency of test single-family homes in Southeast and South Central regions.

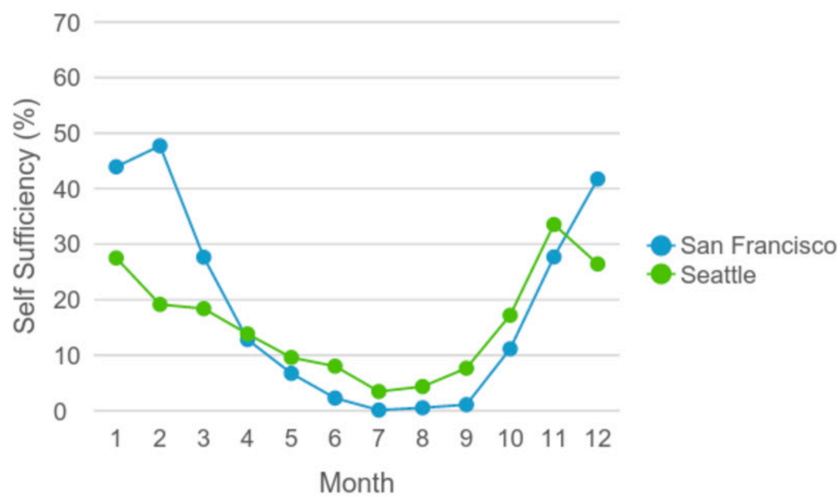

Figure 4: Water self-sufficiency of test single-family homes in Pacific cities.

4.4. Northeast and Mid-Western regions

The pattern of seasonal water self-sufficiencies in Northeast and Midwestern cities is similar, higher in summer and lower in winter (See Figure 6). However due to its proximity to the Atlantic Ocean, in the Northeastern region, higher precipitation is available nearly throughout the year. The water self-sufficiency in New York is the lowest in February at 20% and highest in July at 30%. This uniformity of seasonal water self-sufficiency has an advantage of rainwater cisterns being utilized near full capacity throughout the year. In the Midwestern region such as Chicago, Detroit and Minneapolis, water self-sufficiencies are high in summer and low in winter. This seasonal disparity is more pronounced in inner continental cites such as Minneapolis than Detroit. In Minneapolis, the water self-sufficiencies are 7% to 10% from December through February, but are higher than 25% in May through September.

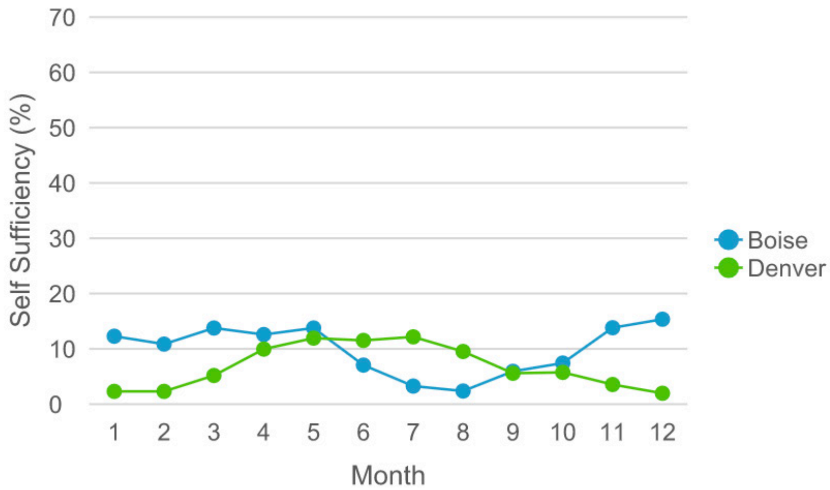

Figure 5: Water self-sufficiency of test single-family homes in in the Mountain Regions

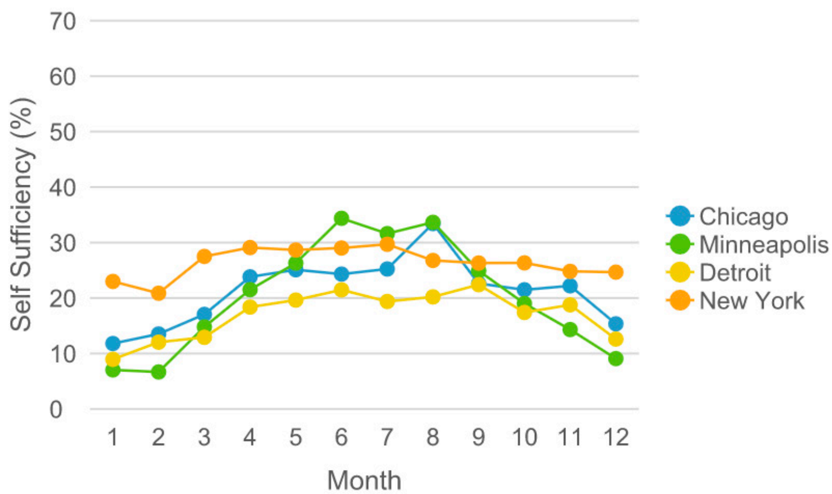

Figure 6: Water self-sufficiency in Northeast and Midwestern cities.

