

# The Effect of Urban Density and Urban Form on Rainwater Capture Efficiency in Arlington, VA and Washington, DC

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## ABSTRACT

Rainwater harvesting is an increasingly important strategy for reducing dependence on imported water and managing urban flooding in growing cities and suburbs. However, limited city-wide research has compared rainwater capture efficiency across different building types, such as high-rises, rowhouses, and detached homes, under real-world usage scenarios in both Washington, DC and Arlington, VA. Therefore, this study investigates how differences in building density and form influence rainwater harvesting efficiency in Arlington, VA, compared to Washington, DC. Building data was obtained from official government websites for both regions and QGIS (Quantum GIS), which was used to quantify building footprint area, density, and distribution (Arlington County Government, 2025; District of Columbia Government, n.d.) Important aspects analyzed include roof coverage percentage, total annual rainwater capture, and per capita rainwater availability relative to average water demand. These metrics were used to evaluate which region demonstrates greater rainwater harvesting potential under similar climatic conditions to test the hypothesis that Arlington, VA would exhibit higher rainwater capture efficiency per inhabitant due to lower building density and greater roof area per inhabitant, although Washington, DC, may have a higher total capture volume due to its larger overall area. By providing a direct comparison between an urban and suburban environment with very similar climate characteristics, this study offers insights into how urban form influences water sustainability and landscaping for both urban and suburban environments to maximise rainwater capture.

## INTRODUCTION

The use of harvested rainwater for non-potable purposes, such as irrigation, can significantly lower water costs and improve urban sustainability (Beirne et al., 2022). Most existing research focuses on a single building-level system rather than a comprehensive, larger-scale analysis on large urban areas (Braga, et al., 2018). In Washington, DC, some advanced systems achieved 95% event harvesting efficacy, and if implemented on a larger scale, rainwater could be maximised to lower water costs and improve urban

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sustainability (Braga et al., 2018). Additionally, building form and roof design play a critical role in rainwater capture, with low-density buildings and larger horizontal structures generally capturing more water than densely packed vertical high-rises (Sahin et al., 2019). In contrast, dense urban environments with taller buildings often face limitations due to space constraints for storage, and higher water demand (Farenny et al., 2011; Boix et al., 2018).

It has been found that low-density areas with detached or low-rise buildings typically perform better because they offer larger roof areas relative to population and water demand, allowing more rainwater to be captured and stored per user (Ennenbach, et al, 2018). In higher-density cities, those with mid- and high-rise buildings, the available roof area per occupant decreases, which can limit the overall volume of harvested rainwater and reduce system efficiency unless designs are carefully optimized. These spatial differences are especially important in cities, where the population is very high, but the space is very limited. Several case studies have been explored on how building type and size affect the efficiency of rainwater capture systems across the world. For instance, Sahin et al., 2019, compares two different building forms and roof-styles in relatively the same area, with the same number of occupants in each. Their conclusion was that the amount of rainwater collected depends on the catchment area, which is a result of the building type. Additionally, Bañas et al., 2023, analyzes the importance of rainwater harvesting, and how useful it can be in both cities and lesser-dense areas like towns or suburbs. Overall, they concluded that rainwater collection efficiency depends on building density and type, the amount of rainwater collected was higher in the area with more space between buildings, a higher roof surface area, and a slanted roof. Lastly, Farenny et al., 2011, discussed the importance of flat roofs compared to slanted roofs for rainwater harvesting, and mentioned how in less dense areas, like suburbs, with the same amount of annual rainwater as cities, usually collect more rainwater due to having more slanted roofs. Lastly, the researchers deduced that between high-rises and average houses, average houses typically collect more rainwater per building. Low-rise or typical houses tend to have more roof area per building footprint, while high-rises concentrate people vertically with relatively smaller roof space (Sahin, et al., 2019).

Arlington, VA and Washington, DC's building form distribution differs due to their contrasting zoning plans, with Arlington including more residential districts and DC including a larger mix of residential, commercial and other zones. Washington, D.C. zoning allows for a greater amount of rowhouses, apartments, and mixed-use buildings and Arlington, VA's zoning causes more low-density single-family zones (e.g., R-5, R-6) (Gridics, n.d.; District of Columbia Office of Zoning. (n.d.))

Rapid urbanization and the increasing pressure on municipal water supplies have intensified the need for alternative water resources. By capturing and storing precipitation from rooftops and other impervious surfaces, rainwater harvesting systems can reduce potable and non-potable water demands (Aladenola et al., 2010).

In Washington DC and Arlington, VA, sustainability initiatives increasingly emphasize stormwater management and water conservation due to high urban density and high population.

Rainwater harvesting systems typically consist of multiple components, including catchment surfaces (such as roofs), conveyance systems (gutters and downspouts), storage tanks or cisterns, pumps, and

filtration or treatment units. Roof surfaces act as the collection area, while gutters and downspouts transport runoff to storage systems (Alim et al., 2023).

Urban design characteristics, including building density, layout, and form play a significant role in determining the potential for rainwater capture. Furthermore, rainwater harvesting represents a critical component of sustainable urban water management. By reducing stormwater runoff, Rainwater harvesting systems can mitigate urban flooding which is a significant challenge in older cities such as Washington, DC. Furthermore, harvested rainwater can reduce demand on potable water supplies (Qin, 2020). This study builds on existing research by examining how rainwater harvesting potential in Arlington, Virginia, and Washington, DC is shaped by roof shape, urban density (building design and space between each building), providing insights to support more sustainable water management strategies.

