Assessment of Rooftop Potential for Solar Energy and Rainwater Harvesting in Islamabad: A Geospatial Approach Towards Sustainable Urban Development

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Introduction/Importance of Study:
The growing water and energy crises, exacerbated by abnormal temperature fluctuations, shifting precipitation patterns, and rapid urban expansion, have disrupted sustainable processes in many urban areas. This study explores the untapped potential of urban rooftops in contributing to sustainable urban development by assessing their viability for solar energy generation and rainwater harvesting. By focusing on this underutilized aspect of urban infrastructure, the study aims to address critical issues related to water and energy management in cities.

Novelty Statement:
This research employs advanced geospatial techniques to evaluate rooftop characteristics, assessing their potential for solar energy generation and rainwater harvesting. The integration of cutting-edge geospatial data and methodologies provides new insights into the sustainable use of urban rooftops.

Material and Method:
To estimate the total rooftop area, the study utilizes Open Buildings V3 Polygons data with a resolution of 50 cm, which is freely accessible. Current rooftop uses and characteristics are derived from remote sensing data and analyzed using Geographic Information System (GIS) methodologies. The potential for renewable electricity generation is evaluated using Global Solar Atlas data, while rainwater harvesting potential is calculated based on precipitation data from the Pakistan Meteorological Department.

Results and Discussion:
The analysis reveals that the rooftops in Islamabad have the capacity to harvest approximately 778.92 million gallons of rainwater annually and generate about 16,504.29 MWh of solar energy per year. These findings indicate that rooftops could significantly contribute to meeting the capital city's water and energy needs. Notable potential for solar energy and rainwater harvesting is observed in the sectors of I8, I9, H9, H13, I14, the Blue Area, Rawat Industrial Area, and DHA. Based on these results and public feedback, recommendations for future energy policies, urban planning, and the sustainable use of rooftop spaces are proposed. Islamabad is well-positioned to lead the way towards a more sustainable future.

Concluding Remarks:
Implementing the proposed systems for solar energy generation and rainwater harvesting could reduce reliance on non-renewable energy sources and mitigate urban flooding risks. This approach offers a viable solution for enhancing sustainability in urban environments and improving resource management.

Keywords: Sustainable Urban Planning, Remote Sensing, GIS, Solar Energy, Rainwater Harvesting

Introduction:

Over half of the global population now resides in urban areas—a figure that continues to rise, particularly in densely populated cities—the challenges associated with rapid urbanization are becoming increasingly significant [1]. This urban growth leads to climate change and overconsumption of resources, resulting in critical shortages of essential resources such as water and energy [2]. In Islamabad, a city with a population of nearly 2 million, the influx of immigrants driven by its status as the federal capital, housing government institutions, universities, and affiliated services, exacerbates these pressures [3,4]. The growing population intensifies the strain on natural resources and has adverse environmental impacts [3,4].

Addressing these challenges effectively requires transitioning from traditional power generation methods to renewable energy sources [5]. Nations worldwide are striving to develop alternative energy solutions to meet the goal of limiting global warming to below 1.5°C [6]. Among renewable energy sources, solar photovoltaic (PV) technology has seen the most rapid growth since 2018 [7]. Studies highlight that installing solar panels on rooftops offers a practical solution for sustainable urban development, providing suitable sun-facing locations for energy generation while mitigating environmental impacts [8,9,10].

As urban land becomes increasingly scarce and expensive, rooftops present a viable solution for solar energy generation. These spaces, often underutilized and directly exposed to sunlight, are increasingly being leveraged for clean energy production [10]. Pakistan faces two major energy-related issues: a severe energy crisis, with frequent power disruptions [11], and reliance on non-renewable energy sources that contribute to environmental degradation [12]. The use of solar energy not only addresses these issues by improving air quality and reducing greenhouse gas emissions but also has the potential to meet up to two-thirds of a city's electricity demand, depending on specific local conditions [13,14].

Additionally, the global water shortage, driven by factors such as expanded irrigation, population growth, improved living standards, and changing consumption patterns, poses significant challenges [15]. Reports indicate that up to 20% of the global population may face water shortages in the near future [16,17]. To address this, two strategies are available: finding new sources of fresh water or implementing water-saving measures. Unfortunately, the former is often prioritized without effective policies to prevent severe water shortages [18]. Pakistan, already categorized as a water-stressed country by the Asian Development Bank, faces dire consequences from extreme population growth [19]. Sustainable management of water resources is crucial, and rainwater harvesting offers a promising solution [20,21].

Rooftop rainwater harvesting (RRWH) systems are gaining popularity due to the significant surface area provided by rooftops, which cover approximately half of metropolitan surfaces [23,24]. These systems are essential for sustainable urban development, as they help conserve water supplies, reduce storm runoff, and restore natural water cycles [25]. RRWH is practical at commercial, household, and community levels [26,27], and is critical in addressing the challenges posed by rapid population growth [28]. By reducing urban floods, improving environmental sustainability, and decreasing water pollution from surface runoff, RRWH presents numerous research opportunities [29,30].

