The Impact of Location on Decentralized Water Use in Urban Agriculture

Tammy E. Parece

Abstract Urban Agriculture is becoming more prevalent across the world because of its ability to provide healthy and nutritious food for urban populations and contribute to urban ecosystem services. Generally, potable water is the main source of irrigation for urban agriculture, and in many regions, this negatively impacts ecosystem services because of the energy required to transport and treat potable water. Rainwater harvesting is a decentralized water strategy and urban agriculture is a decentralized food production method. This chapter reviews the literature on rainwater harvesting for urban agriculture, two decentralized strategies promoting urban sustainability. Four case studies in the Unites States (two are in wet regions and two are in semi-arid regions) are used to analyze rainwater harvesting's ability to irrigate urban agriculture, save energy, and reduce greenhouse gas emissions. Study results show that location does matter because rainfall directly affects the ability for cities in semi-arid regions to harvest rainfall for irrigation. A significant difference is apparent in rainwater availability between arid and wet regions of the US because of the significantly lower amount of precipitation in arid regions, as well as the number of days in arid regions where there is insufficient rainfall to produce runoff.

Results also demonstrate that, even in arid regions, rainwater harvesting has the potential to lower potable water use, save energy, and reduce greenhouse gas emissions.

Keywords Food security · Urban agriculture · Rainwater harvesting · Greenhouse gas emissions · United States

1 Introduction

A United Nations (UN) 2009 report noted that, for the first time in human history, more than 50% of the world's population lived in urban areas [1]. By 2018, that percentage increased to 55% (~4.3 billion people) and is expected to continue

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T. Younos et al. (eds.), *Resilient Water Management Strategies in Urban Settings*, Springer Water, https://doi.org/10.1007/978-3-030-95844-2_9

increasing to 68% by 2050 [1, 2]. The percentage of people living in urban areas varies by country, from 13% in Burundi to 100% in Kuwait and Singapore [2]. Additionally, as the economic activity of a country increases, the number of people moving into urban areas also increases [3, 4], and those countries, with the lowest percentage of urban versus rural population, are experiencing the highest rates of urban growth [5]. Although moving into urban areas offers the prospects of "*food, employment and security*" [6], in developing countries, almost 1 in 3 people live in a slum household with a lack of access to food, clean drinking water and sanitation services [3].

In 2019, three billion people did not have access to a healthy diet because they could not afford it [7]. The FAO estimates that about two billion people (26.4% of the world's population) face moderate or severe levels of food insecurity [8]. People with moderate levels of food insecurity do not have regular access to nutritious and sufficient food; people with severe food insecurity also face the possibility of persistent hunger [8]. Food insecurity rates have been increasing, not decreasing, since 2015 [8], and significantly increased during the COVID-19 pandemic. Food insecurity can create health issues such as malnutrition, obesity, low birthweight, child stunting, and inability to focus in school, among other things [7].

The FAO [9] estimate that 80% of food produced, worldwide, is consumed in urban areas, and it is widely believed that people residing in rural areas have the greater chance of exposure to food insecurity than urban residents. However, two factors contradict this belief (1) rural residents have access to land in which they grow most of their food, and (2) in low- and middle-income countries, urban residents spend, on average, between 50 to 75% of their household budgets on food [10]. So, while people living in urban areas purchase their food, many urban poor lack the financial resources to make such purchases [6]. The Resource Center for Urban Agriculture and Food Security notes "Malnutrition (both under-nourishment and overweight and obesity) has become a major urban issue, affecting low income and vulnerable residents in particular" [11]. As such, the FAO considers urban agriculture (UA) an essential part of its Special Program for Food Security, yet a complicating factor to implementing UA is access to land and water for food production [12].

Water is essential for food production. The purpose of this chapter is to review the potential of harvesting rainwater for irrigating urban agriculture. Section 2 of this chapter introduces UA and discusses why it is a functioning greenspace with positive impacts on urban sustainability. Section 3 reviews urban water and rainwater harvesting for UA. Section 4 reviews the quantification methods for determining rainwater harvesting volume, energy needs for potable water, and greenhouse gas emissions. Section 4 also introduces the four case study sites. Section 5 discusses the results, the influence rainwater harvesting for UA has on the future of urban sustainability initiatives, and limitations of this study.

2 Urban Agriculture

2.1 Urban Agriculture, Defined

UA is "the growing, processing, and distribution of food and nonfood plants and tree crops and raising of livestock, directly for the urban market, both within and on the fringe of an urban area" [13]. Urban agriculture has been practiced since urban areas were first established [14], but in the United States (U.S.), UA was not initially encouraged. It has, however, gradually intensified over the past 100 years; during periods of national crisis−both World Wars and the Great Depression [15–17], and most recently during the time of COVID-19 [18]. Over the past twenty years, interest in UA has expanded worldwide because of the growing disparity in wealth between the lowest and highest wage earners (affecting access to food), its qualification as locally grown food (decentralized production), the ability to contribute to urban sustainability, and its potential to help alleviate food insecurity for urban residents [16, 17, 19].

2.2 Urban Greenspaces and Urban Sustainability

Urban planning includes initiatives to reduce ecological footprints and increase sustainability, which would result in reduced energy use, enhanced water and air quality, and increased greenspaces. A greenspace is defined as "land that is partly or completely covered with grass, trees, shrubs, or other vegetation" [20], and "functions as productive green areas that are able to deliver useful products (wood, fruits, compost, energy, etc.) as a result of urban green maintenance or construction" [14]. Urban greenspaces provide positive benefits for both humans and wildlife [21–24]. Examples of positive benefits include:

- Increases in ecosystem services [14, 25–28];
- Increases in water infiltration, thus increased groundwater recharge, reduced stormwater runoff, and improved water quality [14, 21, 28, 29];
- Controls air temperature and reduces the urban heat island effect [14, 21, 30];
- Provides an area for increased physical exercise and stress reduction [14, 21, 22]; and
- Increases human social interaction and acts as a place of community for urban residents [14, 18, 22, 31].

2.3 Urban Agriculture Scope

Urban agriculture ranges in size from plants in small containers (see Fig. 1) to large plots as commercial enterprises [32]. The most common form of UA are backyard

Fig. 1 Two container gardens—peppers and squash on the left and strawberries on the right. (Photo by author, 2021)

gardens [33, 34]—people growing food on land next to their home for their own consumption or to share with friends, neighbors and relatives [34] (Fig. 2).

Meso-scale forms of UA include allotment gardens and community gardens [34, 35], see Fig. 3. These gardens normally consist of a plot of land shared by a community—each person cultivates their own plot within the garden and shares the tasks of maintaining the common areas. The major difference between an allotment garden and a community garden is that allotment gardens are provided by the government in lower income areas [36]. The land for a community garden can be provided by any number of entities—churches, governments, private individuals or non-profits

Fig. 2 Backyard garden, shows inter-cropping with corn, beans, tomatoes, and squash. (Photo by author, 2021)

Fig. 3 Mountain view community garden, Roanoke, Virginia. Photo on left as displayed in Google Earth Pro 2019, photo on right by author, 2015

and the individual gardeners pay a small annual fee for participating [18, 34, 35]. Community gardens can also include schoolyard gardens [31].

UA's largest forms (by area) are urban farms (see Fig. 4), and in many instances are identified as a for-profit business [33]. Urban farms are not limited to row crops, they can include greenhouses, aquaculture, rooftop gardens, and hoop houses (as noted in Fig. 4 and seen in Fig. 5). Exceptions to the for-profit characteristic are

Fig. 4 Wilson Street Urban Farm, Buffalo, New York, 2018, as displayed in Google Earth

Fig. 5 Examples of hoop houses. Wilson Street Urban Farm on left (as displayed in Google Earth Street View, 2020) and Colorado Mesa University in Grand Junction on right. (Photo on right by author, 2021)

found, especially in areas undergoing mass emigration, such as Detroit, Michigan [16].