To evaluate how differences in building density and building type influence the efficiency of rainwater capture systems in Arlington, Virginia, and Washington, DC, this study will employ an approach using QGIS spatial analysis to quantify potential rainwater capture relative to urban form and to compare efficiency between the two areas.

## **METHODS**

This study used QGIS-based spatial analysis to calculate rainwater yield based on building footprint area, building density, and land-use type in Arlington, VA and Washington, DC (QGIS Development Team, 2024). Datasets on building footprints per area were captured from Arlington and DC's open data portals and then calculated by QGIS's software to get the surface area of building footprints in each city in  $m^2$  (Arlington County Government, 2025; District of Columbia Government, n.d.). For this first-order estimate, building footprint area was used as a proxy for roof catchment area, although actual capture area may vary depending on roof slope, material, overhangs, rooftop equipment, and drainage design. Each dataset was clipped to the respective city boundary and projected into a meter-based coordinate system (EPSG). Building footprint areas were then summed using QGIS geometry tools to calculate total roof surface area for each city.

QGIS also allowed for mapping urban density to assess how variation in density correlates with rainwater harvesting potential (QGIS Development Team, 2024).

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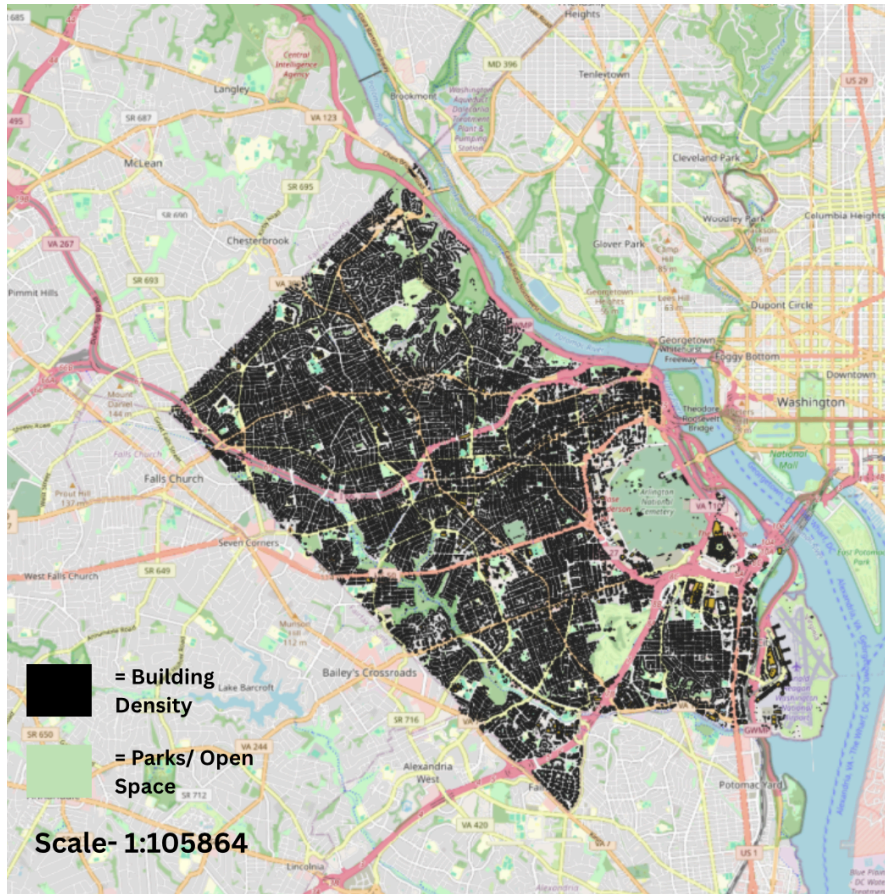


Figure 1: Map of Arlington, VA in QGIS

Figure 1 displays the spatial distribution of building footprints across Arlington, VA. The dispersed, low-density pattern results in greater roof area per capita, directly increasing potential rainwater capture efficiency per person.