Analyzing the potential of unused rooftop areas is crucial for solving problems in densely populated cities. The effectiveness of rooftop utilization for environmental sustainability depends on local climate conditions, population dynamics, and growth rates. This study combines GIS and Remote Sensing techniques to assess the potential of rooftops for both rainwater harvesting and solar energy generation. Using rainfall data from the Pakistan Meteorological Department and solar potential data from the Global Solar Atlas, the study aims to highlight the significance of rooftops in mitigating urbanization effects and provide recommendations for local authorities to address energy and water crises effectively.

Objectives:

- To emphasis the need of sustainable rooftop uses for mitigating the impact of urbanization.
- To highlight the importance of the efficient use of underused areas of urban settings.
- To provide guidance for combating urban problems in terms of sustainability, local weather improvement and water and energy crises.
- To highlight the importance of rooftops to harvesting natural resources in urban settings.

Novelty Statement:

This study employs high-resolution remote sensing data and GIS techniques to assess the potential of rooftops for rainwater collection and solar energy generation. Both rainwater harvesting and solar energy are recognized as environmentally sustainable solutions. Despite their individual merits, previous research has not thoroughly explored the integration of these systems for sustainable rooftop applications. This study aims to provide a comprehensive analysis of sustainable urban development by incorporating both rainwater and solar energy systems. Additionally, open-building V3 polygon data was utilized to accurately measure rooftop areas.

Material and Methods

Investigation Site

Islamabad, the capital city of Pakistan, is strategically located between the provinces of Punjab and Khyber Pakhtunkhwa. The city is nestled in the foothills of the Himalayan range and is situated within the Margalla Hills. Covering a total area of 1,015 square kilometers, Islamabad is divided into distinct zones: residential, administrative, and industrial [31]. The city's geographic coordinates are approximately 72°48' to 73°22' east longitude and 33°28' to 33°48' north latitude [32].

Rapid population growth has led to significant transformations in the city, both anticipated and unanticipated. The continuous expansion of urban development and increasing population density have resulted in various environmental challenges. Islamabad's climate is classified as humid subtropical, with five distinct seasons: winter (November-February), spring (March-April), summer (May-June), monsoon (July-August), and fall (September-October) [33]. The hottest month is June, with temperatures often exceeding 38°C, while July sees significant rainfall. In contrast, January temperatures can approach freezing [34].

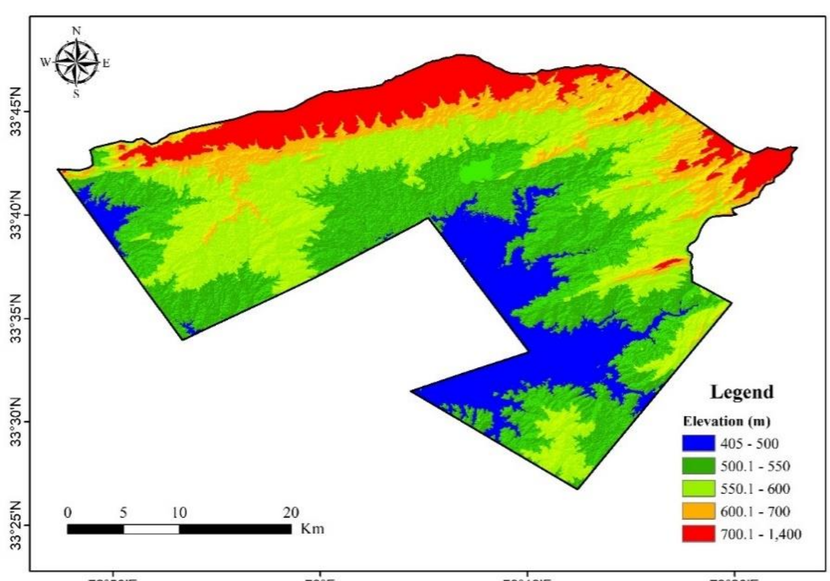

Figure 1: Study Area map of Islamabad

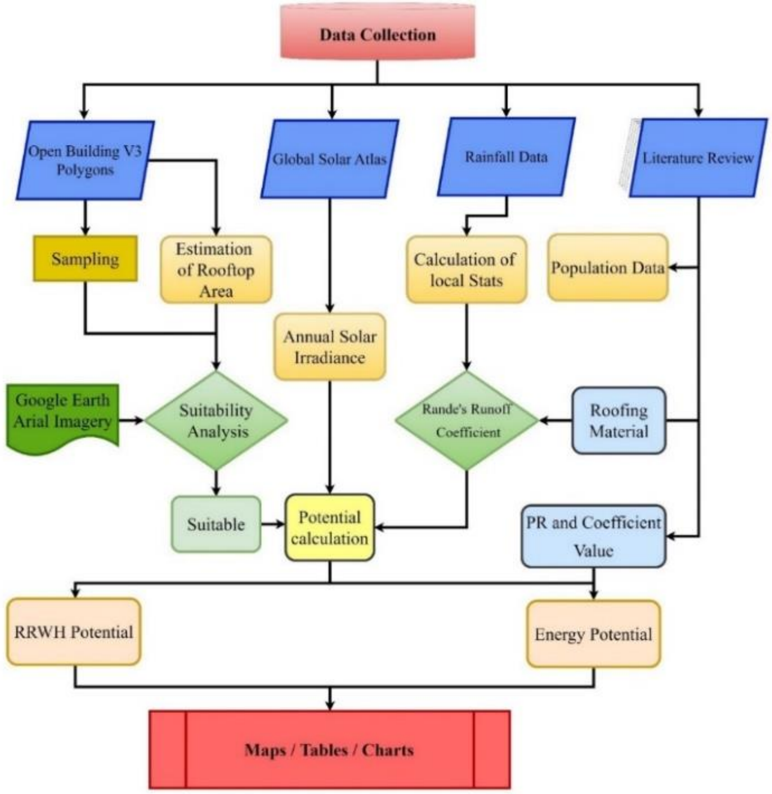

Figure 2: Workflow diagram of study

Material and Methods:

The calculation of rooftop potential for both rainwater harvesting and solar energy relies on the precise measurement of rooftop areas, which corresponds to the area defined by building footprints. This assessment begins with the Open Buildings V3 Polygons dataset, which is accessible through platforms such as Google Earth Engine (GEE) and the Google Research Forum. The dataset, derived from high-resolution satellite images with a 50 cm resolution, covers over 1.8 billion building instances across Africa and Southeast Asia, encompassing a total area of 58 million square kilometers. Each entry includes a polygon representing the building's footprint, a confidence score reflecting the accuracy of the detection, and a plus code indicating the building's center. The confidence score is crucial for assessing the reliability of the data; higher values signify more accurate detection, while scores below 80 suggest the need for further validation on the ground. For this study, only building footprints larger than 177 m^2 were considered, based on the assumption that households with rooftops exceeding approximately 7 Marla are more likely to invest in sustainable practices. By filtering the dataset according to these criteria, the total rooftop area was calculated using Google Earth Engine (GEE). This methodology, including the steps for filtering and area calculation, is detailed in Figure 2, ensuring that the rooftop area data used for evaluating potential sustainability applications is both accurate and relevant.

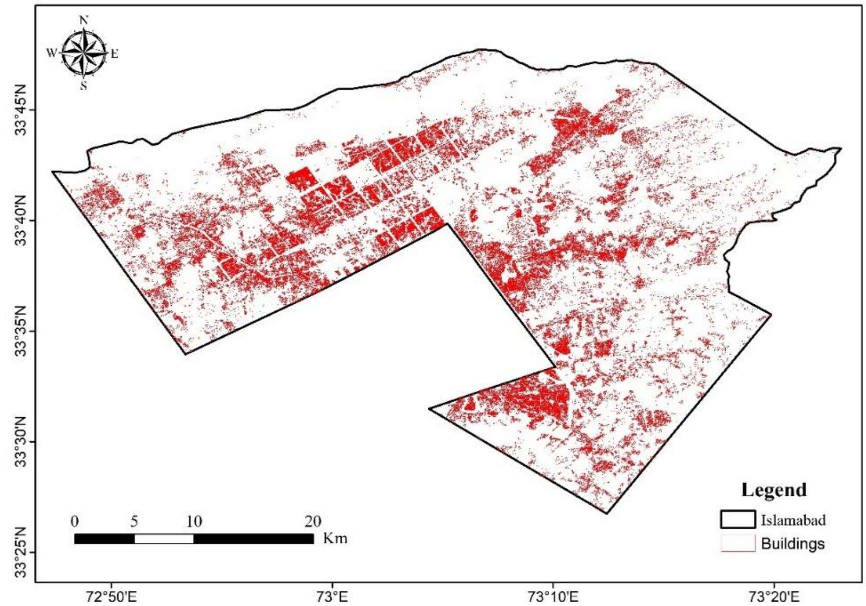

Figure 3: Building footprint considered for study after applying two conditional filters.

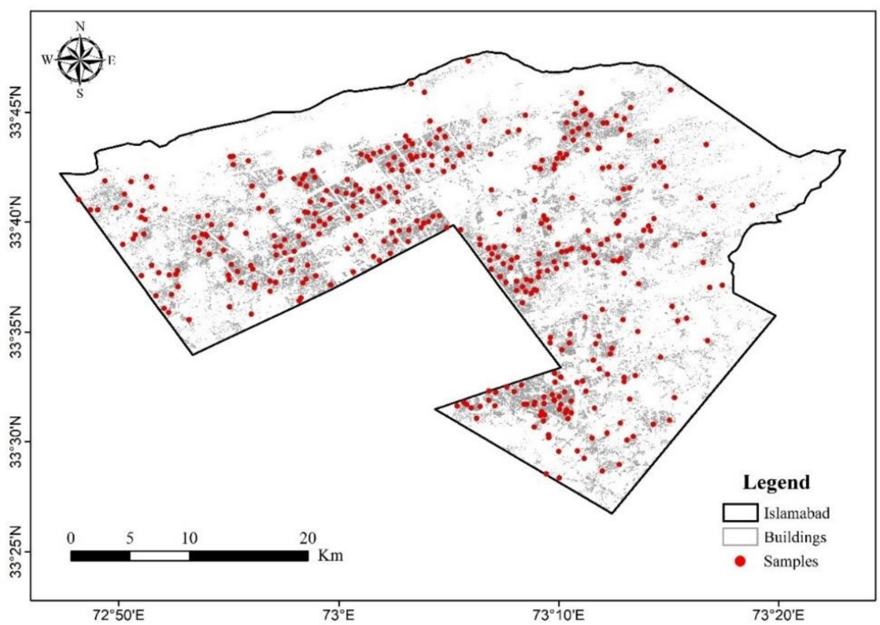

Figure 4: Islamabad Rooftop Area Sampling

Two primary parameters essential for this study include analyzing flat rooftops, roofing materials, rooftop utilization, and structural integrity to ensure accurate results. Given the extensive time required to assess each roof's suitability individually, a random sampling approach was adopted for this analysis. Statistically, approximately 385 samples were required; however, the sample size was rounded up to 400 to enhance the robustness of the findings, with all sample points illustrated in Figure 4. This comprehensive sampling aimed to evaluate the condition, structure, and availability of rooftops across the study area.