While each form of UA has specific characteristics, characteristics are not exclusive for any specific form. For example, produce from community gardens, home gardens and patio gardens are frequently sold; food forests can be planted by governments for consumption by their citizens; and some urban farms are owned by non-profits food banks (for example Growing Goodwill Garden in Roanoke, Virginia and the Rob and Melani Walton Urban Farm in Phoenix, Arizona).

UA qualifies as a greenspace but also provides benefits beyond most other urban greenspaces (parks and urban trees). These benefits include provisioning of fresh, nutritious fruits and vegetables, economic opportunities from selling agricultural products [33, 37], and nurturing a sense of land/environmental stewardship and ownership [38, 39]. Additionally, since UA uses space and water more efficiently (not just horizontal but also vertical, and in smaller plots), produces shorter life-cycle crops, and uses inter-cropping [33, 40, 41], it can produce a greater output (kilograms per unit area) than traditional agriculture [42, 43]. It reduces food miles (the distance food travels from where it is grown to where it is ultimately consumed) and provides urban residents access to locally grown food [2]. Urban agriculture is also widely recognized as an important social aspect of urban environments, one which political ecologists argue embodies social justice issues found in most urban areas [44].

3 Urban Water

Current water infrastructure is based on twentieth century technology; for urban areas, this means water is stored in reservoirs and then energy is used to collect, transport and then treat to potable standards for urban residents [45]. In a study of 11 US water companies, Young reports that the energy use to treat, convey and distribute potable water ranges from 500 to 3500 kWh per million gallons (0.132 to 0.925 kWh per m^3), with an average of 2,300 kWh per million gallons (0.608 kWh per m^3) [46]. (See Chapter 1 of this book for more information.)

The amount of energy used is highly dependent on whether transporting water from source to city is gravity fed. Although New York City obtains the majority of its potable water from a watershed over 100 miles north of the city [47], it is gravity fed. The town of Blacksburg, Virginia's water source is the New River and while transport only occurs over a distance of 2 miles, it is uphill the entire way. Thus, energy per cubic meter is significantly higher for Blacksburg than New York City.

Urban water use includes water used for consumption (residential and commercial), irrigating greenspaces (lawns, flowers, ornamental bushes, gardens), washing real and personal property, and in manufacturing. Additionally, it includes construction and maintenance of the infrastructure to support these activities and to remove wastewater and stormwater runoff.

As discussed in the Introduction (Sect. 1), human populations in urban areas will continue to increase. Along with this population growth, comes conversion of open lands into the built environment, and increasing demands for municipal services, including water for domestic consumption and other uses. Competing demands for urban water are complicated by lack of available water resources, especially in arid or semi-arid regions, and increasing costs for new infrastructure, or for maintenance and repair of aging infrastructure [48]. Harvesting rainwater as a substitute for some uses can help alleviate pressures on overall water demand (See Chap. 5 of this book for a specific case study).

3.1 Rainwater Harvesting in Urban Areas

Impervious surfaces in urban areas—building rooftops, sidewalks, roads and parking lots—reduce underground infiltration and increase stormwater runoff. Runoff from sidewalks, parking lots and roads create stormwater that could be a source of human-health risks to those consuming food produced, and from working in contaminated soils [49–52], as such, "Rainwater harvesting captures, diverts, and stores rainwater from ***rooftops*** [emphasis added]" [53]. Harvesting rainwater in urban areas has many applications. For this purpose of this chapter, only one use is discussed in the next sub-section—for urban agriculture. (See Chap. 7 of this book for more uses.)

3.2 Water for Urban Agriculture

The FAO recommends two specific alternative water sources for UA water use—(1) reusing treated or partially treated wastewater and (2) harvesting rainwater [54]. Literature on rainwater harvesting in urban areas is plentiful and many researchers reference the possibilities of rainwater harvesting for irrigation purposes (e.g. [6, 31, 55], but case studies calculating rainwater harvesting potential for UA are recent phenomena. The following studies relate to rainwater harvesting for urban agriculture:

- Ward et al. [48] estimated water demand for a hypothetical garden using the water requirements and crop yields from traditional agriculture in Australia. Their results showed household potable water demand would have a significant increase with a related increase in household expenses. They opined that alternative sources of water for UA, such as rainwater harvesting, should be considered.
- Redwood et al. [56] completed a cost/benefit analysis of actual rainwater harvesting and greywater use for urban farms using a local school as a test site in Tunisia. Their results produced economic benefits for urban farmers. After the success of the case study, rainwater harvesting systems were installed at 20 urban farms.

- Lupia & Pulighe [57] quantified water demand for existing home gardens and calculated the potential rainwater harvesting volume that could be used for irrigation water in Rome Italy. Their results estimated that (with the exception of vineyards and olive groves) harvested rainwater from roof areas would adequately meet water needs for all existing home gardens.
- Richards et al. [58] constructed two vegetable raingardens (one lined and one unlined) and two control sites on the Burnley Campus of the University of Melbourne in Australia. In their study, 2/3 of harvested rainwater was directed to raingardens and 1/3 stored for supplemental irrigation. Their results showed lined raingardens needed no additional irrigation during dry periods.
- Parece et al. [59] identified existing locations of UA, and calculated rooftop areas of adjacent buildings and rainwater harvesting potential for the city of Roanoke, Virginia, USA. Their results calculated the potential volume of rainwater harvested and reduction in energy and greenhouse gas emissions when using that rainwater, in place of potable water, for irrigation.
- Petit-Boix et al. [60] used a hypothetical family home with a 40 m^2 garden, and estimated rainwater harvesting for toilet flushing, laundry, and lettuce production and precipitation volumes of 21different cities in the USA, Europe, and India. They used three different scenarios—no food production, only food production and a combination. Their results were averaged over all cities, and showed that rainwater harvesting supplied the water demand—no food production (60%), food production only (84%), both (47%).
- For Rome Italy, Lupia et al. [61] estimated water needs for 2,631 gardens and rainwater harvesting potential from building rooftops to identify self-sustaining gardens vs. gardens with supplemental water needs by land use type (horticulture, mixed crops, olive groves, orchards and vineyards). Their results demonstrated that rainwater harvesting could provide between 19 and 33% of water needs in irrigated landscapes, depending on the efficiency of the irrigation system; and between 22 and 44% of water needs in non-irrigated gardens.
- Weidner and Yang [62] completed a comparative analysis between Lyon, France and Glasgow, Scotland. They evaluated a food-water-energy-waste nexus, including seasonal and greenhouses and no rainwater harvesting and rainwater harvesting with short term and reservoir storage. Their results revealed that with rainwater harvesting, potable water input was reduced to zero when storage is included (for hydroponics—rainwater harvesting produced more water than was needed). They noted that the difference documented between the two cities was related to the amount of annual rainfall.

The studies identified above have quantified and demonstrated that rainwater can be harvested and used for UA production. All rainwater harvesting studies described only harvesting from rooftops, not from any other type of impervious surface. The question is whether rainwater harvesting is a viable method for all urban areas (both water-rich and arid environments), and if so, what impact would it have on energy use and greenhouse gas emissions.

4 Methods and Study Sites

This section reviews how rainwater volume, energy needs for potable water, and greenhouse gas emissions are quantified, and introduces the four urban study sites in the U.S. For this comparative analysis: two sites are in the water rich east—Roanoke, Virginia and Buffalo, New York, and two sites are in the arid west—Grand Junction, Colorado and Phoenix, Arizona (Fig. 6). For each location, the urban area and urban agriculture for that city are described, and water and energy sources introduced. The results—rainwater harvesting potential and reductions in energy and greenhouse gas emissions are presented in Sect. 5 (Results and Discussion).