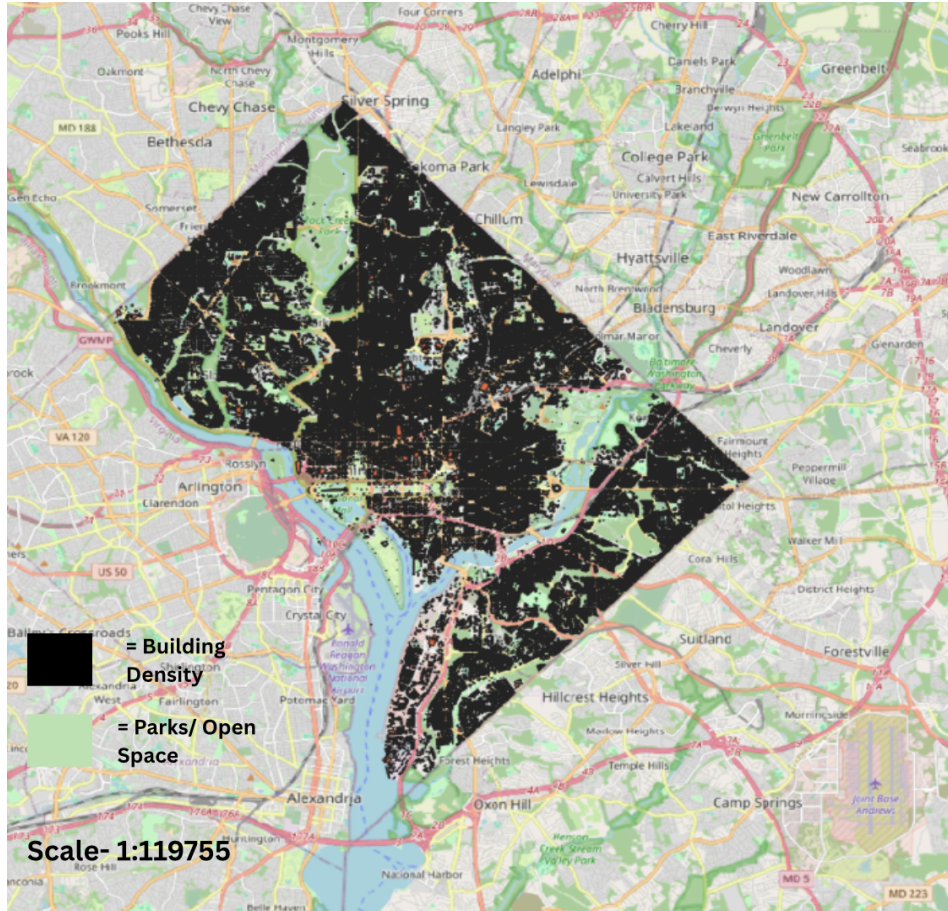


Figure 2: Washington, DC in QGIS

The high concentration of structures in Washington DC reduces roof area per building, therefore decreasing per capita rainwater capture despite a greater total catchment area.

All analyses and area calculations were performed in QGIS. Building footprint and total land area measurements were extracted using QGIS tools, providing the basis for calculating roof coverage and estimating rainwater capture potential. Three primary metrics were calculated: (1) roof coverage percentage, (2) total annual rainwater capture per city, and (3) per capita rainwater capture compared to water demand.

To calculate roof coverage percentage, the total area of all building footprints was added up and divided by the total land area of each city (calculated in QGIS in  $m^2$ ), and then multiplied by 100 to be converted into a percentage. This value demonstrated the proportion of the city's surface capable of capturing rainwater.

$$\text{Equation 1: Roof Coverage (\%)} = [\text{Total Roof Area (} m^2 \text{)} / \text{Total City Area (} m^2 \text{)}] \times 100$$

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Total annual rainwater capture was calculated by using the total building footprint area ( $m^2$ ) and multiplying that by the average annual rainfall (converted to meters) and a runoff coefficient to account for water loss due to material, evaporation and inefficiencies across water collection. Annual rainfall data was used for both cities due to their similar climate conditions, and acquired from the national weather service for 2025 (National Weather Service, n.d.). Additionally, the runoff coefficient was the same for DC and Arlington, as the rooftop surface has similar material properties and runoff behavior across Washington, DC and Arlington, VA. The runoff coefficient was derived from Washington, DC, data and was calculated by finding the general average of runoff coefficients across typical land uses (commercial, low-density dwellings, general industry) (District Department of Energy and Environment [DOEE], 2013).

Equation 2: Total Rainwater Capture ( $m^3$ /year) = Roof Area ( $m^2$ )  $\times$  Annual Rainfall (m)  $\times$  Runoff Coefficient (0.8)

For the per capita analysis, the previously calculated total annual rainwater capture was divided by the population of each city to estimate rainwater availability per person (USA Facts, n.d.; Arlington County Government, 2025). This value was then compared to average annual water demand per capita, which was done separately for Arlington and DC as water usage patterns differ between the two areas, affecting overall demand. Water demand was derived from an approximation of daily water use as of 2025 from Arlington and DC converted to cubic meters per year (DC Water, n.d.; Arlington County Government, 2024). This comparison allowed for evaluation of how much of total water demand could potentially be met through rainwater harvesting.

Equation 3: Per Capita Rainwater Capture ( $m^3$ /person/year) = Total Annual Rainwater Capture / Population

