Irrigating Urban Agriculture with Harvested Rainwater: Case Study in Roanoke, Virginia, USA

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Contents

Abstract Considered at the global scale, urbanization forms the principal source of landscape change. Worldwide, urban areas are increasing in size, both in land area and in population, causing losses of vegetated lands, increases in impervious surface cover, and increased demands on existing infrastructure and upon municipal services such as water and waste management. Urbanization, by reducing vegetative cover and increasing impervious surfaces, alters hydrologic cycles by reducing infiltration, increasing runoff volume and rates, lowering groundwater tables, decreasing evapotranspiration, and creating precipitation anomalies. Urban greenspaces are recognized as providing environmental benefits, including reduced stormwater runoff, increased evapotranspiration, and increased subsurface infiltration, which, in turn, raise groundwater tables. Urban agriculture forms a greenspace that can provide these environmental benefits, among others, in addition to contributing to food security for local populations. This chapter provides an overview of urban agriculture and its potential benefits. Then, we provide a case study based upon the City of Roanoke, Virginia, USA. We identify areas of existing urban

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agriculture using aerial imagery. We discuss land available for potential new urban agricultural sites. From aerial images and city geospatial data, we identify and calculate roof areas that can be used to capture rainwater. Then using precipitation data and equations identified from the literature, we calculated amounts of rainwater that could be harvested to provide irrigation water for these locations. Finally, we discuss reductions that could occur in stormwater runoff and greenhouse gas emissions if harvested rainwater were used instead of municipal water supplies. Additionally, we discuss future research areas for urban agriculture and rainwater harvesting.

Keywords Community gardens • Greenhouse gas emissions • Rainwater harvesting • Roanoke, Virginia, USA • Urban agriculture

1 Introduction

Humans have modified over 50 % of the Earth's land surface [1]. Modifications began thousands of years ago when humans first transitioned from hunters and gatherers to developing the land for agriculture [2]. The first urban areas developed in regions of the world amenable to food production (i.e., fertile soils adjacent to water), e.g., Mesopotamia (4000 BCE–3000 BCE) and the Indus Valley (2500 BCE–1500 BCE) [2, 3]. Innovations in the ability to produce and store excess food formed the capacity to sustain growing populations [2].

Worldwide human population first reached one billion in 1804 and then grew exponentially because of enhanced human welfare due to Industrial Revolution, the ability to provide potable water and sanitation services, and innovations in healthcare. Exponential growth is expected to continue with worldwide population to reach 9.6 billion by 2050 [4].

The year 2009 was a significant milestone. Prior to 2009, worldwide, the majority of people lived in rural areas; after 2009, the majority lived in urban areas. The United Nations estimates that the percentage of people living in urban areas will rise to 66 % by 2050 [5]. Furthermore, the World Bank [6] predicts that, by 2050, the number of people living in urban areas will actually exceed world population totals in 2000. The proportion of people living in urban versus rural areas varies across the world – an average of 75 % for developed countries and 45 % for less developed countries. These trends are also predicted to increase – North America, Latin America, and Europe to >80 %, Asia to 64 %, and Africa to 54 % – all by 2050.

Landscape change due to accelerated urbanization is the most significant land modification occurring in the world today [7, 8]. Although urban areas are increasing in size with respect to both land area and human population [7–9], rates of conversion to urban land uses greatly exceed rates of urban population increases

[9]. In developing countries, urban land area increases are largely related to increasing populations. In many areas of the developed world, some urban areas are expanding because of population growth and expansion as people move from urban centers to urban fringes, and coupled with this expansion comes land abandonment of inner cities [10].

Ultimately, effects of urbanization, demographic and environmental across the world, have similar impacts. These effects include losses of vegetated lands, expansion of impervious surface cover, disruption of the hydrologic cycle (reduction in evapotranspiration and ground infiltration and increased stormwater runoff and flashiness of rivers and streams), increasing demands on existing infrastructures, higher air temperatures as compared to adjacent rural areas, and increasing demands on municipal services such as potable water and waste management [8]. Urban areas must import food, energy, and clean water to meet basic needs of their populations, and, as such, adverse effects of urbanization extend well beyond political boundaries [7, 8, 11–13]. In order to prevent these problems from expanding and to mitigate current effects, officials are evaluating and implementing efforts to make urban areas more sustainable. Urban agriculture forms a significant greening effort gaining wide attention because of its ability to mitigate these effects as it simultaneously provides nutritional food for populations [6, 14–17].

In this chapter, we introduce urban agriculture as a functional greenspace and review its potential to assist in efforts to improve urban sustainability. Most specifically, we focus on its potential to reinvigorate the hydrologic cycle by increasing vegetation, increasing infiltration and groundwater recharge, increasing evapotranspiration, and reducing stormwater runoff and greenhouse gas emissions. We start this chapter with a brief discussion on urban greenspaces in general, and then we define urban agriculture and discuss its role as a beneficial greenspace, its differing forms, and its water needs. We conclude our discussion on urban agriculture with a review of the literature on rainwater harvesting for urban agriculture. Our chapter then focuses on a case study – rainwater harvesting potential for the City of Roanoke, Virginia, USA. We review the state of urban agriculture in Roanoke and calculate the potential volume of rainwater that could be harvested and resultant reduction in stormwater flow and greenhouse gas emissions.

2 Urban Agriculture Is an Urban Greenspace

2.1 Urban Sustainability and Greenspaces

Urban initiatives to reduce ecological footprints, i.e., the impact of human activities, and move toward sustainability include reducing energy use, enhancing water and air quality, and increasing greenspaces. A greenspace is defined as "land that is partly or completely covered with grass, trees, shrubs, or other vegetation" [18]. Greenspaces positively affect the health and welfare of both human and wildlife populations residing in urban areas [19–23]. Examples of greenspaces' positive benefits include:

- Generating of ecosystem services [24–26]
- Contributing to biodiversity [21, 25, 27]
- Reducing air pollution and increasing air circulation [21, 25, 27, 28]
- Reducing stormwater runoff, increasing groundwater recharge, and improving water quality [12, 21, 25, 27, 29]
- Reducing the urban heat island effect [21, 25, 30]
- Generating health benefits from environmental improvements and also from increased physical exercise and stress reduction for urban residents [21, 22, 25]
- Increasing social interaction and a sense of community among urban residents [21, 22, 25, 31]

2.2 *Urban Agriculture*

Within an urban area, a greenspace "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" [25]. Urban agriculture is "the growing, processing, and distribution of food and nonfood plant and tree crops and raising of livestock, directly for the urban market, both within and on the fringe of an urban area" [32]. Urban agriculture is a productive use of green areas and clearly provides benefits beyond those provided by other greenspaces, for example, contributions to food security through production of fresh, nutritious fruits and vegetables, economic opportunities from selling agricultural products or from releasing income which can be used elsewhere [33, 34], and nurturing a sense of place [35, 36].