4.1 *Equations and Data Inputs*

This section discusses the three equations to be used for the analysis of each city. This section also defines the variables that are used in each equation.

Fig. 6 Reference map of study sites. Tiger line shapefiles from [63] overlaid on Landsat satellite imagery in ArcGIS Pro

4.1.1 Equation 1: Usable Rainwater Volume

To quantify the amount of rainwater that can be harvested and used for irrigation (hereinafter referred to as usable rainwater volume or URV), Eq. 1 (from [64]) is used.

$$\mathrm{URV}\left(\mathrm{m}^3/\mathrm{timeperiod}\right) = \mathrm{RoofArea}\left(\mathrm{m}^2\right) \times \mathrm{AverageRainfall}(\mathrm{m}/\mathrm{timeperiod}) \times \mathrm{C} \tag{1}$$

The variable C is collection efficiency, which allows for splash and evaporation. The amount of splash varies based on roof materials and pitch. The amount of evaporation depends on air temperature, time of day (impacts roof temperature), and humidity. Variable C can range from 0.75 to 0.9, so an average of 0.8 is normally used in rainwater harvesting calculations [64].

For rooftop areas (the rainwater harvesting collection site) are calculated from aerial photos (e.g. [59, 61]), or using the building footprint (area) from municipal GIS files. The method used for each city in this analysis will be addressed under each city site below. Additionally, with the exception of Roanoke, Virginia (as discussed under Sect. 4.2.1), two analyses will be completed for each city—a microscale analysis using a few existing locations of urban agriculture (and related buildings), and a macroscale analysis for potential backyard gardens using one-family dwellings (for roof areas).

The input for average rainfall are precipitation rates, which are recorded by the U.S. National Weather Service (NWS). The NWS has climate records for over 100 years, including daily, monthly, and annual rates along with normal rates. Annual rates are the amount of rainfall recorded for a specific year. Normal rates are averages calculated on a 30-year basis; the most recent available is for 1991—2020 [65].

The results from Eq. 1 estimates the potential volume of rainwater that can be harvested and the potential reduction in both stormwater runoff and potable water use. Equation 1 can be used with a microscale (e.g. [60]) or a macroscale analysis (e.g. [59, 61]).

4.1.2 Equation 2: Energy Used Per Volume of Potable Water

To calculate the energy saved from reducing potable water use, Eq. 2 from [64] is used:

$$\begin{aligned} &\mathrm{EnergyConserved}(\mathrm{kWh}) \\ &= \mathrm{PotableWaterSavings}\left(\mathrm{m}^3\right) \times \mathrm{EstimatedEnergyUse}\left(\mathrm{kWh}/\mathrm{m}^3\right)) \\ &\quad - \mathrm{Indoor}/\mathrm{OutdoorPumpEnergyNeed}(\mathrm{kWh}) \end{aligned} \tag{2}$$

URV (from Eq. 1) is used as the input for the potable water savings. If available, the estimated energy use will be gathered from the annual reports from the local water authority for each location. If not available, the energy use (from [46]), will be used.

The energy needs for pumping the harvested rainwater varies substantially and depends on multiple factors. These include if the pump is "on demand" (in constant ready mode), the size of pump, pump power, water pressure to be delivered, the distance water travels, the purpose of the water (indoor, outdoor, irrigation, multi-use, etc.) and volume of water [66, 67]. An additional factor is whether a pump is actually needed or not, for example, a pump is not needed for a system wherein rainwater is harvested from a rooftop, caught in a "rainbarrel," and used for an adjacent garden (water flow is handled by gravity).

The results from this equation is the energy not needed if rainwater is used in place of potable water, thus is the energy conserved.

4.1.3 Equation 3: Reduction in CO_2 Emissions Related to Reduction in Energy Use

The final equation (from [64]), calculates the reduction in greenhouse gas (GHG) emissions:

$$\begin{aligned} &\mathrm{CO_2 emissions(kilograms)} \\ &= \mathrm{EnergyConserved(kWh)} \times \mathrm{CO_2 outputrate(kilograms/kWh)} \end{aligned} \tag{3}$$

The input for energy conserved is the result from Eq. 2. The carbon dioxide output rate depends on the fuel source for the electricity [68]. The fuel source will be gathered from the annual reports for the energy company for each location. The CO_2 output rate is calculated using the values in Table 1.

Table 1 Carbon dioxide emissions from electric power generation

Fuel type	CO_2 output rate (kilograms per kWh)
Coal*	1.0
Natural gas*	0.41
Hydroelectric**	0.018
Nuclear**	0.012

* [68] reports pounds per kWh; converted to kilograms per kWh (1 pound = 0.454 kg). ** [69] reports these as a global average in grams, converted here to kilograms

4.2 Urban Study Sites

4.2.1 Roanoke, Virginia USA

Roanoke is located in a valley in southwest Virginia (Fig. 6) and was established in 1852 as a railway hub [70]. It is the largest city in southwest Virginia with a population of 99,143 over 110 km^2 [71], a density of 900 persons per km^2. Its current commercial activity includes as a hub for railway and road traffic, finance, manufacturing, trade, and healthcare with a school of medicine.

Roanoke's greenspaces include tree canopy cover, park land (city and national), and UA (including home gardens, community gardens (an example is Fig. 3) and urban farms) [59]. Review of the UA in Roanoke (through the American Community Garden Website, the Roanoke Community Garden website, and Google Earth and Maps) shows that, since 2016, although one urban farm has expanded (Lick Run Urban Farm) and some gardens have not changed (Growing Goodwill, Mountain View and Hurt Park), others have either reduced the area under cultivation (Heritage Point Farm) or suspended operations (Frank Roupas Community Garden).

Rainwater harvesting is permissible in Virginia, without restrictions. While rainwater harvesting is available at some community gardens (see Fig. 3 as an example), most locations use potable water for irrigation. As noted in Sect. 3.2, Parece et al. [59] completed a macroscale rainwater harvesting evaluation of existing UA for the entire city with a microscale analysis for two specific sites (Growing Goodwill Community Garden and Heritage Point Farm).

The amount of electricity used for potable water varies as the city has five different sources of water—Carvin's Cove Reservoir, Crystal Spring, Spring Hollow, Falling Creek and private wells [72], Fig. 15 in [59]. Whereas Parece et al. [59] were able to obtain the energy usage for each water source that information has not been updated on the water authority documents, so this chapter will use the same breakdown as in [59].

Electricity for Roanoke is provided by the Appalachian Power Company, Inc. (an American Electric Power company (AEP), a conglomerate of local power companies in several U.S. states). However, AEP's annual report does not separate the individual companies' fuel use for energy generation, so this analysis uses the breakdown for the entire corporation. The Annual report does identify the renewables used by each company, and for Appalachian Power, the renewables include only hydro (solar is under development). The breakdown in fuels are coal (44.8%), natural gas (31.1%), nuclear (8.2%), renewables (hydro, solar and wind—13.2%), and other (2.7%) [73], these data for their current fuel sources are a significant change from that used in [59].

Roanoke's normal annual precipitation is 1,048 mm (41.25 inches) of precipitation [65]. Normal precipitation (averages calculated on a 30-year basis) is relatively unchanged from that reported in [59] as 1,097 mm. Normal by month is shown in Table 2 and shows that precipitation is prolific in all months.

Table 2 Roanoke, Virginia normal precipitation (cm) by month [65]

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
(cm)	7.42	7.34	8.79	8.56	10.31	9.73	10.26	9.04	9.88	7.34	8.64	7.47

For Roanoke, the macro-scale analysis in this chapter will use the rooftop area already calculated and subdivided by water source in [59].