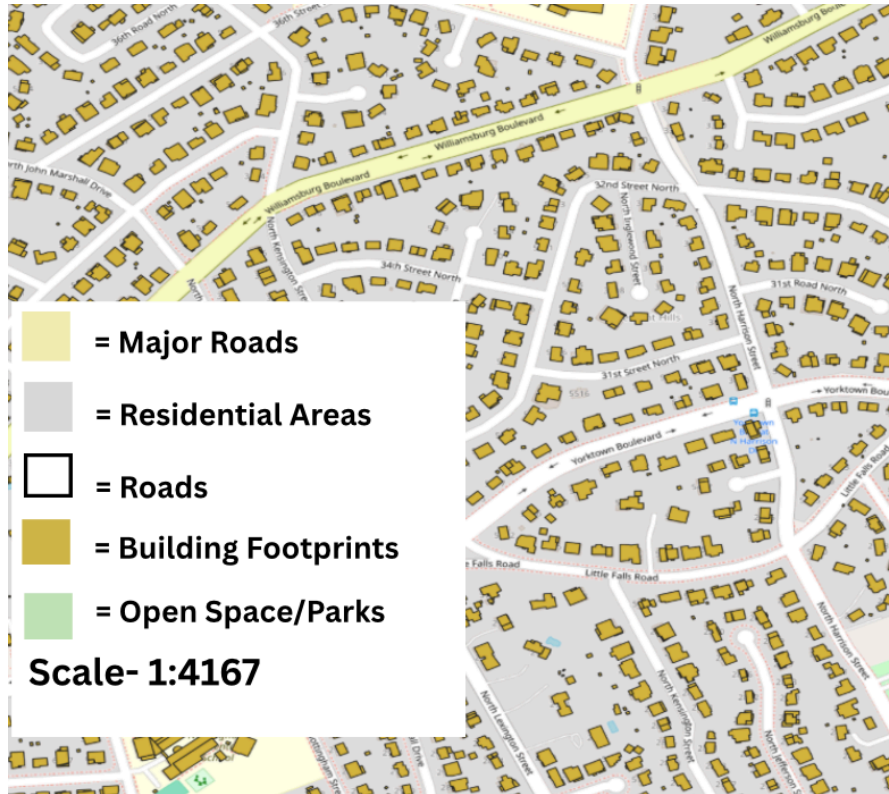


Figure 3: Building Density Close-up in Arlington, VA from QGIS

Arlington, VA, utilizes detached, single-family rooftops distributed across low-density areas to maximize individual catchment area, supporting higher per capita rainwater yield.

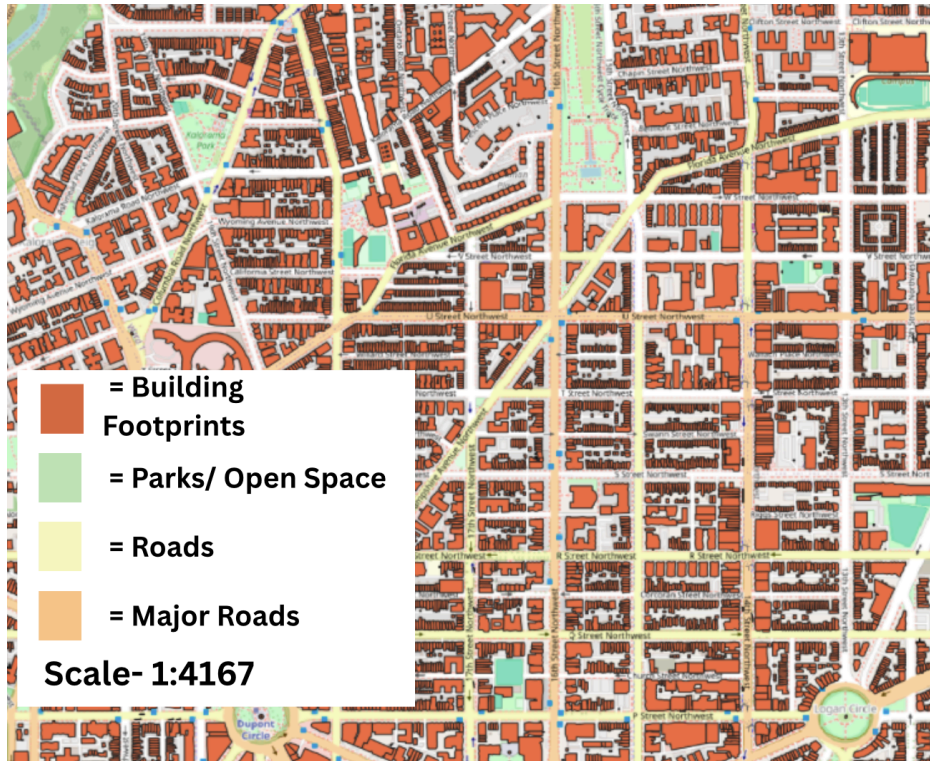


Figure 4: Building Density Close-up in Washington, DC From QGIS

The densely packed buildings limit how much roof area each resident can access, reducing individual access to rainwater capture.

Zoning areas for both Arlington, VA and Washington, DC were also analyzed to identify dominant building and land-use types, and zoning maps were obtained from DC's official government website and another certified zoning website for Arlington (Arlington County Government, n.d.; District of Columbia Office of Zoning, n.d.). The specific region was broken down into R1, R2, R3, commercial and other zones, but the data was split into 5 categories : residential (single + multifamily), transportation infrastructure, commercial, government owned institutions and open land.