Furthermore, although urban agricultural productivity depends upon the same variables as rural agriculture, i.e., soils, length of growing season, water availability, and solar insolation, studies have shown that urban agriculture's output is greater in kilograms per unit area than rural agriculture [37, 38]. Urban agriculture's higher production rates are related to more efficient use of space and water (e.g., using horizontal and vertical spaces, smaller plots), producing crops with shorter life cycle, and multi-cropping [33, 39–41].

Urban agriculture is not a new phenomenon; it has been practiced since urban areas were first established [25]. Urban agriculture history in the United States (US) exceeds 100 years [42], intensifying during periods of national crisis, such as both World Wars and the Great Depression [7, 10, 43, 44]. Today, it is experiencing a revival because of current economic conditions, the recognition of benefits of locally grown food, the ability to contribute to urban sustainability, and the potential to alleviate food insecurity in low-income urban areas [10, 43, 45].

Worldwide, one in nine people suffer from chronic malnutrition due to food insecurity [46]. Food insecurity also exists in the United States – more than one in ten households suffer from food insecurity [47, 48]. Many of the food-insecure people live in urban areas since the majority of people now live in urban versus rural areas. Thus urban agriculture has become a major focus across the world [49], and it's estimated that about 800 million people participate in urban food production [50]. In a study of 15 developing countries, FAO [51] estimated up to 70 % of urban households participate in agriculture [the rates vary by country – the lowest percentage in Indonesia (around 10 %) and the highest in Vietnam (70 %)]. These percentages increase dramatically (5–40 percentage points) when one examines those households in the lowest 20 % of average incomes [51]. While urban agriculture covers production of both plants and animals for food, the predominant form is plant production for household subsistence.

2.3 Urban Agriculture's Water Needs

Land availability, access to water, and quality of soil are important factors for urban agriculture. The amount of water needed for urban agriculture depends on the type of food produced, but more importantly upon form and size of production [52].

2.3.1 Urban Agriculture Forms

Urban agriculture ranges in size from micro-gardening (i.e., containers on balconies and patios – Fig. 1), to mesoscale (i.e., shared garden plots), to macroscale (i.e., urban farms) [53]. *Home gardens*, usually identified as backyard gardens, are the most common form of urban agriculture (Fig. 2) [33, 54] and usually involve a household growing food for its own consumption on land area adjacent to their residence [54].

Community gardens (Fig. 3) are becoming a prevalent form of urban agriculture all over the world [54, 55] and are broadly defined as a community of people, sharing a relationship, cultivating an area of land. Each community member gardens an individual plot and shares in maintenance of common areas. In most instances, the land is owned by an entity (local governments, churches, nonprofit organizations) which allows the community to use the land for gardening [44, 54, 56]. The broad heading of community gardens can also include allotment or noncommercial gardens [54] and schoolyard gardens [31].

Urban farms (Fig. 4) are the largest (in areal extent) of all urban agriculture forms [33], with an identifying characteristic as a for-profit business. This urban agriculture form can include greenhouses, orchards, rooftop gardens, and community-supported agriculture, usually owned by a family or commercial operation.

Each of these various forms does have specific characteristics, as briefly described above; however, these characteristics are not exclusive to each. For example, people gardening in containers on patios, balconies, and home gardens

Fig. 1 Container garden on a patio in Blacksburg, Virginia, USA (Photo: First author, 2015)

may sell their products for profit. Orchards can be planted by municipalities for harvesting and consumption by local residents, and some urban farms exist as parts of nonprofit food banks.

2.3.2 Water for Urban Agriculture

While urban agriculture is touted as a greenspace that should be included as part of urban sustainability planning, in most cases, potable water is often used for plant and crop irrigation (Fig. 5). However, with urban areas expanding, continued use of potable water for agriculture presents many obstacles – competing demands for urban water; lack of available water resources, especially in arid or semiarid regions; and escalating costs [52]. Aiming to quantify the exact demand on

Fig. 2 Home garden in a backyard, Blacksburg, Virginia (Photo: First author, 2015)

Fig. 3 Day Avenue Community Garden, Roanoke, Virginia, USA (Photo: Third author, 2015)

municipal water supplies for expansion of urban agriculture in four Australian cities, Ward et al. [52] estimated water demand for a theoretical garden using water requirement and actual crop yield information from rural agriculture. They noted that household water demand would increase significantly, along with overall household expenses, and therefore alternative sources of water for urban agriculture should be considered. In addition, FAO [51] recommends targeting two research areas for urban agriculture water use – (1) reusing treated or partially treated wastewater, and (2) harvesting rainwater. Chapter "Urban Wastewater for

Fig. 4 A portion of Heritage Point Urban Farm, Roanoke, Virginia, USA (Photo: Third author, 2015)

Fig. 5 Potable water supply for Growing Goodwill Community Garden, Roanoke, Virginia, USA (Photo: Third author, 2015)

Sustainable Urban Agriculture and Water Management in Developing Countries" (of this book) discusses uses of wastewater in the context of urban agriculture, so we do not discuss that topic here.

Rainwater harvesting collects water runoff from impervious surfaces and, in some instances, floodwaters during rain events. Impervious surfaces can include rooftops, roads, and parking lots. Throughout existing urban agriculture literature, many authors cite uses of rainwater harvesting for irrigation purposes (e.g., [33, 57, 58]), yet scientific studies of rainwater harvesting for urban agriculture use are sparse.

The few studies identified on this topic vary in design and purpose, usually related to specific study site characteristics. Three such studies are summarized here.