The analysis indicated that a significant portion of rooftops in Islamabad are flat and underutilized, making them highly suitable for rainwater harvesting (RRWH) and solar energy generation. Notably, the F7/2 sector was identified as having a high number of inclined rooftops, which diminishes its suitability for photovoltaic energy generation, as depicted in Figures 5, 6, and 7. Islamabad, renowned for its advanced urban planning, is divided into five zones. Zones 1 and 2 are primarily residential, subdivided into 2 km by 2 km sectors, while the remaining zones include industrial and less developed areas. The analysis revealed that buildings in Islamabad are not densely clustered, with well-aligned layouts, further supporting the potential for effective rooftop utilization for sustainable practices.

Figure 5. Rooftops View of ISB [37]

Figure 6. Rooftop Cafe, ISB [36]

Figure 7. Rooftop Garden ISB [38]

Rainwater Harvesting Potential:

The calculation of RWH potential (Equation 1) is derived from the Rooftop Catchment Method as defined by [27].

$$S = A_c \times R_m \times C_R \quad (1)$$

Where A_c represents the area of the catchment, R_m represents the average rainfall annually, and C_R represents the coefficient of runoff. The total area of the rooftop is calculated by utilizing open-source building footprint data provided by Google Research - Open Buildings in GEE. For the accuracy of the result, about 5 to 6 houses were physically visited for measurement purposes. The magnitude of rainfall is a crucial factor in assessing the potential for RRWH. The data from the Pakistan Metrological Department (PMD), Islamabad, covering a period of 5 years from January 2019 to December 2023, has been acquired. This data is utilized to illustrate the pattern of precipitation in Islamabad. The total monthly precipitation is calculated using this data and analysis is conducted on the mean annual rainfall data of 5 years in order to determine RRWH potential. The total mean monthly precipitation in each month from 2019 to 2023 is also calculated in order to determine annual cycle of precipitation, with the maximum and the minimum precipitation levels. (Figure 8) displays the mean monthly precipitation map of Islamabad.

Rande's Runoff Coefficient:

Rande's coefficient (Table 1) is actually dependent on the type of roof material metal, concrete cement, bricks, or tile. It's about the material's capacity to retain water, for instance vegetation can lower the coefficient value. The runoff coefficient is a ratio that expresses the relationship between the amount of rainfall and the pace at which runoff occurs. It is a factor that does not have any dimension. The factor is obtained by taking into account the inability to capture all the rainwater runoff from a catchment surface. A significant quantity of runoff is consistently lost from the catchment surface as a result of evaporation or retention on the surface. The combined catchment losses is observed [39].

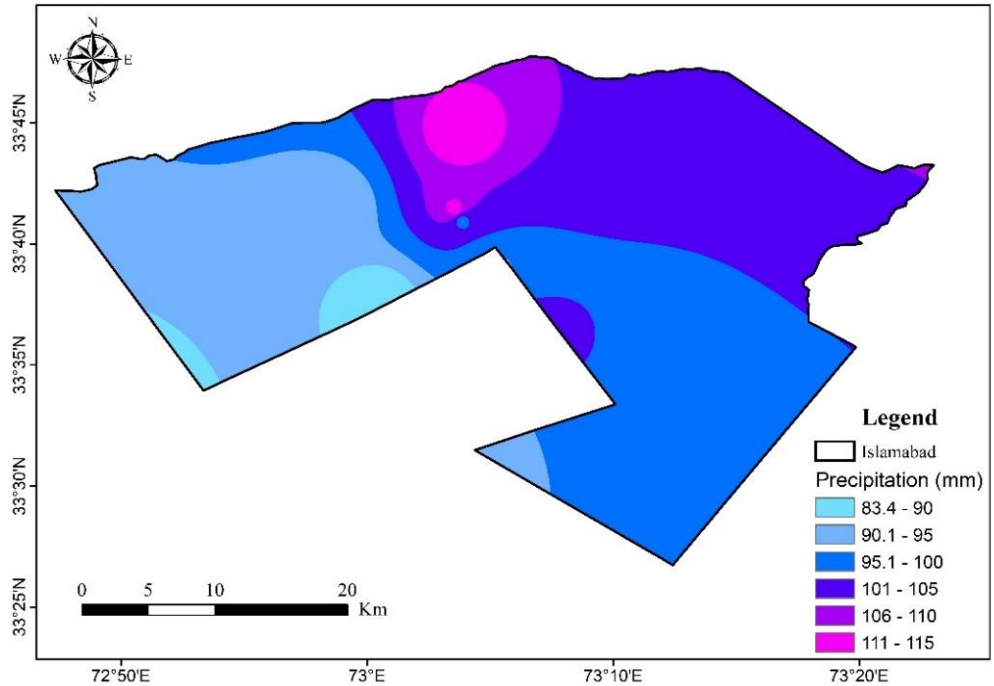

Figure 8: Spatial distribution of average annual Precipitation in Islamabad city from 2019 to 2023 (Source, PMD).