## RESULTS

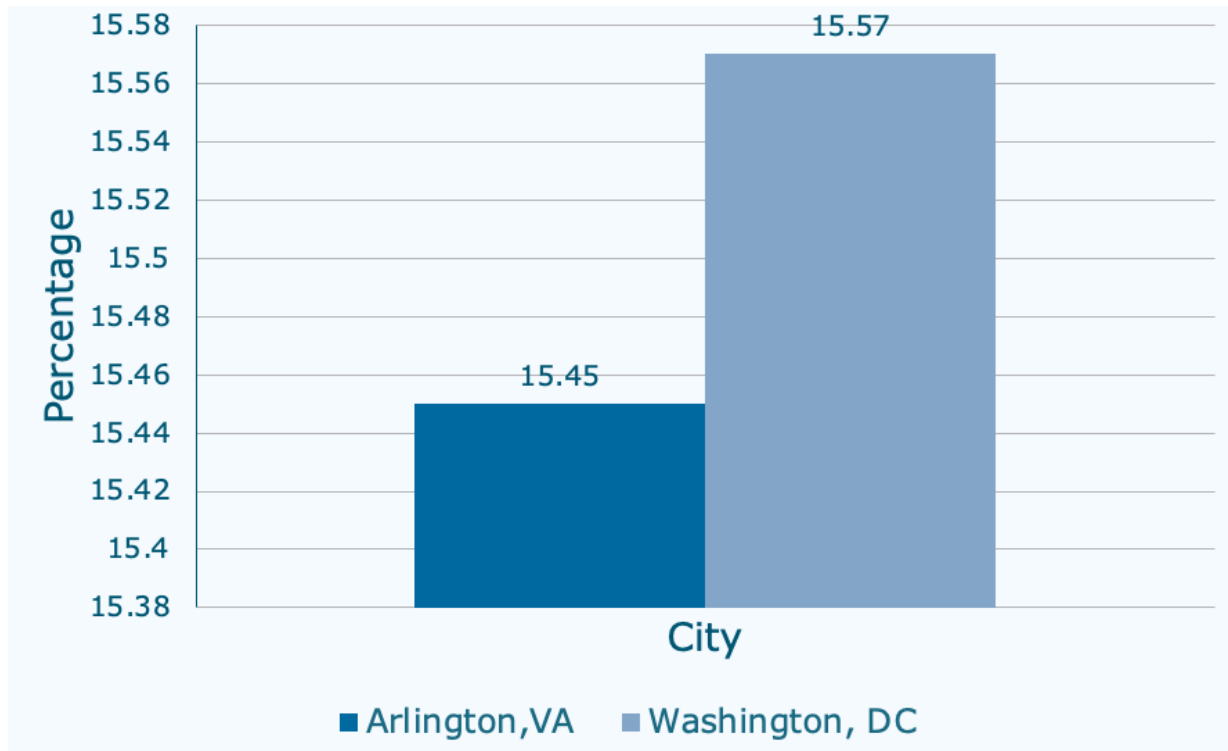


Figure 5: Roof Coverage Percentage of Entire City Area.

Both cities have similar roof coverage, suggesting that differences in per capita capture are driven more by population density and urban form than by total roof coverage alone.

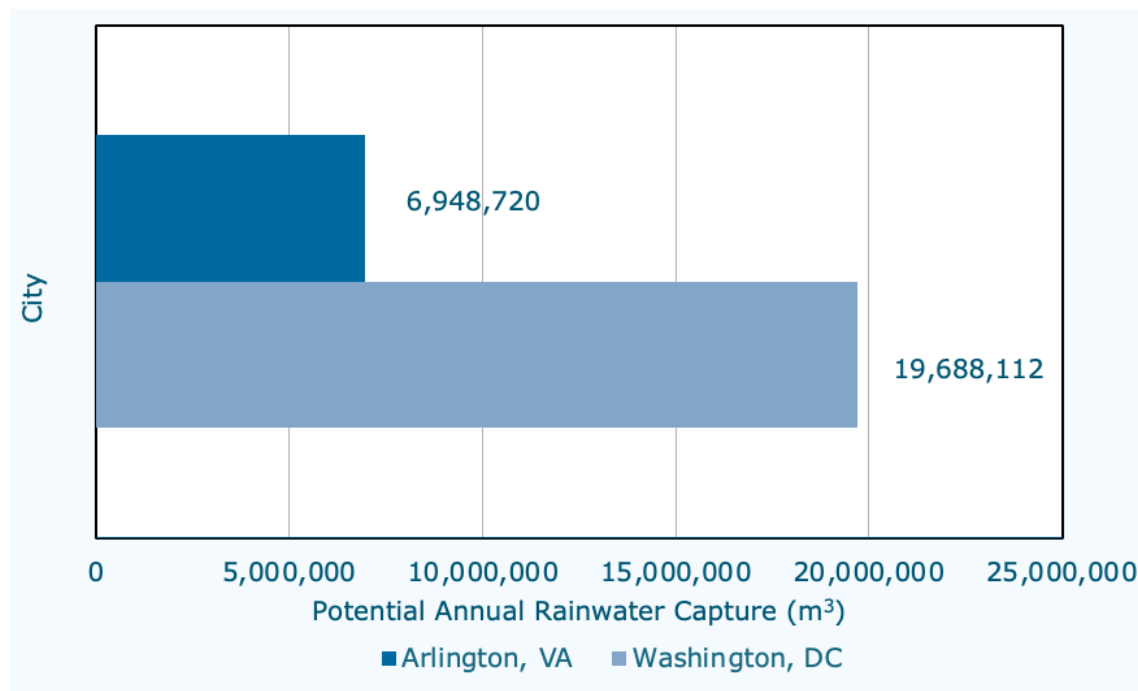


Figure 6: Total Potential Rainwater Capture Annually for Arlington, VA and Washington, DC ( $m^3$  per year)

The large difference comes mainly from DC's larger land area, not from better roof coverage or harvesting efficiency.