Lupia and Pulighe [59] performed a similar urban agriculture water need assessment as [52] above, but quantified water demand for existing home gardens in Rome, Italy. They also calculated rainwater volume that could be harvested and used as irrigation water for these home gardens. Lupia and Pulighe [59] outline procedures for calculating rainwater harvesting potential similar to what we will discuss later in our case study, Sect. 3: rainwater harvesting from roof areas of adjacent buildings, calculating rainwater volume, and using a constant to represent the rainwater losses due to splash and evaporation. Their study estimated that (with the exception of vineyards and olive groves) harvested rainwater from roof areas would be adequate to meet water needs for all existing home gardens in Rome.

Redwood et al. [60] conducted a cost/benefit analysis of actual rainwater harvesting and gray water use (not discussed here) for urban farms in Tunisia, an arid region, and a region where recent political instability has disrupted outside food supplies. The study first evaluated the efficacy of a rainwater harvesting system, using a local school as the test site. Rainwater was collected from rooftops and greenhouses via pipes leading to a storage tank. The collected water was then pumped to greenhouses as irrigation for crops produced outside of the normal growing season. Their analysis revealed that installing such systems would create economic benefits for local urban farmers. The authors also conducted a survey of 150 urban farmers, revealing that most relied on their food production to feed their families, and more than half earned income from selling their products. Most importantly, the survey revealed that during an economic crisis, when other urban residents lost income and faced food shortages, urban farmers were able to continue to feed their families. The rainwater harvesting system was subsequently installed at 20 urban farms. Evaluation of these systems is continuing.

Richards et al. [61] constructed two vegetable rain gardens (one lined and one unlined) for subirrigation systems and prepared two control vegetable gardens using surface irrigation at the University of Melbourne, Burnley Campus (Australia). The objective of the study was to evaluate differences in yields and the need for additional irrigation during dry periods over an 18-month period. Rainwater was harvested from a nearby roof and delivered via a pipe to rain gardens where two thirds of the harvested rainwater was directed to the vegetable gardens and the remaining one third was stored in a tank for use as supplemental irrigation water. Results show that the lined rain garden needed no additional irrigation during dry periods, but the unlined rain garden and the two control vegetable gardens did require more water. Production yields were comparable, except during the winter growing season, but more importantly, the rain gardens reduced the volume and frequency of runoff by more than 90 %.

All three rainwater harvesting studies described above use only rainwater harvested from rooftops. It's suggested that rainwater runoff from impervious surfaces such as roads, sidewalks, and parking lots should be avoided in urban agriculture systems. Studies have shown that runoff from these impervious surfaces often contains contaminants such as heavy metals (common pollutants from motor vehicles); polycyclic aromatic hydrocarbons (PAHs), contaminants originating from tires, fuels, and road surfacing materials; and biological pathogens such as fecal coliform and *Escherichia coli* originating from animal waste [57]. These contaminants present human health risks to those consuming food produced and to urban gardeners working in contaminated soils [62–66].

3 Case Study

This section of the chapter describes a case study on rainwater harvesting potential for existing and potential urban agriculture sites within the City of Roanoke, Virginia, USA. The first segment provides background information on the study site. We then discuss data needs for input into the three equations that calculate (1) rainwater harvesting potential, (2) energy savings from not using municipal water supplies for irrigation, (3) reductions in stormwater runoff, and (4) reductions in greenhouse gas emissions. We next discuss methods used to identify locations of existing urban agriculture sites, new potential urban agriculture sites, and locations suitable for harvesting rainwater. Lastly, we provide study results for site identification and calculations.

3.1 Study Site

The City of Roanoke, Virginia, USA, the largest city in southwestern Virginia (Fig. 6), is 111 km^2 with a population of 99,428 [67]. The city's land use and commercial sectors are influenced by its history as a transportation hub for rail and road traffic and supporting services and industries. Additional activities include finance, distribution, trade, manufacturing, and healthcare facilities. City of Roanoke area contains 642.5 ha of parks and 96.7 ha of US National Park Service land. Its major land covers include 47.9 % tree canopy [68], 31.9 % impervious surfaces (as calculated by the first author using geospatial analysis), and the remaining land cover comprised of water, grass, bare earth, and some agriculture.

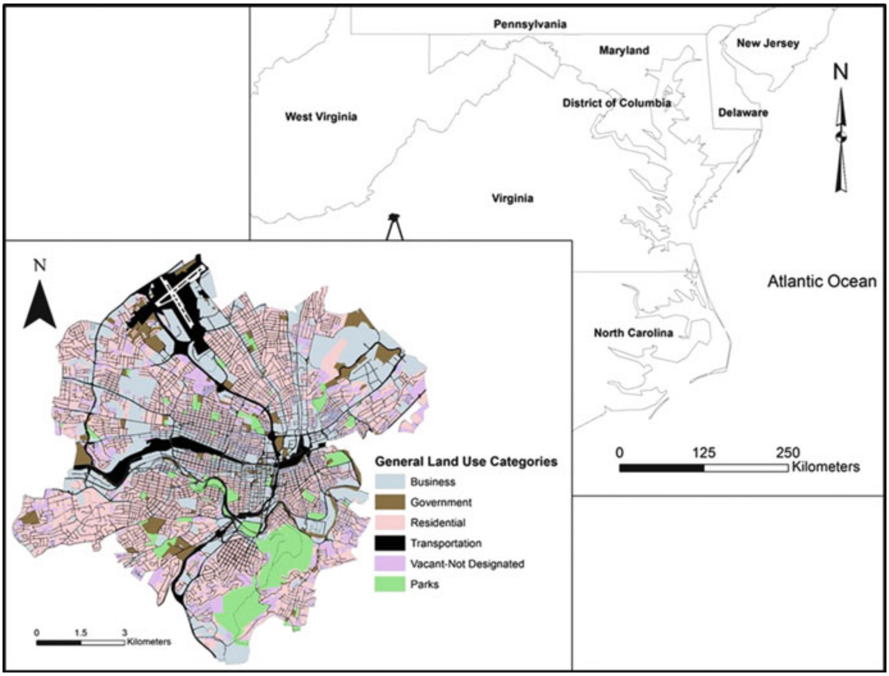

Fig. 6 Roanoke reference and land use map (*Source*: City of Roanoke Parcels Shapefile, 2015, as processed by the first author)

Although Roanoke has significant amounts of greenspace (tree canopy cover and park land), annual greenhouse gas (GHG) emissions from the city are estimated at 2,076,700 US tons (~1.9×10^9 kg) of CO_2 for 2012 [69]. In addition, the city is frequently flooded because of its proximity to the Roanoke River and which is further exacerbated by urban stormwater runoff (Fig. 7). Many segments of the Roanoke River and tributaries flowing within the city are listed as impaired due to contaminants such as *E. coli*, high water temperatures, and heavy metals exceeding Virginia's water quality standards [70].