4.2.2 Buffalo, New York USA

Buffalo is located in the western part of New York State and adjacent to Lake Erie (Fig. 6). Buffalo began as a small trading post in 1789. As a transportation hub, it grew rapidly during the 1800s industrialization boom [74]. Its current population is 255,284 over 105 km^2 [75], a density of 2,431 persons per km^2. It is dominated by service industries such as health, finance and sales [74].

Urban agriculture in Buffalo is extensive with at least four urban farms and 17 community gardens (when using those terms in the Google Search Engine and the American Community Garden Association website [76]), and in 2020, the University of Buffalo received a grant to expand UA in the city [77]. Buffalo's microscale analysis will include three urban farms—Common Roots Urban Farm, Growing Green Urban Farm and Wilson Street Urban Farm.

Common Roots Urban Farm was established in 2012 as a neighborhood cooperative farm. It occupies 4,047 m^2 (1 acre) but only ½ is cultivated [78]. Many of the lots surrounding the farm are vacant (Fig. 7), thus there are only five buildings that can be used for rooftop rainwater harvesting, including a pavilion and a hoop house on the farm.

Growing Green Urban Farm was established by neighborhood residents in 1992, and incorporated as a non-profit in 2000 [79]. It has greatly expanded over several vacant lots. Their farm includes two large greenhouse and solar panels on the main building (Fig. 8). It is in a densely built-up area of Buffalo and surrounded by many building, mostly residential structures. All buildings surrounding the farm (except the area concealed by solar panels), and the two greenhouses will be used as rooftop areas for harvesting rainwater.

Wilson Street Urban Farm has also expanded substantially, from an empty lot in 2009. Figure 9 shows the farm expansion from 2009–2018 [80]. In the top image (2009), it is mostly vacant land with two hoop houses within the red oval (and on the left in Fig. 5). Within the center image (2011), some cultivated fields are seen within the white box and new clearing in the black box. The bottom image shows that by 2018, most of the location is under cultivation. Adjacent to the farm is the Family Dollar Store on the south and several residential lots on the west. The rooftops of the Family Dollar, the residences to the west, and the hoop houses on the farm will be used to calculate rooftop areas for rainwater harvesting. The residential areas across

Fig. 7 Common Roots Urban Farm displayed in Google Earth

the street will not be used since the street creates an impediment to safely moving water.

Rainwater harvesting in New York State is permissible and promoted by all levels of government. The water source for Buffalo is Lake Erie [81]. Water is transported by gravity through an initial phase of chemical treatment, and thereafter, lift pumps are used to transport the water through final phases of chemical treatment and fine particle deposition [82]. After water is treated to potable standards, pumps transport the water through 800 miles of pipes and to over 80,000 individual service connections [81]. Examination of Buffalo Water's financial reports (available at https://buffalowater.org/) does not identify the energy use for treating and transporting water. As such, the US average per kWh (from [46]) for treating and transporting water will be used.

Energy is deregulated in New York State, as such users choose their own company if more than one company provides service (as in Buffalo). National Grid is the largest supplier in the state and for the city of Buffalo. National Grid provides service in two countries—the United Kingdom and the United States. Within the United States, it services Massachusetts, New York and Rhode Island [83]. Their annual report does not specifically list the breakdown in energy source for their electricity generation neither by country, nor in the US by state. The report does note that the company has reduced their CO_2 emissions by 70% since 1990. The total emissions are reported as

Fig. 8 Growing Green Urban Farm displayed in Google Earth, top and Google Earth Street View, bottom

6.5 million tonnes of CO_2 for 28,223 GWh of total power generated. This converts to 230.3 tonnes per GWh, or 0.23 kg per kWh.

Buffalo's annual normal precipitation is 1,033 mm (40.68 inches) per year [65]. Normal by month is shown in Table 3 and shows that precipitation is prolific in all months.

For the microscale analysis of the specific UA locations identified above, aerial photos displayed in Google Earth will be used for rooftop areas of adjacent buildings. For the macroscale analysis of the rainwater harvesting potential for backyard gardens, building footprint areas (from [84]), will be used as a substitute for rooftop areas.

Fig. 9 Wilson Street Urban Farm. Aerial photos as displayed in Google Earth (2009 top, 2011 center, 2018 bottom)

Table 3 Normal Precipitation (cm) by month for Buffalo, New York [65]

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
(cm)	8.51	6.32	7.34	8.56	8.56	8.56	8.20	8.13	10.41	10.24	8.89	9.53

4.2.3 Grand Junction, Colorado USA

Grand Junction (GJ) is located in the western part of Colorado, about 40 km from the Utah border, and in an area generally called the Grand Valley of Colorado (Figs. 6 and 10). GJ was established in 1882 at the confluence of the Colorado and Gunnison Rivers [85]. It is the largest urban area on the western slope of Colorado. Total population in the Grand Valley is 147,803. GJ's population is 63,597 over 99 km^2 [86], a density of 642 persons per km^2. This region is a semi-arid to arid climate situated on high desert lands and considered an important agriculture area for Colorado (as noted in inset map in Fig. 10 and [87, 88]. Additionally, Grand Junction is home to the largest university in western Colorado—Colorado Mesa University.

GJ has a significant amount of greenspace (as seen in Fig. 10), which includes city and state parks and extensive agricultural lands (mostly commercial). Urban

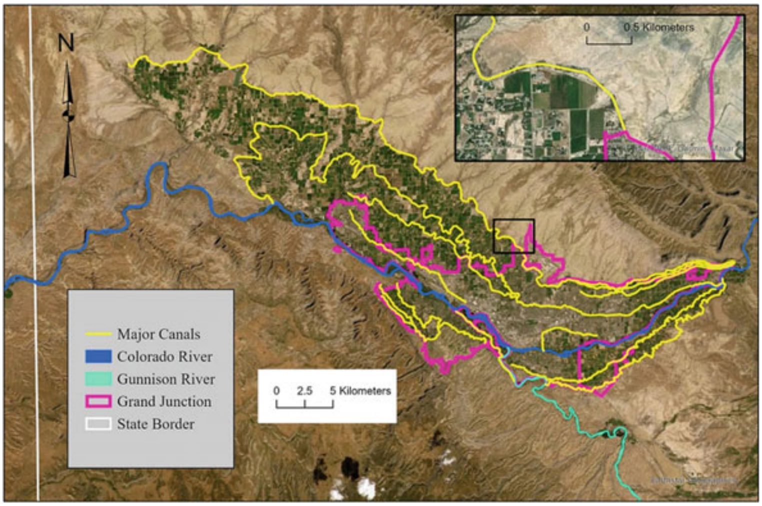

Fig. 10 The Grand Valley in western Colorado—Landsat image, 2021, as displayed in ArcGIS Pro; GIS files from [63, 89]

agriculture includes mostly home gardens and one community supported agricultural farm—Rooted Gypsy Farms. Community gardens are rare in GJ, only three have been personally identified by the author (two are shown in Fig. 11—Copper Creek Homeowners Association and Colorado Mesa University), and none are found when using the Google Search Engine or the American Community Garden website [76].