Tabel 1: Roofing Material Types along with runoff Coefficient Values

Roofing Material Types	Estimated Efficiency [40]
Concrete Cement	80 - 85
Metal Sheets	60- 70
Tiles	85- 90
Unpaved Soil	30 - 40

Roofing Material:

The majority of Islamabad's population, approximately 80%, resides in separate houses, while the remaining 20% residing in flats and apartments. The majority of houses in Islamabad are built with cement concreted rooftops, but a minority of residences have tiled roofs. This material is beneficial for RRWH because it effectively manages the quick runoff from concrete surfaces and minimizes water losses [41]. So, we used Cr value of 0.8.

Table 1: An overview of the rooftops of Islamabad

Description	Related Facts
Total Area of Islamabad	1015.03 km^2
Total Rooftop Area	58.22
Building area > $177m^2$	37.69 km^2
Unused area of rooftops	90%
Used %	10
Residents Accessibility to rooftop	Higher
Energy efficiency of rooftops	Very High
Flat roof tops	97%
Inclined rooftops	3%
Structural stability for RRWH	Yes
Structural stability for Solar	Yes

Solar Power Potential:

The World Bank Group partnered with Solargis, a leading global provider of solar data and analysis, to develop the Global Solar Atlas. This atlas, based on Solargis's extensive database of solar resources, aims to provide accessible and comprehensive data on solar potential and photovoltaic power at a regional level [42]. Utilizing the solar atlas data, the study computed global horizontal irradiance, which includes key solar radiation characteristics such as Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI). These parameters are crucial for evaluating solar radiation since solar power potential depends on the interaction of solar radiation with the Earth's atmosphere and its wavelength, with scattering influenced by environmental objects [43].

The estimation of solar radiation reaching the Earth's surface involves three main factors: DNI, which represents the sun's direct radiation without interference; DHI, which accounts for radiation scattered by clouds and other objects [44]; and Global Horizontal Irradiance (GHI), a measure of the potential solar energy [45]. The GHI is calculated using the formula:

GHI=Cos(θz)×DNI+DHIGHI = \text{Cos}(\theta_z) \times DNI + DHIGHI=Cos(θz)×DNI+DHI

where Cos(θz)\text{Cos}(\theta_z)Cos(θz) is the cosine of the zenith angle, which adjusts for the angle of incoming solar radiation [46]. To accurately estimate solar power potential, knowledge of at least two of these factors, along with the zenith angle, is required [47]. Figure 9 illustrates the spatial distribution of GHI across the study area. Within a GIS environment, this GHI map was overlaid with a building footprint shapefile to focus exclusively on rooftop radiation. The resulting map was classified to highlight areas with higher solar radiation, indicating greater energy potential for rooftops that receive more sunlight.