The city population is supplied by a variety of water sources (Table 1). Electricity consumption for providing public water varies by water source (Table 1). Carvins Cove reservoir's electricity use is significantly less than the United States' average as its drinking water treatment plant uses conventional water treatment methods (coagulation/sedimentation and filtration), and the city's location is downhill from the reservoir which is located in the mountains northwest of the city. However, within the city, approximately 25 % of Carvins Cove water is pumped uphill to some residential areas, increasing energy use about fourfold [71]. Crystal Spring uses a micro-filtration with a disinfection system which is an energy-intensive water treatment process. Spring Hollow uses a newer filtration system with less chemical use, but such systems have much higher energy needs [71]. Appalachian Power Company, Inc. provides energy for the Water Authority, the city, and residents [71]. Fuels used for energy generation are coal (75.6 %), natural gas (14.2 %), and hydro (10.2 %) [72].

Fig. 7 Example of flooding (from stormwater runoff) on a major thoroughfare – US 460/Orange Avenue (downtown Roanoke is seen on the right behind the overpass) (*Source*: Public Domain, 2013, image obtained from Roanoke Civic Center Facebook site no longer in use)

Table 1 Electricity consumption versus water source [71]

Water source	kWh/million gallons	kWh/cubic meter
Carvins Cove reservoir	306.7 (75 % of customers)	0.081
	1306.7 (25 % of customers)	0.345
Crystal Spring	1751.4	0.463
Spring Hollow	5726.4	1.513
Falling Creek	Unknown	Unknown
Private wells	Unknown	Unknown

Table 2 Precipitation (cm) by month for Roanoke, Virginia, June 2014–May 2015 [74]

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Year	2015	2015	2015	2015	2015	2014	2014	2014	2014	2014	2014	2014
Cm	7.4	7.3	8.8	8.6	10.3	9.7	10.3	9.0	9.9	7.3	8.6	7.5

Roanoke receives an average of 109.7 cm (43.2 in.) of precipitation per year [73]. Total rainfall per month is fairly uniform throughout the year, with just slightly more during the months of May–September, most of Roanoke's growing season (Table 2).

Roanoke's urban agriculture scene includes community gardens, home gardens, and urban farms operated by two local food organizations. The Roanoke Natural Foods Co-op operates one urban farm at Heritage Point (Fig. 4) in northeast Roanoke and two local natural food stores. The farm's land, purchased by the Co-op in 2012, approximately 10.1 ha, is located near an industrial park [75]. The second urban farm, Lick Run, is located at the site of a defunct nursery within a residential neighborhood. It was purchased by a private citizen in 2010 with the intention of starting an urban farm and farmer's market; portions are now under cultivation (Fig. 8).

Fig. 8 Lick Run Urban Farm and Community Market, area under cultivation in photo on the left, farm house in photo on the right (Photos: Third author, 2015)

Fig. 9 Rainwater harvesting systems at Hurt Park Community Garden, photo on the *left* shows a 1500 gal (5.7 m^3) barrel to the left of the pavilion; photo on the *right* shows a second barrel to the right of the pavilion (Photos: Third author 2013)

The Roanoke Community Garden Association (RCGA) (established in 2008) cultivates several locations. Members of RCGA are environmentally conscious, as all gardens are organic and incorporate rainwater harvesting at most locations (Fig. 9). Mountain View Community Garden (established 2013) and Growing Goodwill Community Garden (established 2014) are the most recent gardens. The land for Mountain View is owned by the city but leased to RCGA for 5 years; food production started in 2014. The newest garden, Growing Goodwill Community Garden (Fig. 5), is located on property owned by Goodwill Industries of the Valleys; food production started in 2015, and additional cultivation plans include a food forest (i.e., orchard). Many RCGA gardeners (~30 %) are either refugees or recent immigrants. RCGA plans for future locations across the city, the next to be sited on land owned by a church [76]. RCGA has performed exceptionally well in siting their community gardens to assist with food security in lower-income populations – all of their community gardens are located in areas with poverty rates that exceed US national and Commonwealth of Virginia averages [77].

Home gardening is practiced within the city; these locations are identified in Sect. 3.2.

3.2 Methods

For our case study, we intend to show how much rainwater can be harvested for existing urban agriculture within the City of Roanoke and for potential new urban agriculture sites. Hereinafter, we refer to the potential amount of harvested rainwater as usable rainwater volume (URV). For calculation of URV, we use the rooftop areas of all structures located within the same parcel as the urban agriculture plot. We used rooftop areas only because of concerns, noted in Sect. 2.3.2, regarding potential contaminants from impervious surfaces on the ground – such stormwater runoff could contain pollutants from vehicle emissions (e.g., roads, sidewalks, or parking lots). As noted, contaminants from said runoff could accumulate in soils or crops, thus creating a potential human health hazard.

We also include scenarios for two large existing urban agriculture locations (Growing Goodwill Community Garden and Heritage Point Urban Farm) for which URV calculations include nearby commercial/industrial rooftops. For our final calculation of URV, we perform analysis based upon a land inventory of open areas for potential urban agriculture sites for Roanoke completed by Parece and Campbell [78].

In addition, we will calculate reductions in greenhouse gas (GHG) emissions that would occur from substituting harvested rainwater for irrigation instead of public water supplies. These scenarios calculate not only conservation of water and energy by harvesting rainwater but also reductions in stormwater runoff that could be achieved.

3.2.1 Important Equations

Variables that are important to our case study include the volume of rainwater that can be harvested, roof areas of available buildings, amount of energy used to treat and deliver potable water, and amount of greenhouse gas emissions from the fuel source for the electricity-generating power plant.