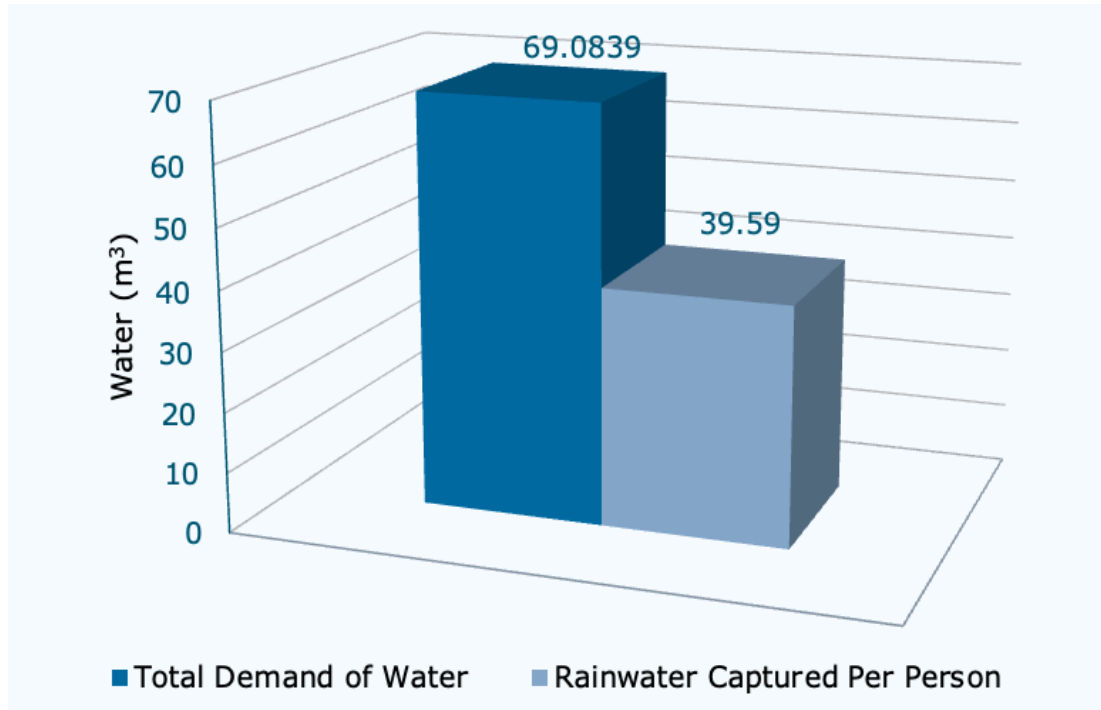


Figure 7 : Average Demand of Water (Potable and Non-Potable) Per Capita Annually vs. Potential Rainwater Capture Volume Per Inhabitant Annually ( $m^3$  per person) in Arlington, VA

Rainwater capture (39.59  $m^3$ /person) could meet 56.52% of total annual demand (69.08  $m^3$ /person), showing that rainwater harvesting is a realistic water management option in lower-density areas.

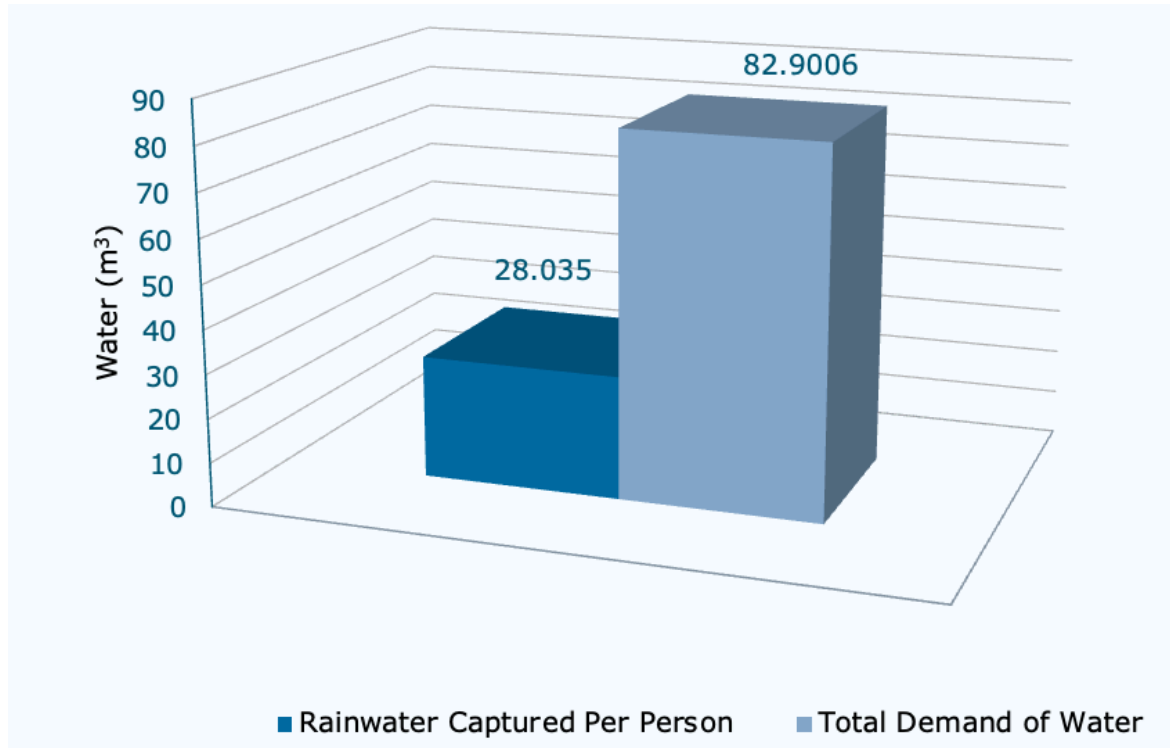


Figure 8: Average Demand of Water (Potable and Non-Potable) Per Capita Annually vs. Potential Rainwater Capture Per Inhabitant Annually ( $m^3$  per person) in Washington, DC

Rainwater capture (28.04  $m^3$ /person) only meets 32.53% of total demand (82.90  $m^3$ /person), showing that higher density limits how effective harvesting can be.