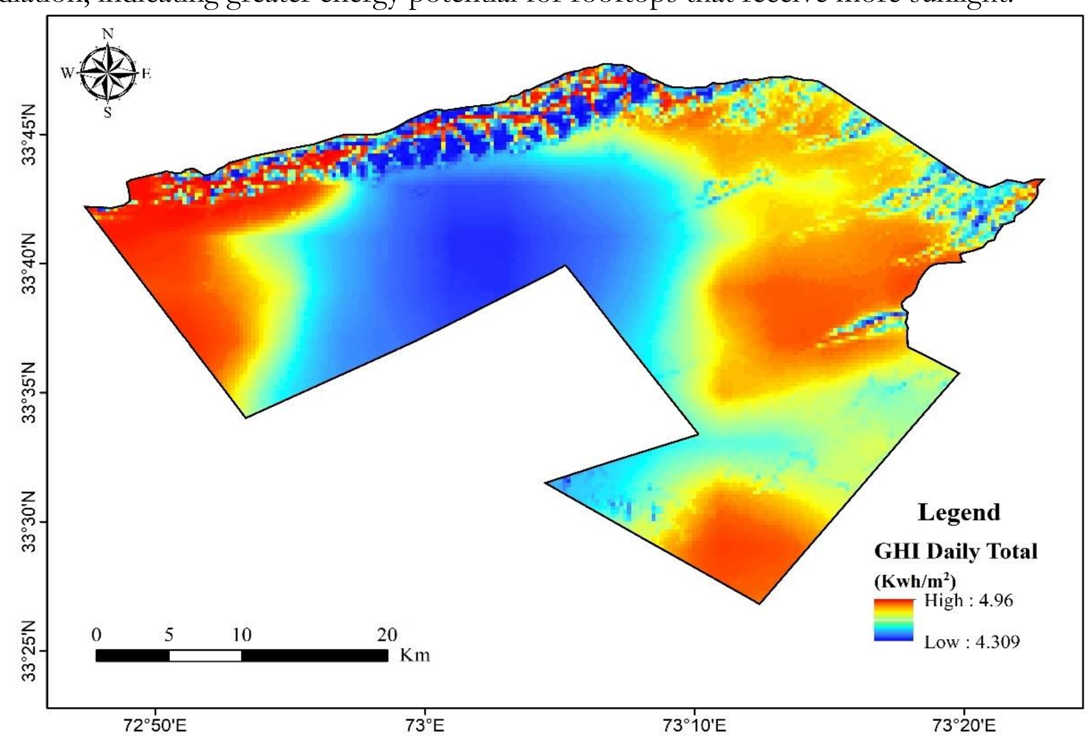

Figure 9: Annual mean GHI map of Islamabad

The estimated electricity generation from the solar PV system is referred to as the potential of the rooftop area. The equation used to calculate the efficiency of the rooftop solar PV module (Equation 3) in this study has been widely applied by numerous other studies [48] [49].

$$E = A \times r \times H \times PR \qquad (3)$$

Here E is the energy potential represented in the unit of Kwh, A is the area of all rooftops of the study area being considered in this study after applying the minimum area and confidence level filter, r is the efficiency of the panel, which has a range of 15 to 18, PR is the performance ratio, which represents the energy loss in the inverter, cables, and dust on the panels and ranges from 0.5 to 0.9, and H is the solar radiation received by the panels, which will be GHI in this study [50] [51]. Here the value of PR 0.8 is used, it depends upon the system status given in (Table 2). 0.8 is used in this study as a result of discussion with popular system supplier in city.

Table 2: PR values w.r.t System

System Status	PR values [52].
Proper maintained system	0.8 – 0.90
Average maintained system	0.75 – 0.8
Substandard management	Less than 0.75

Result and Discussion:

The primary objective of this study was to examine the integration of solar power generation and rainwater collection on the rooftops of houses in Islamabad, with a specific focus on sustainable urban development. According to rainfall statistics, Islamabad receives approximately 1200 mm of rainfall annually. This indicates significant potential for capturing and storing this water for domestic use. Over the past few years, the combination of fog and smog has resulted in more than 25 days in December where megacities in Punjab province have not been able to witness a sunrise [56].

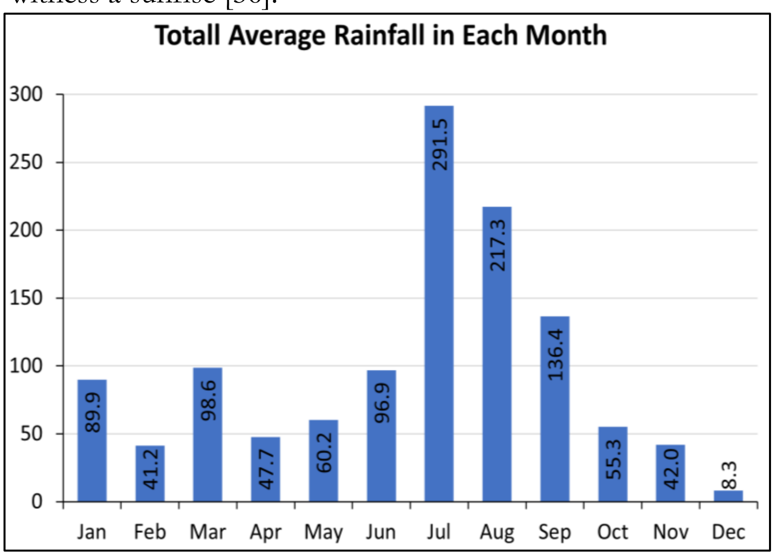

Figure 10. Annual Cycle of precipitation (mm/month) in Islamabad. Bar graph represents monthly precipitation value.

In contrast, Islamabad's air quality is significantly better compared to Punjab, which enhances its potential for solar energy generation, even during the winter months. The city's total land area is approximately 1,015 square kilometers, with a built-up area of 58.22 square kilometers after applying standard filters, including the Open Buildings V3 model's confidence threshold and a minimum footprint size of 177 square meters. This leaves about 37.69 square kilometers of built-up space, which includes approximately 109,719 houses suitable for both rainwater harvesting and solar energy generation. For rainwater harvesting, using a runoff coefficient of 0.8, the total potential is estimated to be 778.92 million gallons annually, based on an average annual rainfall of 1,200 mm (see Figure 10). Currently, Islamabad requires approximately 125.48 million gallons of water per day, but the supply falls short at just 73.97 million gallons per day, resulting in a daily deficit of 51.72 million gallons [57]. Rainwater harvesting could significantly mitigate this deficit, contributing around 778.92 million gallons annually, which would ease the strain on local water management and help improve groundwater levels (see Figure 11). Regarding solar potential, rooftop sampling indicates that sectors I8 and F7 exhibit the highest potential for solar energy generation, showcasing the city's favorable conditions for implementing solar power solutions.