To calculate the amount of usable rainwater volume, from [79], we use the following equation:

$$\text{URV}\left(\text{m}^3/\text{time period}\right) = \text{Roof-Area}\left(\text{m}^2\right) \times \text{Average Rainfall}\left(\text{m}/\text{time period}\right) \times \text{C} \tag{1}$$

The variable C, in Eq.1, is collection efficiency – usually 0.8 – which allows for loss from splash and evaporation [79]. Again, this equation not only estimates rainwater harvesting ability, it also provides the volume reduction in stormwater runoff and the volume reduction in potable water use.

Using the reduction in potable water use, we can also calculate the amount of energy conserved from not using treated potable water and the resultant reduction in GHG, two very important factors in improving sustainability of urban areas. These two amounts are calculated from the following two equations [79]:

Table 3 Carbon dioxide emissions from electric power generation [80][a]

Fuel type	Carbon dioxide output rate (grams per kWh)
Coal	960.3
Natural gas	596.0
Petroleum	868.6
Hydroelectric	10.0

[a]Kloss [80] reports pounds per kWh; we converted to grams per kWh (1 lb = 453.592 g)

$$\begin{aligned}&\text{Energy Conserved (kWh)}\\&= \left(\text{Potable Water Saving}\left(\text{m}^3\right)\text{ x Estimated Energy Use}\left(\text{kWh/m}^3\right)\right)\\&\quad\text{- Indoor/Outdoor Pump Energy Need (kWh)}\end{aligned} \tag{2}$$

$$\begin{aligned}\text{CO}_2\text{emissions (g)} &= \text{Energy Conserved (kWh)}\\&\quad\times\ \text{CO}_2\text{output rate (g/kWh)}\end{aligned} \tag{3}$$

An input to Eq.3 is the CO_2 output rate, which depends on the fuel source for the electricity-generating power plant. We are using amounts as reported in [80] (Table 3).

3.2.2 Identifying Urban Agriculture Within Roanoke

First, we mapped the locations, using geographic information systems (GIS) software, of both urban farms and all community gardens, using information from the Roanoke Community Garden Association's website, 2011 Virginia Base Mapping Program (VBMP) aerial imagery, site visits to locations, and the city's parcels shapefile.

For home gardens, we examined 2011 VBMP aerial imagery displayed in GIS, creating polygons for each site identified. The VBMP imagery was obtained during early March, leaf-off [81], so it was sometimes difficult to distinguish between a dormant plot (no current crop growth) and a bare tract of land (see left of Fig. 10). So, we also used Google Earth™ as a cross-reference. The most recent images in Google Earth™ are National Agriculture Imagery Program (NAIP) aerial imagery taken in June 2012; thus, for instances of actual urban agriculture, a bare plot in the 2011 March imagery was seen as rows of crops (right of Fig. 10).

3.2.3 Identifying Roof Area for Existing Urban Agriculture

To identify the area of rooftop impervious surfaces within each parcel containing urban agriculture, we first intersected the shapefile for urban agriculture with the city's parcel file. Then we used the selected parcels to identify those structures (from the city's buildings shapefile) that were located within each parcel. We

Fig. 10 Example of three bare plots in residential areas – 2011 VBMP aerial imagery (*left*) – the same plots in Google Earth™ display of 2012 NAIP imagery (*right*) clearly show that these plots are cultivated

Fig. 11 Mountain View Community Garden, shed and pavilion (Photos: First author, 2015)

verified structures against the same aerial photos used in the home garden identification, to ensure that we had identified all structures; we included houses, garages, sheds, and gazebos.

In a few instances, we measured structures for rooftop areas. Most specifically, neither Mountain View Community Garden (Fig. 11) nor Growing Goodwill Community Garden appears on either aerial photos (2011 and 2012) because these gardens were established (2013 and 2014, respectively) after the images were obtained.

Additionally, Growing Goodwill Community Garden has only a shed within its boundaries but is located in very close proximity to one of the Goodwill donation centers (Fig. 12, in the background). As stated under Sect. 3.1, plans for this garden include a food forest, so its irrigation needs reach beyond that of a community garden that raises only cultivated crops. Larger rainwater harvesting systems (such as those discussed in chapter "Sustainable Water Management in Green Roofs") could be established for this location. As such, we used both the shed roof area and the donation center's roof area to calculate URV.

A similar situation applies for Heritage Point Urban Farm (a very large urban farm of 10.1 ha); irrigation needs exceed what can be generated from harvesting rainwater from roofs of buildings and greenhouses on the farm's premises.

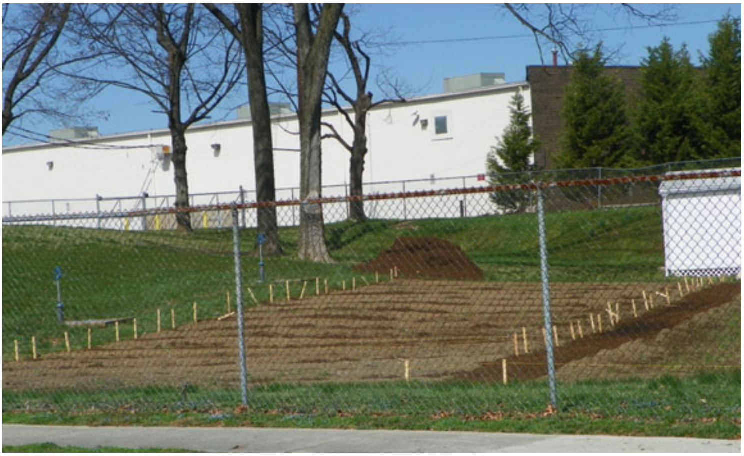

Fig. 12 Goodwill Donation Center (building in the background) near the Growing Goodwill Community Garden (Photo: First author 2015)