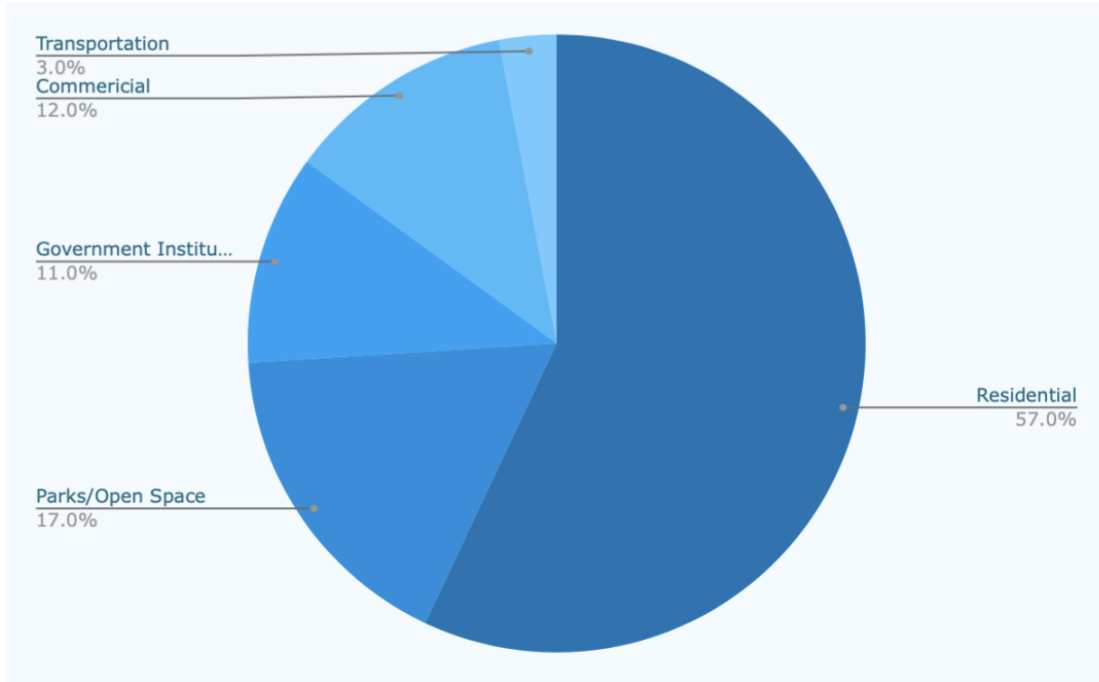


Figure 9: Arlington, VA Zoning Distribution (percentage is rounded to nearest whole number)

The large portion of residential zoning (57%) reflects Arlington's low building density, which explains the higher roof area per person and stronger rainwater capture efficiency found in this study.

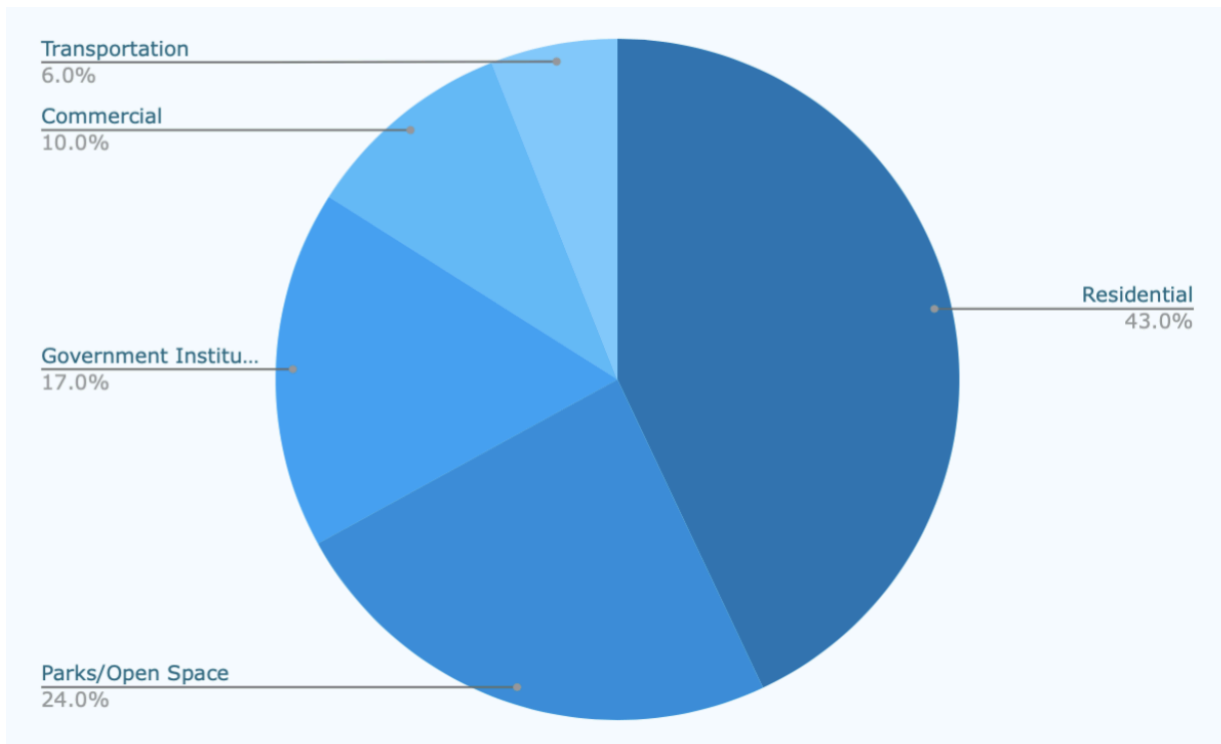


Figure 10: Washington, DC Zoning Areas Distribution (percentage is rounded to nearest whole number)

The more even spread across residential (43%), parks/open space (24%), and government institutions (17%) reflects a denser, more mixed-use city where roof area is distributed across many land use types, leaving less available for residential rainwater harvesting.