Rainwater harvesting is prohibited in Colorado except for single family (or up to 4-unit multi-family) residences, and limited to two containers with a total maximum capacity of 110 gallons (0.416 m^3). Rainwater can only be harvested from rooftops and only for outdoor uses on the same property where it is collected (with minor exceptions) [90]. The Ute Water Conservancy District provides potable water for the

Fig. 11 Copper Creek community garden (left), Colorado Mesa University community garden (right). Photos by author (2021)

Fig. 12 A major canal extending from the Colorado River into the Grand Valley (left), a minor canal extending to individual parcels (right). Photos by author 2021

region, and it is the District's policy that "it will not sell taps solely for irrigation or landscape maintenance purposes" [91], p. 28. As such, irrigation canals extend from both the Colorado and Gunnison Rivers. The canal network is extensive, with 328.7 km (as calculated from Mesa County's GIS files [89]) of major canals (Fig. 10 and on left in Fig. 12), and an unknown number of smaller canals (right in Fig. 12) extending river water to individual parcels of property. Both community gardens and the urban farm, identified in the previous paragraph, are irrigated with canal water.

Pumps transport irrigation water from the canals. Figure 13 shows a variety of pumps used in GJ. Image A shows the intake valve from a major canal and Image B shows the related pump house required for pumping water into a neighborhood (photo of equipment is not available). Image C shows the pump required from a minor canal which services the Copper Creek Community and its community garden (mentioned above). Image D shows the use of a solar panel to run a pump for water from a minor canal and used to irrigate a small common area in the Copper Creek North 2 community.

Electricity for GJ is provided by Xcel Energy. Xcel also provides energy to other locations in Colorado and many other states. Xcel's 2020 Annual Report identifies fuel use for energy generation, but does not break down its energy generation by location. The report does note, for Colorado, by 2030, they plan to retire or replace their remaining coal generating plants and add additional wind and solar generation. The 2020 breakdown in fuels are coal (21%), natural gas (32%), nuclear (13%), renewables (hydro, solar and wind—34%) [92]. In the US, there is an increasing trend toward renewable use.

GJ's normal annual precipitation is 230 mm (9.06 inches) per year [65]. However, it is well known that the Colorado River Basin is undergoing a mega-drought [93].

Fig. 13 Types of irrigation pumps used in the Grand Valley. (Photos by author 2021)

Precipitation totals for each year, 2016–2019, are shown in Table 4 and shows substantial variability year to year. Normals by month are shown in Table 5, again showing substantial variability. The NWS tracks daily rainfall amounts in multiple categories including the number of days less than 0.01 inches (0.25 mm) and for GJ, 69.2% of those days where precipitation occurs (71.6 of 103.5 days), less than 0.25 mm (0.01 inches) is received [65], thus runoff does not occur, so normal annual precipitation amounts cannot be used in this analysis. Table 6 lists the precipita-

Table 4 Grand Junction, Colorado normal per annum precipitation (cm), 5 years [65]

Year	2020	2019	2018	2017	2016
Amount	13.0	21.7	20.9	12.9	22.4

Table 5 Grand Junction, Colorado normal precipitation (cm) by month [65]

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Amount	1.55	1.35	2.03	2.49	2.11	1.04	1.5	2.34	3.02	2.51	1.55	1.52

Table 6 Grand Junction, Colorado precipitation (cm) by month for January–May, 2021 and June–December, 2020 [65]

Year	2021					2020						
Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Total	0.91	0.81	1.35	0.76	1.35	1.30	0.13	0.18	2.87	1.5	0.28	0.81
Usable*	0.53	0.46	1.12	0.66	1.19	0.91	0	0	2.79	1.5	0	0.58
Days**	1	1	3	1	2	2	0	0	2	2	0	1

* rainfall rates $\geq$ 0.25 mm. ** number of days that rainfall rates $\geq$ 0.25 mm

tion by month for 12 months (January—May, 2021 and June—December, 2020), including the number of days precipitation was greater than or equal to 0.25 mm and the total precipitation for only those days. These amounts in Table 6 would equate to the amount of precipitation that actually could be harvested for irrigation and this total (97.4 mm) will be used as the average rainfall input for Eq. 1.

The microscale analysis of for GJ will be an analysis of a single-family home. Manual measurement of the building's footprint will be used for roof area as the collection point and to determine if harvested rainwater will even meet the maximum harvest allowed under Colorado law (two barrels totaling 0.416 m^3). For the macroscale analysis of the rainwater harvesting potential, single family residential building footprints (from [89]) will be used as a substitute for rooftop area.

4.2.4 Phoenix, Arizona USA

Phoenix is located in southwest Arizona within the Salt River Valley (Fig. 6). It has ancient roots, having been previously settled by the Pueblo for approximately 700 years (700–1400 A.D.). By 1868, it was established as a town (incorporated as a city in 1881) and irrigation canals were dug to provide water from the Salt River [94]. Currently, Phoenix is known as a corporate and industrial center of the southwestern US and has a population of 1,680,992 over 1,341 km^2 [95], and is one of many cities within a greater metropolitan area (which includes Tempe, Scottsdale, Peoria, among others) (Fig. 14).

The largest employers in Phoenix are healthcare, sales, and multiple universities. Phoenix is home to extensive recreational facilities including tennis, pickleball and other sports courts, golf courses, parks (playgrounds, dog, and skate, among others), swimming pools, community centers, and walking trails [96] (see Fig. 14 for examples).

UA in Phoenix is extensive, at least eight community gardens were identified in the city alone from the American Community Garden website [76], and many more were identified within the greater metropolitan area. Community gardens include Coronado Neighborhood Community Garden (Fig. 15a), Growing Together Garden (Fig. 15b), and Cartwright Community Garden (Fig. 15c).

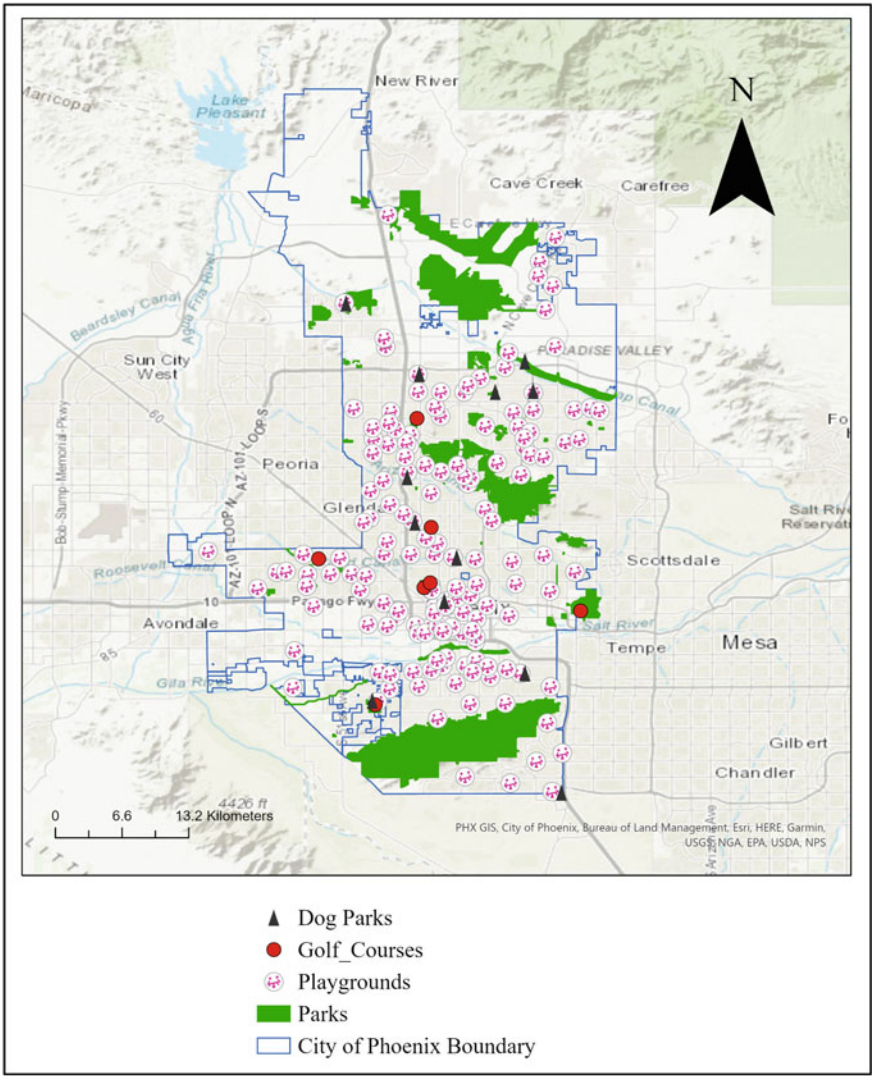

Fig. 14 Phoenix' location in the greater metropolitan area, including recreation facilities within the city (GIS files from [96] as overlaid on topographic maps in ArcGIS Pro)

Coronado Neighborhood Community Garden is for members of the Coronado Neighborhood Homeowners Association [97]. As can be seen in Fig. 15a, the location has substantial rooftop area for harvesting rainwater from its community center and a large home located adjacent to the garden, on the east.