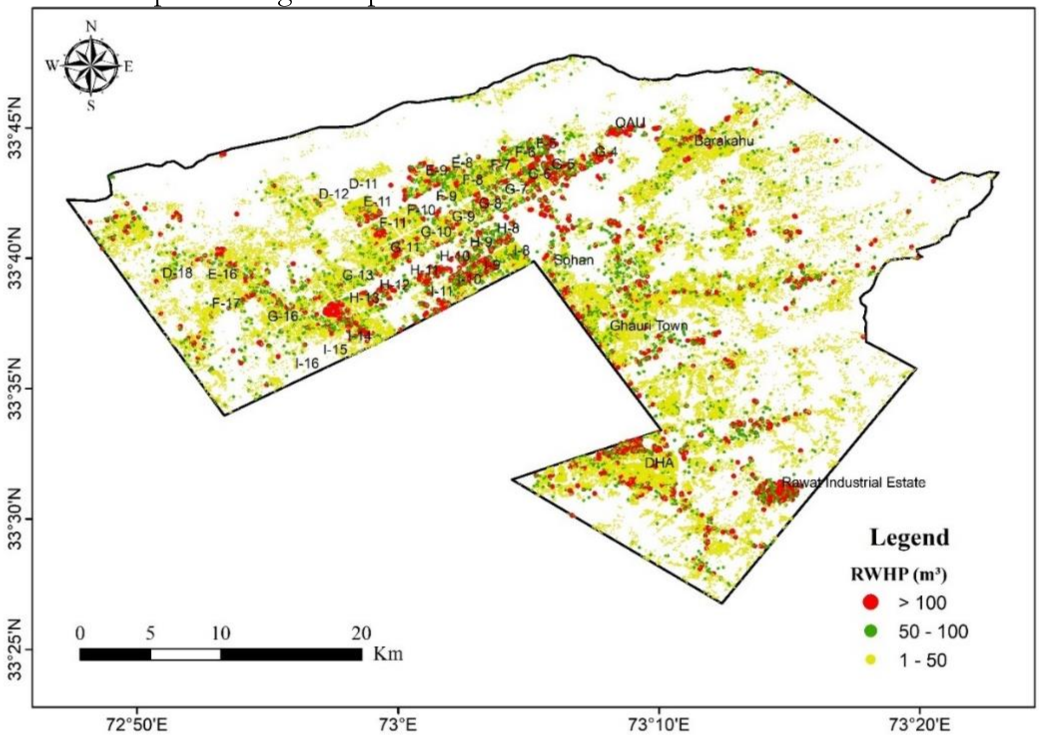

Figure 11: Rooftop Rainwater Harvesting Potential (m^3) for Islamabad.

Currently, about 90 percent of rooftops in Islamabad remain unused, presenting substantial opportunities for solar power installations. Given that not all rooftop areas can be utilized due to shading or obstructions such as water tanks, this study accounts for these factors by reducing the usable rooftop area by 25%. Thus, only 75% of each rooftop area was considered for solar power installations. Based on this adjusted area, the solar power potential was calculated. The results indicate that the central regions of the city, including Diplomatic Enclave, Blue Area, F6, and G6, as well as the southwestern areas like Rawat and DHA Phases I and II, exhibit significantly higher potential for solar energy generation. Conversely, other areas show moderate to low potential. The analysis suggests that installing solar panels on rooftops in these high-potential zones could generate approximately 16,504.29 MWh annually, as illustrated in Figure 12. This indicates a substantial opportunity to harness energy by utilizing rooftop space effectively. During summer, the demand for electricity spikes compared to other seasons. Pakistan has faced persistent power shortages over the past two decades, with the electricity deficit exceeding 8,500 MW in 2023, leading to extensive load shedding across the country [58]. By adopting sustainable solar power practices and strategically implementing solar installations in high-potential areas of Islamabad, it is possible to address the energy crisis and reduce the strain on the national power grid. This approach can ensure that residential energy needs are met year-round, regardless of seasonal fluctuations.