The results between Arlington, VA and Washington, DC's rainwater harvesting potential demonstrate a clear distinction between total rainwater capture and per capita efficiency. While Washington, DC has a significantly higher total potential rainwater capture than Arlington, (19,688,112  $m^3$  vs. 6,948,720  $m^3$ ) due to its larger land area, Arlington demonstrates greater efficiency on a per capita basis (39.59  $m^3$  vs. 28.035  $m^3$  / per person). This supports the initial hypothesis that lower-density environments with greater roof area per inhabitant allow for more effective rainwater harvesting at the individual level.

Although both cities have nearly identical roof coverage percentages (approximately 15.5%), their differing urban form and density lead to contrasting outcomes in water capture efficiency. Arlington's predominantly residential areas and lower-density development result in more roof area per person, increasing the amount of rainwater that can be captured per inhabitant. In contrast, Washington, DC's higher building density and prevalence of more vertical buildings reduce roof area per capita, limiting access to harvestable rainwater. Additionally, in Arlington, potential rainwater capture (39  $m^3$  per person) represents a substantial portion of total annual water demand (69  $m^3$ ), which is 56.52%, whereas in DC, rainwater capture (27  $m^3$ ) is much lower relative to demand (83  $m^3$ ), and is 32.53%. These findings suggest that total water capture is primarily influenced by city size, while per capita efficiency is driven by urban density and land use patterns. The findings have important implications for water sustainability and the feasibility of rainwater harvesting systems. In Arlington, the potential rainwater captured per capita represents a substantial proportion of total annual water demand, indicating that rainwater harvesting could significantly offset non-potable (greywater), as greywater accounts for approximately 69% of domestic water consumption (Oteng-Peprah et al., 2018). Average greywater usage is 45.42 cubic meters per person per year, and rainwater harvesting in Arlington per person per year can meet 87.16% of that need while Washington, DC can meet 61.72% (Ecoview Water Management, n.d.). Washington, DC shows a much lower proportion of rainwater capture compared to demand, meaning that while rainwater harvesting can contribute to water supply, it is unlikely to meet a large share of non-potable demand without large-scale infrastructure development.

These results align with prior research indicating that building form and density strongly influence rainwater yield (Sahin et al., 2019). Additionally, this study expands on previous work, which primarily focused on individual systems, by demonstrating how these principles apply at a city-wide scale (Braga et al., 2018). The comparison between Arlington and Washington, DC highlights how urban planning and zoning decisions directly impact the potential for sustainable water management.

However, several limitations should be considered. This analysis assumes that all roof surfaces are equally effective for rainwater collection and does not account for variations in roof angle, material

type, both can significantly affect runoff efficiency. For example, steeper roof angles may increase runoff speed, while flat roofs may retain or lose water differently. Additionally, the study assumes a completely similar rainfall distribution between Washington, DC and Arlington, VA, which may not reflect the variability between the places. Economic factors, including installation, maintenance, and infrastructure costs, were also not considered and may influence the practical implementation of rainwater harvesting systems at a larger scale. Lastly, Most studies on rainwater harvesting do not differentiate rainwater capture efficiency between residential (R1, R2 and R3) and commercial zones, which may have distinct water usage patterns and storage needs. Future research should examine these differences to ensure system design and policy incentives are appropriately targeted and effective across different areas.

Future research should incorporate more detailed building characteristics, including roof slope, material composition, and drainage efficiency, to produce more accurate estimates of rainwater capture. Additionally, integrating economic analyses, such as cost-benefit analyses and payback periods for residential and community-scale systems, as well as policy considerations like stormwater fee reductions, would improve understanding of the feasibility of these rainwater harvesting systems. The results of this study suggest that future urban planning efforts should prioritize rainwater harvesting in lower-density areas, where it is most effective per capita, but continue to implement strategies for higher density areas, particularly for outdoor landscaping usage. As rainfall variability and urban water demand continue to change, strategies such as green roofs, underground storage tanks and smart monitoring systems should be tailored to urban form and density to improve long-term water sustainability.

## **CONCLUSION**

This study demonstrates that building density and land use patterns between areas with similar climates determine whether rainwater capture can be a meaningful water solution or only a minor supplement. Rainwater harvesting potential is strongly influenced by building density and land use, even in areas with similar climates. Lower-density, residential environments like Arlington, VA can capture a large portion of non-potable water demand, 56.52% for Arlington compared to 32.53% for Washington, DC, demonstrating that decentralized rainwater systems can be both practical and impactful. In contrast, denser urban environments like Washington, DC face limitations; although the city can collect a substantial total volume of rainwater (19,688,112  $m^3$ ), smaller roof area per person reduces the impact of rainwater harvesting per inhabitant. Arlington, with a total capture potential of 6,948,762  $m^3$ , illustrates how greater surface availability in low-density neighborhoods enhances the effectiveness of rainwater collection.

Ultimately, this research underscores that effective water sustainability strategies must be tailored to the structure of the city itself. Designing solutions that reflect the differences of urban form and density will be essential for achieving meaningful and scalable impact for the area.

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