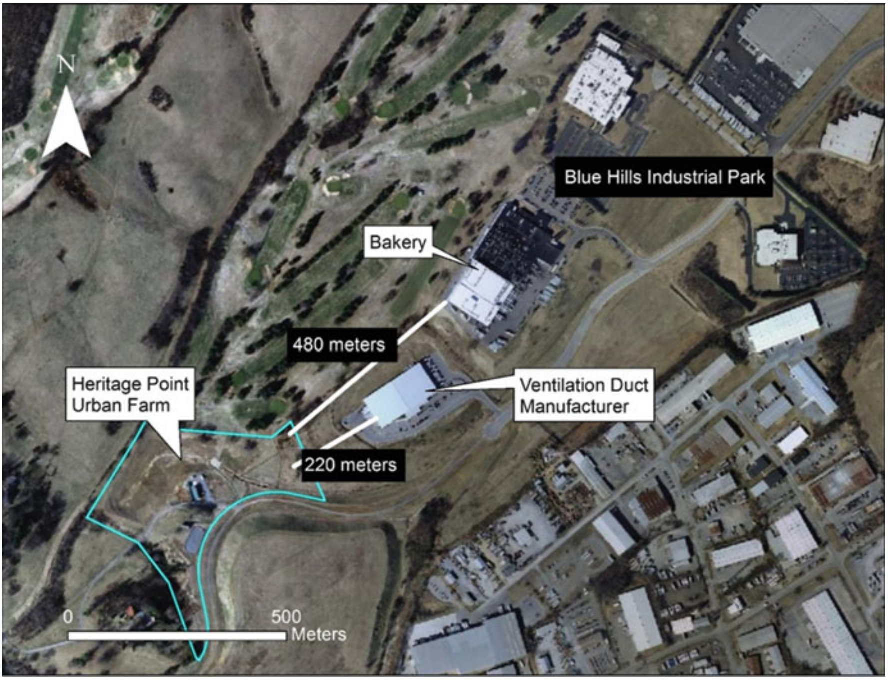

Fig. 13 Heritage Point Urban Farm and distance to commercial buildings within the industrial park (*Source*: VBMP, 2011)

But since the farm is located downhill from an industrial park, rainwater could be harvested from roofs of commercial buildings just up the road (Fig. 13).

Fig. 14 Erosion on Heritage Point Urban Farm's property caused from unchanneled stormwater runoff from the industrial park's buildings and parking lots (Photo: First author 2013)

Furthermore, stormwater runoff is actually directed from this industrial park downhill toward the farm, causing considerable erosion on the farm property (Fig. 14). So, if we include the two commercial buildings closest to the farm – a ventilation duct manufacturer and a bakery – in our calculations, URV will increase and erosion would be reduced or eliminated.

3.2.4 Identifying Roof Area for Potential Urban Agriculture Sites

For the City of Roanoke, Parece and Campbell [78] completed a land cover and land use analysis to determine if any land was open, available, and potentially suitable for new urban agriculture sites. From the analysis, they calculated that 2311.6 ha of open areas have potential for home gardens, community gardens, orchards, and urban farms. However, not all of these open areas can be placed under cultivation because portions of land available for urban agriculture would need to be used for access, equipment storage, and space for social interaction and to house rainwater harvesting equipment. In addition, not all locations identified by Parece and Campbell [78] were within parcels that contained structures – many hectares were vacant parcels with no structures – constituting highway cloverleaves, roadway and median strips, and non-parcel areas within residential neighborhoods.

As such, for this specific analysis, we use a percentage of the potential area (2311.6 ha) to estimate the roof area from which rainwater can be harvested. To determine what percent to use, we took the total rooftop impervious surface area as calculated under Sect. 3.2.2 above (including the commercial roof areas added for the Goodwill Donation Center, the ventilation duct manufacturer, and the bakery) divided by the total area of existing urban agriculture. We used all roof areas as many of the potential urban agriculture locations identified by Parece and Campbell [78] included urban farms and orchard locations that would benefit from a larger volume of harvested rainwater which could be collected from nearby commercial buildings.

3.2.5 Calculating Usable Rainwater Volume (URV)

Using roof areas (in m^2) identified under Sect. 3.2.3 and the amount of annual and monthly precipitation amounts (in m) identified under Sect. 3.1 we used Eq. (1) to calculate URV (in m^3) both annually and for the growing season only (April through October), for all existing urban agriculture sites.

Using the roof area (in m^2) identified under Sect. 3.2.4 and the amount of annual precipitation (in m) identified under Sect. 3.1 we used Eq. (1) to calculate URV (in m^3) annually for potential new urban agriculture sites.

3.2.6 Calculating Reduction in Greenhouse Gas (GHG) Emissions

To calculate reduction in greenhouse gas emissions related to energy reduction achieved from using harvested rainwater instead of public water supplies for existing urban agriculture locations, we first identified the public water source for each site. To accomplish this, we downloaded the most recent water quality report from the Western Virginia Water Authority [82]; within this document, a thematic map of the city identifies sources providing water for different areas of the city. We georeferenced this map in GIS, using the city boundary and streets shapefiles as references. We then overlaid the existing urban agriculture shapefile on this thematic map and identified each existing urban agriculture site's water source.

We identified the portion of URV (in m^3) for each water source and, using Eq. (2), calculated the amount of energy that would have been used had the same amount of water originated from the public water supply. Finally, we took the energy use and calculated the amount of carbon dioxide (in kg) for each fuel source (using Eq. 3), based on values from American Electric Power (as noted under Sect. 3.1 – coal (75.6 %), natural gas (14.2 %), and hydroelectric (10.2 %)), and estimated grams per kWh for each fuel source, as noted by [80].

3.3 Results

3.3.1 Locations of Existing Urban Agriculture and Its Water Source

We identified 461 parcels with active urban agriculture within the City of Roanoke – including the two urban farms, all community gardens, and all home gardens (Fig. 15). The Carvins Cove reservoir delivers water for 306 locations, including both urban farms and all the community gardens. Spring Hollow is the source for