Growing Together Garden was initially established in 2009 and moved to its current location at the Living Streams Church in 2017. The site provides food to local charities but also acts as a place of education and community unity [98]. This

Fig. 15 Community gardens in Phoenix Arizona, as displayed in Google Earth

garden also has potential for rainwater harvesting from using the adjacent buildings, including the roof of the church (Fig. 15b).

Cartwright Community Garden does not have a website and its Facebook page only has a few pictures. By using the Historical Imagery in Google Earth, the garden plots first start showing up in aerial photos from December of 2017. As can be seen in Fig. 15c, with the exception of a small rooftop just south of the garden, no other buildings are present within the confines of the parcel (it is surrounded by roads).

Only one urban farm was located—the Rob and Melani Walton Urban Farm (indicated by the red arrow in Fig. 16), which is part of The Society of St. Vincent de Paul. The farm opened in 2018 and has one acre under cultivation [99]. It several adjacent buildings, and The Society of St. Vincent de Paul includes the substantial white rooftop in the lower part of Fig. 16, from which to harvest rainwater.

In Arizona, it is legal to harvest rainwater on one's own property [100]. Potable water in Phoenix is provided by the City of Phoenix Water Services. Potable water sources for the region include the Salt and Verde Rivers (treated at 3 different plants) and approximately 50% of the water supply, the Colorado River (treated at 2 plants) and 47% of the supply, and groundwater wells for 3% [101]. At least one treatment plant uses solar power. No prohibitions on using potable water for irrigation was identified. No information was located on the city's website as to the electricity usage to treat and transport the water from the various treatment plants.

Salt River Project (SRP) provides electricity in addition to canal water for the region. Canal water is used for various irrigation purposes and for supplies to the city for treating water to potable standards. Nine major canals are in the valley and were established between 1898 and 1968. Over 1,000 miles of smaller canals take

Fig. 16 Rob and Melani Walton Urban Farm, top of the image, as displayed in Google Earth

canal water to delivery points for irrigation [102]. No information was found on the SRP website with regards to locations served with canal water.

Energy is provided by a variety of fuel sources through SRP. SRP reports its carbon footprint, "As of April 30, 202a carbon intensity of 934 lbs CO_2 per MWh. (Includes clean energy products from *large customers* and opt-in *carbon-reducing energy products* for residential customers)" [103]. This converts to 0.4237 kg/kWh.

Phoenix' annual normal precipitation is 183 mm (7.22 inches) per year [65]. However, Phoenix is in the lower basin of the Colorado River and is included in the mega-drought region [93]; and recent reports indicate that "massive water restrictions" will limit to the flow in the lower Colorado River basin in 2022 [104]. Normal monthly precipitation is listed in Table 7, but in 60% of those days where precipitation occurs (33.4 out of 55.6 days), less than 0.25 mm (0.01 inches) is received, thus runoff does not occur [65]. Table 8 lists the precipitation by month for 12 months (January—May 2021 and June—December 2020), including the number of days precipitation exceeded 0.25 mm and the total precipitation for only those days. Since

Table 7 Phoenix, Arizona normal precipitation (cm) by month [65]

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
(cm)	2.21	2.21	2.11	0.56	0.33	0.05	2.31	2.36	1.45	1.43	1.45	1.88

Table 8 Phoenix, Arizona precipitation (cm) by month for January–May, 2021 and June–December, 2020 [65]

Year	2021					2020						
Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Total	1.73	Trace	0.94	0.03	Trace	Trace	0.25	2.29	Trace	0	Trace	1.14
Usable*	1.68	0	0.89	0	0	0	0	2.29	0	0	0	1.14
Days**	3	0	2	0	0	0	0	2	0	0	0	1

* rainfall rates ≥ 0.25 mm. ** number of days that rainfall rates ≥ 0.25 mm

normal annual precipitation cannot be used, the amounts in Table 8 would equate to the amount of precipitation that actually could be harvested, and this total (60 mm) will be used as the average rainfall input for Eq. 1.

For the microscale analysis of the specific UA locations, aerial photos displayed in Google Earth will be used for rooftop areas of adjacent buildings. For the macroscale analysis of the rainwater harvesting potential, single family residential building footprints (from [96]) will be used as a substitute for rooftop area.

5 Results

5.1 Roanoke, Virginia

Table 9 provides the Eqs. 1 and 2 results for the macroscale analysis, similar to that was accomplished by [59]. Table 9 includes the breakdown in URV by water source; total URV (using the same roof area as [59]) is 69,423.88 m^3. This amount would also constitute the amount of potable water saved if rainwater were harvested from these rooftops. These URV results are then used as the input into Eq. 2, along with the energy usage by water source (from [59]) to provide the total kWh by water source used to treat and transport potable water equivalent to the amount of URV. The total energy usage is 23,506.77 kWh, and represents the amount of energy savings if

Table 9 Roanoke, Virginia roof areas, usable rainwater volume and total energy use by water source

Water source*	Roof area (m^2)*	URV (m^3) (Eq. 1)	kWh/m^3*	Total kWh (Eq. 2)
Carvin's cove	40,390.7	33,863.56	0.081	2,742.95
Carvin's cove	13,463.6	12,126.28	0.345	4,183.57
Crystal spring	21,113.0	17,701.14	0.463	8,195.63
Spring hollow	6,837.9	5,732.90	1.513	8,673.87
City total	81,805.2	69,423.88		23,506.77

* from [59]

Table 10 Roanoke, Virginia potential reduction in energy use and CO_2 emissions, annually

Fuel source for roanoke (from Sect. 4.2.1)	Total kWh (Eq. 2)	CO_2 emissions (kg) (Eq. 3)
Coal (44.8%)	10,531.03	10,531.03
Natural Gas (31.1%)	7,310.61	2,997.35
Hydroelectric (13.2%)	3,102.89	55.85
Nuclear (8.2%)	1,927.56	23.13
Other (not specified—2.7%)		
Total		13,607.36

that amount of water was harvested and not treated to potable standards. For Eq. 2, the energy usage for any irrigation pumps is assumed as zero for reasons noted in Sect. 4.1 and further discussed in Sect. 6.

Table 10 provides the Eq. 3 results. As the inputs, total energy savings for the entire city was used, the breakdown in fuel source is from AEP Annual Report [73], and the CO_2 emissions by fuel source in kilograms from Table 1. Total CO_2 emissions from the energy to treat and transport 69,423.88 m^3 of water is 13,607.36 kg, which equates to the reduction in CO_2 emissions if this amount of water was harvested instead of treated to potable standards.