4.5. Southwest Desert Regions

As expected for desert climates, water self-sufficiencies of the Southwest regions are the lowest in the US (See Figure 7). Due to the proximity to the Pacific Ocean, the water self-sufficiencies of Los Angeles are higher than two other test cities: Phoenix and Las Vegas. In Los Angeles, the water self-sufficiencies during December to March are relatively higher than other months, ranging from 10% to 20%. Because water is more precious in arid regions, rainwater during the wet season in the city should be regarded as valuable natural resources to be harvested. In Phoenix and Las Vegas, the water self-sufficiency was less than 5% throughout the year. Here it should be noted that the low water self-sustainability in these two cities is due to not only low precipitation but also high water consumption. The per capita residential water consumption in Las Vegas is about three times higher than that of average American cities and Phoenix two times. The high water consumption in these desert cities is ascribed primarily to outdoor uses such as landscape irrigation and swimming pools. Accordingly, in arid regions, water conservation must be a higher priority strategy for enhancing the water self-sufficiency of residential buildings.

5.0 INDOOR WATER SELF-SUFFICIENCY

Water uses in single-family homes can be categorized in two types: indoor and outdoor uses. Outdoor water uses in American homes include primarily irrigation for gardens and lawns and swimming pools. According to a study conducted by the AWWA Research Foundation, the volume of indoor water uses per capita in America is, by and large, very uniform regardless of climatic regions. However, outdoor water uses vary significantly depending on the climatic regions. The high domestic water consumption in the cities in the American Southwest, Las Vegas, Phoenix and Los Angeles, are due primarily to outdoor uses. Garden and lawn water uses can be reduced or avoided by incorporating water conserving landscaping methods such as indigenous landscaping, xeriscaping, or drip irrigation.

Outdoor water use can be characterized as non-essential, while indoor water uses are essential. In order to assess how much rainwater harvesting can meet essential indoor water demands of residential buildings, water self-sufficiency of single-family homes that excludes outdoor water uses was conducted. Figure 8 shows the fraction of "indoor" water uses that can be met by rainwater harvested on a yearly basis. In humid regions, a significant fraction (40% in Houston and 50% in Miami) of indoor water consumption can be met by rainwater harvested. In arid regions, indoor water self-sufficiency increased to a 10.6% in Los Angeles, 6.6% in Phoenix and 3.5% in Las Vegas. The indoor water self-sufficiencies of the test cities across the country are significantly, 40 to 90%, higher than the total (indoor and outdoor combined) water self-sufficiencies.

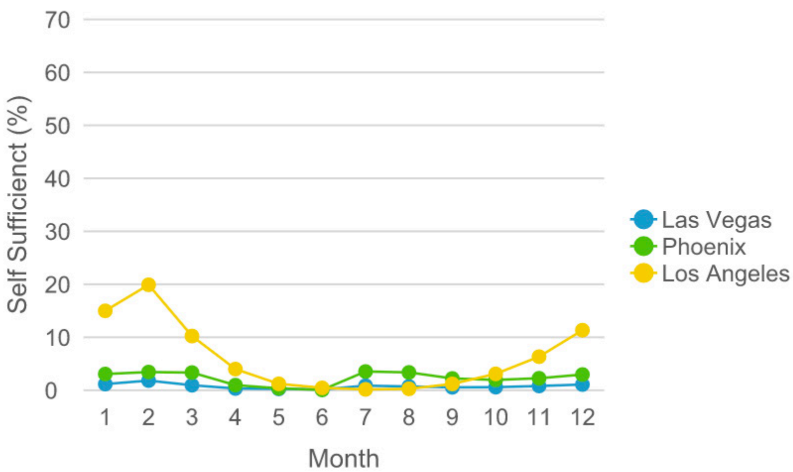

Figure 7: Water self-sufficiency of test single-family homes in Southwest desert cities.

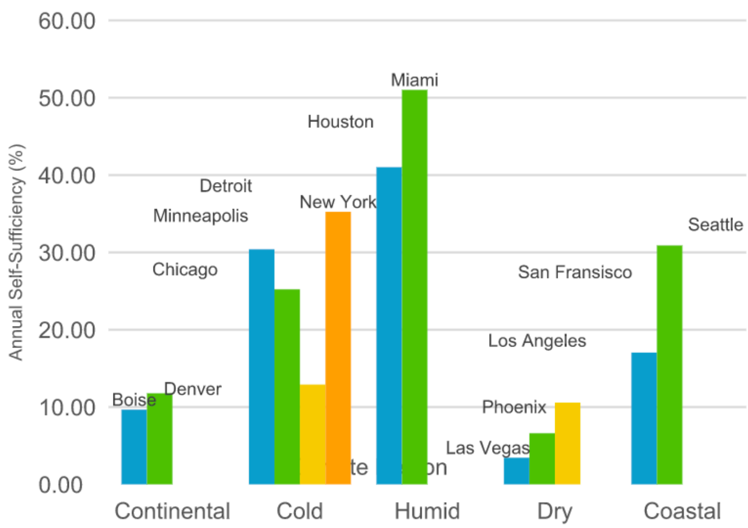

Figure 8: Annual indoor water self-sufficiency of single-family homes in 13 US cities