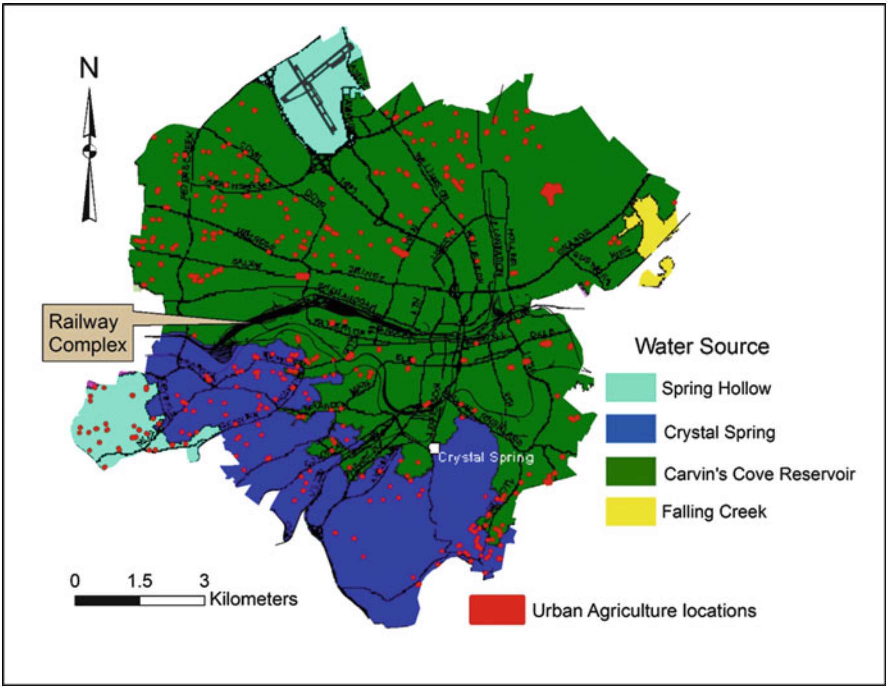

Fig. 15 Locations of existing urban agriculture and their source of water (Source of thematic water source map: Western Virginia Water Authority, 2015)

32 home garden locations. Crystal Spring is the source for 123 home gardens. Falling Creek is not a water source for any existing urban agriculture.

3.3.2 Rooftop Area Used to Calculate Usable Rainwater Volume (URV)

As Table 4 shows, 788 structures were identified within the same parcels that contain the existing urban agriculture locations. This table also provides results of the roof area calculation (81,805.2 m^2), the division of the existing locations and structures by water source, and the total hectares of urban agriculture by water source.

Table 4 Total number of parcels containing existing urban agriculture, total hectares, number of structures, and total roof area (m^2) by water source

Water source	No. of parcels containing urban agriculture	Area of urban agriculture in all parcels (ha)	No. of structures within each parcel	Roof area (m^2)
Carvins Cove	306	15.6	553	53,854.3
Crystal Spring	123	1.6	184	21,113.0
Spring Hollow	32	0.6	51	6837.9
Total	461	17.8	788	81,805.2

Table 5 URV (m^3) for existing urban agriculture locations by structures contained within the same parcel as the plot

Water source	Roof area (m^2) (from Table 4)	URV (m^3) annually (using Eq. 1)	URV (m^3) growing season only (using Eq. 1)
Carvins Cove (75 % of customers)	40,390.7	35,446.9	21,035.5
Carvins Cove (25 % of customers)	13,463.6	11,815.7	7011.8
Crystal Spring	21,113.0	18,528.8	10,995.7
Spring Hollow	6837.9	6000.9	3561.2
Total	81,805.2	71,792.2	42,604.2

3.3.3 Usable Rainwater Volume (URV) for Existing Urban Agriculture

For those structures contained within the same parcel as the existing urban agriculture location, Table 5 shows the URV, by water source. If harvested throughout the year, the total amount is 71,792.2 m^3, or if only harvested during the growing season (April through October), the amount is 42,604.2 m^3. Using Crystal Spring, as an example of our calculations and as inputs for Eq. 1:

$$21,113.0\ \mathrm{m}^2 \times 1.097\ \mathrm{m} \times 0.8 = 18,528.8\ \mathrm{m}^3 \tag{1}$$

Table 6 shows the results for the additional analysis for Growing Goodwill Community Garden. With only the shed roof area, total annual URV is 15.9 m^3. If we add the roof area of the nearby donation center, the URV amount increases substantially to 88,502.2 m^3. Since orchards are to be included in this area, water need exists for the entire year, not just the growing season.

Table 7 provides the results for the URV potential for Heritage Point Urban Farm, annually. Since greenhouses and orchards are housed at this urban farm, water need exists for the entire year, not just the growing season. URV for just the roof area of the farm buildings is 410.3 m^3. If we include the ventilation duct manufacturer building's roof area, URV increases significantly by 77,917.2 m^3.

Table 6 URV, annually, for Growing Goodwill Community Garden

Building	Roof Area (m^2)	Annual rainfall (m)	URV (m^3)
Shed	18.1	1.097	15.9
Donation center and shed	100,845.7	1.097	88,502.2

Table 7 URV, annually, for Heritage Point Urban Farm

	Roof area (m^2)	Annual rainfall (m)	URV (m^3)
Farm buildings	467.5	1.097	410.3
Duct manufacturer	88,784.4	1.097	77,917.2
Bakery	232,807.6	1.097	204,312.0
Total potential URV for all roof areas			282,639.4

If we include both the duct manufacturer's building's roof area and the bakery's roof area, URV increases to 282,639.4 m^3.

3.3.4 Usable Rainwater Volume (URV) for Potential Urban Agriculture Sites

Total roof area calculated for the first three scenarios above is 504,710.4 m^2; total existing urban agriculture is 17.8 ha or 178,000 m^2. Roof area represents 280 % of that total area. Potential urban agriculture totals 2311.6 ha or 23,116,000 m^2. It is unreasonable to assume that 280 % of this area would be available as roof areas for harvesting of rainwater. As such, we will be conservative in our estimate of roof area available for potential rainwater harvesting for new potential urban agriculture sites. Using 25 % as the potential roof area within the potential urban agriculture sites, we calculate 5,779,000 m^2 of potential roof area for rainwater harvesting or a URV of 5,071,650.4 m^3.