The amount of CO_2 emissions calculated using the current normal precipitation amounts and the current fuel sources for AEP show a significant reduction from [59]. The value of CO_2 emissions from [59] was 19,971.0 kg. The result obtained from this current analysis shows ~ 32% reduction in GHG emissions. The most significant change that impacts these results was in fuel usage of coal, a reduction from 75.5% of all fuel sources to 44.8%.

5.2 *Buffalo, New York*

Table 11 provides the results of the microscale analysis for the three urban farms identified under Sect. 4.2.2. The adjacent roof areas were calculated using Google Earth. Average rainfall input into Eq. 1 was the normal annual precipitation. This URV result was used as an input to Eq. 2. Since Buffalo does not report its energy use for water transport and treatment, the kWh energy input was the average reported by [46], 0.608 kWh/m^3. For Eq. 2, the energy usage for any irrigation pumps is assumed as zero for reasons noted in Sect. 4.1 and further discussed in Sect. 6. The results from Eq. 2 were then used as inputs to Eq. 3 along with National Grid's total CO_2 emissions (0.23 kg/kWh).

Table 11 Buffalo, New York results for urban farms from all 3 Equations

Farm	Roof area (m^2)	URV (m^3) (Eq. 1)	kWh/m^3 [46]	Total kWh (Eq. 2)	Total emissions (kg) (Eq. 3)
Common Roots	570	471.0	0.608	286.4	66.0
Growing Green	2,221	1,835.4	0.608	1,115.9	257.0
Wilson Street	3,570	2,950.3	0.608	1,793.8	413.1
Total	6,361	5,256.7	0.608	3,196.1	736.1

Table 12 Buffalo, New York results for potential home gardens from all 3 equations

Roof area (m^2)	URV m^3 (Eq. 1)	kWh/m^3 [46]	Total kWh (Eq. 2)	Total emissions (kg) (Eq. 3)
348,377	287,898.4	0.608	175,042.2	40,312.2

The total for these three urban farms equated to 5,256.7 m^3 of URV, harvested from rooftops adjacent to the gardens. If this amount were harvested instead of using potable water, then 3,196.1 kWh of energy would be reduced and 736.1 kg of CO_2 emissions eliminated.

For the macroscale backyard garden analysis, the tax assessment files for Buffalo [84] contained information on one-family dwellings along with the square footage for the 1st floor (or the only floor in ranch style homes). There are 37,885 one-family dwellings with a footprint of 3,483,765.8 m^2. Since it is unreasonable to assume that all residences would contain a backyard garden (or want to implement backyard gardens), 10% of this roof area is used as impervious surface area for rainwater harvesting.

Table 12 provides the results of the macroscale analysis. If 10% of the one-family dwellings implemented rainwater harvesting, a total of 287,898.4 m^3 reduction in potable water use would occur. Again, using the average energy from [46] and the emissions rate from National Grid, a reduction of 175,042.2 kWh in energy and 40,312.2 kg of CO_2 emissions would be achieved if the URV harvested were used instead of that same volume of potable water.

5.3 Grand Junction, Colorado

The microscale analysis for this city does not include any urban farms, since farms are not allowed to harvest rainwater (canal water use only). And, in consideration of the small amount of precipitation in this arid region, the first question to ask—is there sufficient precipitation to fill two 55-gallon vessels (0.416 m^3) for use in backyard gardens? To determine this, the backyard garden in Fig. 2 was used to explore

Table 13 Grand Junction, Colorado rainwater harvesting potential for one dwelling

Roof area (m^2)	Total annual precipitation (m)	Annual URV m^3 (Eq. 1)
161.9	0.0974	12.6

rainwater harvesting potential for usable precipitation (from Table 6). The roof area was manually measured at 161.9 m^2. Average rainfall rate used was 97.4 mm. These two figures were used as inputs to Eq. 1. The results in Table 13 demonstrate that rainwater harvesting is possible and sufficient enough to fill two containers totaling 0.416 m^3, several times over.

For the macroscale backyard garden analysis, two GIS files—*Parcels* to identify residential parcels that were zoned as one-family dwellings, and *Buildings* for the area of the building footprint [89]. For the city of Grand Junction only (not the entire Grand Valley or all of Mesa County), there are 31,759 residences with a building footprint of 7,314,619 m^2. As with the Buffalo assessment, 10% of this area was used as the roof area and, as with the microscale analysis, annual usable precipitation of 97.4 mm (from Table 6) as the input annual rainfall inputs to Eq. 1. Since Ute Water does not report energy use by water source, 0.608 kWh/m^3 was used from [46] as the energy input into Eq. 2. The Eq. 1 results are reported in Table 14. Total URV is 56,995.5 m^3, which represents the potential reduction in potable water use if 10% of one-family dwellings in Grand Junction harvested rainwater for backyard gardens. This reduction in potable water use results in a reduction in energy use of 34,653.3 kWh (Eq. 2).

The energy use total from Table 14 was used as an input into Eq. 3. Xcel does report its fuel source, so the kilograms per kWh by fuel source, from Table 1, was used as the other input into Eq. 3. Table 15 reveals the total CO_2 emissions that

Table 14 Grand Junction, Colorado results for URV (Eq. 1) and Energy (Eq. 2) for potential backyard gardens

Roof area (m^2)	URV m^3 (Eq. 1)	kWh/m^3 [46]	Total kWh (Eq. 2)
731,461.9	56,995.5	0.608	34,653.3

Table 15 Grand Junction, Colorado potential reduction in CO_2 emissions, annually

Fuel source for GJ (from Sect. 4.2.3)	kg per kWh (from Table 2)	CO_2 emissions (kg) (Eq. 3)
Coal (21%)	1002.4	7,294.7
Natural Gas (32%)	412.8	4,577.6
Renewables (34%)	18.5*	218.0
Nuclear (13%)	12.0	54.1
Total		12,144.2

*Since Xcel does not split its renewables between solar, hydro and wind, the hydro emissions output from Table 1 was used could be reduced is 12,144.2 kg if 10% of the homes in Grand Junction harvested the rainwater from their dwellings' rooftops.

5.4 *Phoenix, Arizona*

Table 16 provides the results of the microscale analysis for the three of the existing UA locations identified under Sect. 4.2.4. Cartwright Community Garden is not included in Table 16 since there are no adjacent buildings available for rainwater harvesting. Total roof area, as calculated from Google Earth, is 17,655.38 m^2 (Growing Together Garden—4,619.0 m^2, Coronado Neighborhood Community Garden—346.8 m^2, and Rob and Melani Walton Urban Farm—12,689.5 m^2). The normal annual rainfall was not used as an input because, for some days, rainfall is insufficient to produce runoff. Instead usable precipitation from Table 8 was used as the average rainfall input (60 mm) into Eq. 1. The total URV for all three sites is 847.4 m^3.

The URV results obtained from Eq. 1 was used as the input for annual rainfall into Eq. 2. The energy usage for any irrigation pumps is assumed as zero for reasons noted in Sect. 4.1 and further discussed in Sect. 6. Since Phoenix does not report its energy usage for potable water, the average from [46] was used, 0.608 kWh/m^3 as the final input into Eq. 2. The individual results from Eq. 2 and the total for all three gardens (515.2 kWh) were then used as the energy input into Eq. 3. Since SAP does not report its fuel type breakdown but does report its total CO_2 emissions, 0.4237 kg/kWh was used as the second input into Eq. 3, giving a reduction of 218.3 kg in CO_2 emissions for all three locations.