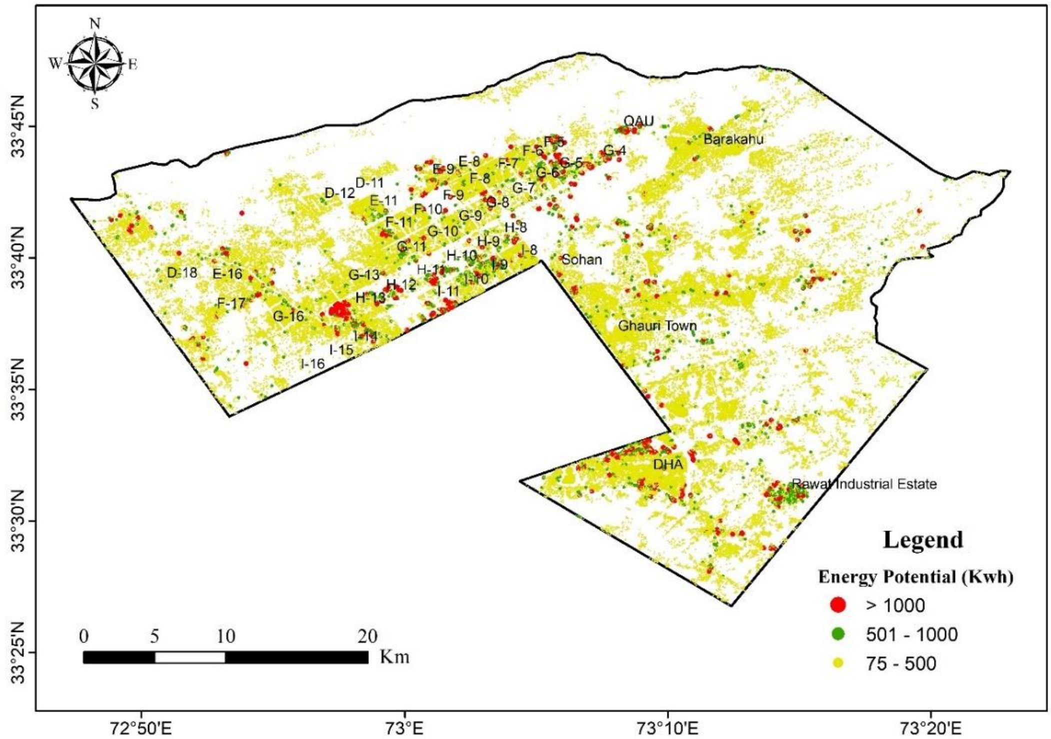

Figure 12: The average annual Energy Potential of Islamabad

Table 3: Potential of RRWH and Solar w.r.t Buildings

Potential of RWH	No of buildings	RWH potential (m3) Annual	Potential of Solar	No of buildings	Energy Potential (Kwh/annual)
Greater than 100	1675	2312559.21	Greater than 1000	476	14618327.5
50 to 100	5058	337259.99	500 to 1000	1621	1077098.578
1 to 50	102986	298917.90	100 to 500	107622	808869.5011
Total	109719	**2948737.09**		109719	**16504295.57**

Discussion:

Islamabad's rapid urbanization is placing significant stress on the city's water resources, making effective water management crucial to ensure a reliable and safe water supply for its residents. Implementing rainwater harvesting systems to capture runoff from rooftops offers a sustainable solution to increase water availability and mitigate urban flooding. Additionally, by integrating solar energy systems on rooftops, Islamabad can move towards a more sustainable future. The study demonstrates that GIS methodologies, remote sensing data, Global Solar Atlas data, and Open Buildings V3 polygon data are highly effective tools compared to traditional methods for analyzing rooftop potential for rainwater harvesting and solar energy. These advanced techniques provide a comprehensive approach to maximizing the benefits of rooftop spaces, ultimately contributing to more efficient water and energy management in the city. The benefits of following the recommendations mentioned in (Table 4) are as follows:

Table 4: Advantages of Solar Power and RRWH

Solar Power	RRWH
Renewable Energy (RE) emerged as the most promising alternative to fossil fuel energy in the critical literature review	Due to climate pattern changes, there is variation in rainfall patterns, making RRWHS an appropriate response to droughts.

The analysis's outcomes suggest that solar energy generation is a sustainable and long-term source of clean energy	The artificial recharging of groundwater through RRWHS has become essential to increasing its natural supply and for natural surface water circulation into groundwater reservoirs. This method promotes groundwater sustainability in decreasing groundwater areas.
Implementing solar power generation can effectively decrease greenhouse gas emissions, address climatic change challenges, and returns economic advantages.	The sustainable utilization of RRWH for domestic purposes includes car washing, toilet flushing, laundry, and gardening.
Solar energy has the potential to fulfill electrical deficit of a city during daylight hours, and the surplus energy can be transmitted to industries	This practice helps local authorities improve their infrastructure and water management plans.
RRWHS has gained popularity due to its lower prices and increased efficiency.	It minimizes burden on the water supply system.

Conclusion:

The primary objective of this study was to evaluate the potential for rainwater harvesting (RRWH) and solar power generation in the residential areas of Islamabad, aiming to leverage rooftops for sustainable purposes. The focus was on Islamabad, the capital city of Pakistan, where rooftop areas were assessed using building footprint data derived from the Building Footprint V3 polygons. To ensure accuracy, two conditional filters were applied with an 80% confidence level to select suitable models and determine the minimum area necessary for implementing RRWH systems and solar installations. A comprehensive analysis of approximately 400 buildings revealed that 90% of rooftops are currently underutilized, while 10% are utilized. Rainfall data from the Pakistan Meteorological Department (PMD) was used to estimate RRWH potential, which indicated that approximately 778.94 million gallons of rainwater could be harvested annually. Solar energy potential was assessed using parameters such as Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI) from the Global Solar Atlas, which revealed that installing solar panels on rooftops could generate around 16,504.29 MWh annually.

The study suggests that implementing photovoltaic (PV) systems on suitable rooftops could significantly meet electricity needs, potentially leading to an energy surplus in larger properties. PV systems offer a viable way to reduce dependence on non-renewable energy sources by harnessing rooftop space with good sun exposure. Additionally, RRWH techniques could address water shortages, providing up to 778.92 million gallons annually. This water could meet public needs for washing, gardening, and potentially contribute to groundwater recharge and potable water after appropriate filtration. The findings highlight that the southern and central parts of the city have substantial RRWH potential, particularly during the rainy months of July, August, and September, when excess water can be conserved for later use. The study concludes that Islamabad has significant potential for both RRWH and solar power, underscoring the need for further national and district-level assessments to ensure future resource sustainability. It calls for state agencies to facilitate the implementation of these recommendations and suggests further research into sustainable measures to address these challenges effectively.

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Conflict of Interest: The authors declare no conflict of interest.

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