3.3.5 Calculations of GHG Emission Reduction

Table 8 shows energy required if potable water, equal to the amount of URV, was used for irrigation. We calculated these amounts, within this table, using Eq. 2, e.g., annual URV (from Table 5) for Crystal Spring equals 18,528.8 m^3. Thus, the annual kWh per m^3 for Crystal Spring is 0.463 (from Table 1).

$$8,578.8 \text{ kWh} = 18,528.8 \text{ m}^3 \times 0.463 \text{ kWh/m}^3 \quad (2)$$

Therefore, using harvested rainwater for irrigation, instead of potable water, for the Crystal Spring water source, saves 8578.8 kWh each year. We did not calculate the

Table 8 Calculation of total energy conserved (kWh/m^3) by water source – annually and for the growing season only

Water source	URV annually (m^3) (from Table 5)	URV (m^3) growing season only (from Table 5)	kWh/m^3 (from Table 1)	Total kWh annually	Total kWh growing season only
Carvins Cove (75 %)	35,446.9	21,035.5	0.081	2871.2	1703.9
Carvins Cove (25 %)	11,815.7	7011.8	0.345	4076.4	2419.1
Crystal Spring	18,528.8	10,995.7	0.463	8578.8	5091.0
Spring Hollow	6000.9	3561.2	1.513	9079.4	5388.1
Total	71,792.2	42,604.2	–	24,605.8	14,602.0

Table 9 Potential reduction in CO_2 emissions (kg) annually and for the growing season only, by fuel source and in total

Fuel source for Roanoke (from Sect. 3.1)	Total kWh annually (Table 8)	CO_2 emissions (kg) annually	Total kWh growing season (Table 8)	CO_2 emissions (kg) growing season
Coal (75.6 %)	18,602.0	17,863.5	11,039.1	10,600.9
Natural gas (14.2 %)	3494.0	2082.4	2073.5	1235.8
Hydroelectric (10.2 %)	2509.8	25.1	1489.4	14.9
Total	24,605.8	19,971.0	14,602.0	11,851.6

energy usage for pumping of harvested rainwater as the energy could be produced using renewal sources such as wind or solar.

For all parcels with existing urban agriculture locations and structures within the same parcels, the reduction in CO_2 emissions is 11,851.56 kg for rainwater harvested only during the growing season (May–October) and 19,971.06 kg if rainwater is harvested throughout the entire year (Table 9). These amounts were calculated by using the kWh usage values from Table 8 for each fuel source (as noted under Sect. 3.1) and the CO_2 emissions per kWh from Table 3, as inputs to Eq. 3. As an example:

$$\text{Total kWh use, annually, for coal is } 75.5\% \text{ of } 24,605.8 = 18,602.0$$
$$18,602.0\,\text{kWh} \times 960.3\,\text{g/kWh} = 17,863.5\,\text{kg/year.} \tag{3}$$

Table 10 provides the CO_2 emission reduction for Growing Goodwill Community Garden, for the shed roof only and also if we include the commercial roof areas.

Table 11 provides the results for Heritage Point Urban Farm, for the farm buildings only. If we include the commercial building roof areas, an additional 5817.96 kg/year and 18,581.49 kg/year, respectively, of carbon dioxide emissions is reduced.

Table 10 Potential reduction in CO_2 emissions, Growing Goodwill Community Garden scenario, each year

	Shed only		Shed and Goodwill store	
Fuel source for Roanoke (from Sect. 3.1)	Total kWh	CO_2 emissions (kg) (Eq. 3)	Total kWh (Eq. 2)	CO_2 emissions (kg) (Eq. 3)
Coal (75.6 %)	Negligible		5420.49	5205.30
Natural gas (14.2 %)			1018.13	606.81
Hydroelectric (10.2 %)			731.34	7.3
Total	1.29		7169.96	5819.4

Table 11 Potential reduction in CO_2 emissions, Heritage Point Urban Farm scenario, each year

	Farm buildings only		Farm buildings, duct manufacturer, and bakery	
Fuel source for Roanoke (from Sect. 3.1)	Total kWh (Eq. 2)	CO_2 emissions (kg) (Eq. 3)	Total kWh (Eq. 2)	CO_2 emissions (kg) (Eq. 3)
Coal (75.6 %)	25.12	24.13	17,307.71	16,620.59
Natural gas (14.2 %)	4.72	2.81	3250.92	1937.55
Hydroelectric (10.2 %)	3.39	0.03	2335.17	23.35
Total	33.23	26.97	22,893.79	18,581.49

4 Conclusions and Recommendations for Additional Research

Our study shows that, for the City of Roanoke, Virginia, USA, a significant amount of rainwater – 442,933.8 m^3/year – could be harvested from adjacent rooftops to provide irrigation needs for existing urban agriculture. This amount also represents the volume of stormwater runoff that could be reduced if we were to use the harvested rainwater for irrigation, a significant volume in light of Roanoke's flooding problems. In addition, this effort would reduce the use of municipal water supplies, energy used to provide that water, and emissions of greenhouse gases. Our methods can be used to estimate similar projections for any other urban area, as has similarly been accomplished for Rome, Italy [59].

Our study does not address if these savings are adequate to meet the water needs of urban agriculture, as agricultural needs are highly dependent upon crop type and timing of rainfall. Estimating Roanoke's water needs for existing urban agriculture is difficult because we do not have knowledge of actual crops grown in an individual plot. Roanoke is located in a water-rich and agriculturally viable area, so the potential diversity of crops produced likely puts such comprehensive estimates for all crop production beyond reasonable capabilities. However, this task will require further consideration when addressing rainwater harvesting abilities of urban areas situated in arid and semiarid regions.

Additionally, we have used average rainfall rates for the entire city. We should note that urban weather stations are often sparse, unevenly distributed, and that rainfall across a specific urban area can be extremely variable [83]. Thus, the effort to estimate the match between urban agriculture's water needs and availability of usable rainwater volume should be accomplished in the context of urban climatology research. Likewise, our calculations are based on local historical rainfall data and do not consider deviations that may result from climate change. Additional data quantified in conjunction with climate research could be used in identifying the right crops for the right location in order to achieve full agricultural potential.

Studies to quantify potential rainwater harvesting volume are extremely sparse. But geospatial technologies (i.e., GIS, remote sensing, and GPS) and the widespread availability of aerial imagery of the world's urban regions and of climate data allow for the identification of existing urban agriculture, available rooftop areas for rainwater harvesting potential, water flows, water sources, and calculation of URV and GHG. As such, these values could be estimated for any urban area, worldwide.

Future research should be based upon implementation of rainwater harvesting systems at a variety of scales (see chapter "Sustainable Water Management in Green Roofs"), to include control garden plots designed without such systems, measurements of the volume and quality of rainwater harvested, records of the volume and nutritional viability of crops produced from such systems, and reporting of actual empirical evidence of diversion of stormwater runoff from said implementation.

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