GIS files for parcels nor buildings are not available for download from the City of Phoenix, or any other related site. The two counties that contain Phoenix are Maricopa and Pinal. The total population of these two counties is 4,948,203, thus Phoenix represents 34% of the population (1,680,992/4,948,203) [95, 105, 106]. "There are about 1.414 million single-family homes across the two counties that make up Greater Phoenix" [107]. Thus, I estimated the number of single-family

Table 16 Phoenix, Arizona URV (Eq. 1) and Energy (Eq. 2) results for microscale analysis on specific UA sites

UA site	Roof area (m^2)	URV (m^3) (Eq. 1)	kWh/m^3 [46]	Total kWh (Eq. 2)	Total emissions (kg) (Eq. 3)
Growing Together	4,619.0	221.7	0.608	134.8	57.1
Coronado Neighborhood	346.8	16.6	0.608	10.1	4.3
Rob and Melani Walton Urban Farm	12,689.5	609.1	0.608	370.3	156.9
Total	17,655.3	847.4	0.608	515.2	218.3

Table 17 Phoenix, Arizona results for potential home gardens from all 3 Equations

Precipitation Rates	Roof area (m^2)	URV m^3 (Eq. 1)	Total kWh (Eq. 2)	Total emissions (kg) (Eq. 3)
Usable	7,076,787	339,685.8	206,529.0	87,506.3

homes in Phoenix at 480,760 (34% of total single-family homes). The average home size in Phoenix, depending on which real estate website is consulted, ranges from 1,584 ft^2 (147.2 m^2) [108] to 2,386 ft^2 (221.7 m^2) for new builds [109]. For this analysis, I used 147.2 m^2 because this allows for multi-story homes (roof area is less than a multi-floor dwellings' total area), which results in 70,767,872 m^2 (480,760 × 147.2 m^2). As with the Buffalo and Grand Junction analyses, I used 10% of the roof area to assume that either 10% of single-family homes have a backyard garden (or would implement a backyard garden).

Using the same inputs as noted under the micro-scale analysis for average rainfall, energy usage and emissions, the results are displayed in Table 17. Total possible URV is 339,685.8 m^3, which equates to a possible reduction in amount of potable water use. If that amount of potable water was reduced, energy saved would be 206,529.0 kWh and CO_2 emissions of 87,506.3 kg would be reduced.

5.5 *Limitations of This Research*

Normal rainfall rates used were from the National Weather Service Stations at each city's airport, which affects this analysis. Rainfall across an urban area can be extremely variable [110], and while many urban areas have more weather stations than those just located at airports, they are often unevenly distributed and precipitation can even vary between the stations. To include such variation in rainfall, identification of weather stations adjacent to each garden would need to be accomplished. Furthermore, normal precipitation values are averages over 30 years and are not updated but once every decade (e.g., 1980, 1990, 2000, 2010, 2020). The analyses within this chapter have benefited from the most recent update, however, it is noted the climate change has had the greatest impact on temperature and rainfall patterns in the past 20 years, so the normal values will not likely reflect this impact until the 2030 or 2040 updates.

Using 10% of available roof areas assumes that 10% of the population would be convinced that this is a viable source of water and would participate in urban agriculture. This rate could be lower or higher dependent upon the population residing within the city, including political affiliation, knowledge of agricultural practices, and funds available to acquire needed equipment. Additionally, the 10% to estimate for all parcels only included those single-family homes (which Buffalo termed one-family dwellings). Multi-family homes, such as condos and townhouses, also have the potential to harvest rainwater but the specific ability to do so depends on homeowners' associations' covenants and bylaws and available land in common areas (or as in the State of Colorado, if it is allowed at all). Additionally, this analysis only looks at rainwater harvesting for urban agriculture. Rainwater harvesting has additionally applications for non-potable uses—irrigation for lawns, flowers and bushes; car washing and other external home uses; and for toilet flushing (additionally uses are discussed in Chap. 5). Other uses require harvested rainwater to be treated to potable standards, thus additional energy is used.

For three of the locations, Buffalo, Grand Junction and Phoenix, the exact amount of energy used to transport and treatment water to potable standards was not available. Thus, the US average from [46] was used as a substitute for this value. Using this average likely had an effect on the final results. If these three locations' energy use is less than average, then ultimately the reduction in greenhouse gas emissions has been over calculated.

The amount of energy used for irrigation pumps is also not calculated as part of this analysis because of the variation in pumps sizes, energy use and amount of water pumped, among other variables, as noted in Sect. 4.1. For many community gardens large rain vessels are being used (see Fig. 3), and the pressure created by the large volume of water (especially their height) in such vessels alleviates the need for pumps to move the water to garden areas. Sufficient rainfall would need to occur to "fill up" such large vessels, a likelihood only in rain rich areas such as Buffalo and Roanoke. Pump energy use would need to be included in calculations for community gardens and urban farms in both Phoenix and in Grand Junction where canal water is used. However, using solar power for the pumps, as seen in Fig. 13D and as noted in Sect. 4.2.4 for Phoenix, would alleviate the need for including pump energy use in calculation energy and emissions savings.

Additionally, these analyses do not address if rainwater harvesting is adequate source for the irrigation of urban agriculture. Agriculture water use is dependent upon crop type, local humidity levels, and timing of rainfall, among other things. Roanoke and Buffalo are located in water and agriculturally rich areas, so the potential diversity of crops produced puts such estimates beyond these analyses, but does present future avenues of research. Grand Junction is also an agriculturally rich area, but uses canal water for irrigation purposes; the calculations would need to include replacing traditional energy pumps with solar-powered (or wind-powered) irrigation pumps.

Finally, these analyses did not include any calculations for virtual water. Virtual water is water used in the manufacture and transport of products, and in the delivery of services (such as fast food restaurants) [111]. Virtual water is considered "hidden" water because it is water that is used in the background. Virtual water use impacts production of any irrigation pumps, solar panels, and has a significant impact on water used for commercial agriculture. This impact should be calculated whether infrastructure is centralized or decentralized and represents a very broad range of future research opportunities.

6 Conclusions and Recommendations for Additional Research

These analyses demonstrate that, even in arid regions, rainwater harvesting has the potential to lower potable water use, save energy, and reduce greenhouse gas emissions. A significant difference is apparent in rainwater availability between arid and wet regions of the US because of the significantly lower amount of precipitation in arid regions, as well as the number of days in arid regions where there is insufficient rainfall to produce runoff (70% of those days in Grand Junction and 60% in Phoenix). A significant difference also exists between the two cities in the arid west–Phoenix does not have the same restrictions as Grand Junction for rainwater harvesting.

For the macroscale analysis of Roanoke, Virginia, a significant reduction occurred in CO_2 emissions between 2016 [59] and this current analysis (2020 values). This reduction is related to the change in fuel type used by American Electric Power, a reduction in coal use of 30.7%. National Grid (Buffalo) reports a similar change in fuel type, which resulted in a 70% reduction in CO_2 emissions since 1990 (2021). Furthermore, Xcel (2021) (Grand Junction) plans to retire their remaining coal generating plants by 2028 and reduce their emissions by 80% by 2030. The Salt River Project (2019) (Phoenix) is already using solar power to treat and transport treated water in at least one of their treatment plants. Moreover, SRP plans on reducing their CO_2 emissions 65% (from 2005 levels) by 2035 and 90% by 2050. These efforts not only impact the sustainability efforts of the four cities in this analysis but all cities, states, and countries served by these energy companies.

Rainwater harvesting and urban agriculture are both decentralized methods to aid in decreasing the ecological footprint of individuals (microscale analyses) and for an entire city (macroscale analyses), even when just targeted for backyard gardens. Decentralized methods are important not just for reducing energy use but to assist in prevention of either terrorist attacks or cyber-attacks on centralized infrastructure which cause wide-spread service interruptions (such as those seen in 2021 on JBS Meat Supplier and the Colonial Pipeline), and represent national security issues.

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