6.0 SUSTAINABILITY OF RAINWATER HARVESTING

A building is an ecological system, in which water is an essential element for the life of people and other living organisms. In order to sustain human biological, hygienic and cultural activities, buildings require year-round reliable supply of water. The most common water supply method in the industrialized counties is distributing public water that was drawn from water-sources. When water that is drawn from water sources is greater than what is being replenished by either precipitations or surface water flow, the balance of water is tipped. The water resources in the local hydrosphere become unsustainable. The drying up of the Colorado River at the Gulf of Mexico is one of the most drastic water resource depletions caused by unsustainable water withdrawal. Efficient use of water and onsite rainwater harvesting reduce the draw, and help sustain the integrity of the local and regional natural water sources, surface waters and aquifers.

Groundwater withdrawal has long been practiced as an alternative source of water procurement around the world. To date, many single-family homes in American suburbia procure water by pumping groundwater from the subterranean aquifer. The long-term sustainability of groundwater withdrawal depends the balance between drawing water from the aquifer and recharging groundwater. Allowing stormwater to infiltrate into the ground is essential for recharging the aquifer. Hard-finished surfaces (roads, parking lots, rooftops, paved yards) hinder the permeation of stormwater. Soft-scaping and permeable paving help recharge groundwater and sustain the water table.

By holding stormwater runoffs, rainwater harvesting helps recharging groundwater. Rainwater collected during rain and using it later for irrigating plants will hydrate soils and recharge groundwater. In addition, rainwater harvesting contributes to the quality of water streams. Stormwater contains high levels of pollutants, fertilizers and herbicides from lawns and other particulate matters. Harvesting rainwater and reducing storm water runoffs prevent pollutants entering water streams and help sustain their water quality.

CONCLUSIONS

As found in water self-sufficiency analysis, it is infeasible to attain a total water self-sufficiency of single-family homes by rainwater harvesting alone, even in most rainy regions in the continental US. However, being unable to attain the total self-sufficiency does not make rainwater harvesting unworthy. A sizable portion of single-family homes' water demands can be met by onsite water harvesting. With an exception of the Southwest desert regions, rainwater harvesting can generally meet 20% to 30% of U.S. domestic water demands. Thus, municipal water supply will continue to be the principal source of water to buildings and cities. Yet a combination of water conservation and onsite water procurement will alleviate the reliance on the public water supply systems.

The first and foremost strategy for sustainable water supply must be geared to increasing the efficiency of water uses. Incorporating design methods and technologies for promoting water efficiency in buildings and site planning is an essential requirement for sustainable architecture. This is particularly the case in arid regions. Water efficient plumbing fixtures such as small size toilets and low-speed showerheads are already widely being used in recent buildings. Because a substantial fraction of residential water consumption in American households is ascribed to outdoor uses, xeriscaping with indigenous plants, limiting size of lawns, or drip irrigation should be applied to landscaping.

Architecture is confronting with another facet of complexity: water as a critical factor for building and site designs. A building needs to be designed as a rainwater collector in terms of formal design and system integration. The roofs should be designed as not only catchment surfaces but also visual elements that expresses flow of water. How to integrating rainwater channeling and storing systems such as gutters, downspouts, rain-chains, scupper, splash basins, and even cisterns as expressive formal elements will be a question to be addressed in process of building design. Further complexity is in site design that must be designed in consideration of sustaining the integrity of the local hydrosphere. Retention ponds to collect and hold stormwater, bioswales that channels storm-water to local water streams, and permeable soft-scaping that allow rainwater to recharge groundwater should be key elements of water conscious site planning. How to make rainwater harvesting as a form-giver in building and site design will be one of key questions in sustainable architecture of tomorrow.

REFERENCES

Inskeep, B. D. and Attari, S. 2014, The Water Shortlist: The Most Effective Actions US Household Can Take to Curb Water Use, Environment Journal.

Mayer, P.W, et. al. 1999, Residential End Uses of Water, AWWA Research Foundation and AWWA, Denver, Colorado.

National Oceanic and Atmospheric Administration, National Centers for Environmental Information, 2016, 1981-2010 Monthly Normals Documentation, https://www.ncdc.noaa.gov/cdo-web/

United State Census Bureau, 2005 American Housing Survey; https://www.census.gov/programs-surveys/ahs/data/2005/2005-ahs-national-puf-microdata.html

United States Environmental Protection Agency, Water Sense, An EPA Partnership Program, https://www3.epa.gov/watersense/pubs/indoor.html

United States Geological Survey, 2016, Estimated Use of Water in the United States County-Level Data for 2010;. http://water.usgs.gov/watuse/data/2010/

United States Geological Survey, 2016, the USGS Water Science School, http://water.usgs.gov/edu/qa-home-percapita.html