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Estimation of Rooftop Rainwater and Solar Power Harvesting Potential at University Campus using Remote Sensing and GIS Techniques

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ABSTRACT

The experiment was conducted during 2023 at Dr. Y. S. Parmar University of Horticulture & Forestry, Nauni, Himachal Pradesh, India to study rooftop rainwater and solar power harvesting potential at Nauni using GIS techniques. Universities consumed large quantities of water and energy, often sourced externally or from non-renewable resources, which contributed to environmental impacts and financial costs. Around 151 university buildings were digitized to estimate the harvesting potential. The total rooftop area of 8,318 m^2 was estimated. The digitized rooftop area was verified manually with an accuracy of 99%. The digitized area and the actual area of the buildings were compared, and the error efficiency of the buildings was calculated. The estimated annual rooftop rainwater harvesting potential was 42,919.24 m^3, whereas the total water consumption of the university campus was 154.22 m^3 day^{-1} and 56,291.77 m^3 $year^{-1}$. The harvested rainwater was sufficient to fulfil 76% of the water needs and 60% of the basic needs of drinking and cooking at the university. The Digital Elevation Model and topographic maps of the campus were prepared to estimate the solar power potential. The south-facing rooftop area was estimated to be 20261.4 m^2. This area was capable of generating daily solar power of 2026.4 kW. The annual rooftop solar potential was estimated to be 2269 MWh, which could fulfil 99.59% of the electricity requirement of the university.

KEYWORDS: Energy, GIS, harvesting potential, rainwater, rooftop, solar power

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Data Availability Statement: Legal restrictions are imposed on the public sharing of raw data. However, authors have full right to transfer or share the data in raw form upon request subject to either meeting the conditions of the original consents and the original research study. Further, access of data needs to meet whether the user complies with the ethical and legal obligations as data controllers to allow for secondary use of the data outside of the original study.

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1. INTRODUCTION

Water and energy resources remain irreplaceable pillars of human and economic progress; however, ominous projections such as a doubling of global population by the 21st century (Anonymous, 2014), a 60% rise in renewable energy demand by 2030, and a 50% increase in total energy consumption by 2035 (Anonymous, 2021) indicate intensifying competition for both resources. Recent global assessments reaffirm their importance amid mounting water-energy stresses across rapidly urbanizing regions (Anonymous, 2020; Anonymous, 2021; Anonymous, 2022). Globally, the water crisis is deepening, with 40% of the population expected to reside in water-stressed areas by 2050 and water consumption projected to increase by 55% (Anonymous, 2014). In India, the situation is particularly difficult: potable water demand is anticipated to exceed availability by 2030 (Anonymous, 2018), and water demand may increase by 70% by 2025 (Gutti et al., 2012). Freshwater withdrawals for electricity generation are projected to reach 20% by 2035 (Brears, 2018), further tightening the water–energy nexus. India's expanding population has more than doubled national energy consumption since 2000, and by 2035, demand is expected to grow another 4.2%, with 57.27% of installed capacity still reliant on depleting coal reserves (Mann, 2015). This urgency underpins India's commitments to achieving net-zero emissions by 2070 and securing 50% of its electricity from renewable sources by 2030 (Anonymous, 2022). RRWH is widely recognized as an effective, low-cost, and locally adaptable method for augmenting water availability, reducing runoff, and supporting both domestic and institutional needs (Patil and Mali, 2013; Athavale, 2003; Awawdeh et al., 2012). India's geographic advantages enable receipt of nearly 5×10^{10} MWh of solar energy annually, with most regions receiving 4–7 kWh/m²/day of solar insolation. The country's renewable energy capacity reached 165.94 GW by 2022, accounting for 40.6% of national installed capacity (Anonymous, 2023), placing India among the top global performers under the Paris Agreement (Anonymous, 2022). Projections estimate India's solar potential to exceed 750 GW by 2047 (Kumar and Majid, 2020). Advancements over the past decade, including improvements in PV efficiency, grid integration, automated rooftop detection, and reduced installation costs, have accelerated rooftop solar adoption (Anonymous, 2020; Sharma et al., 2021; Li et al., 2023; Gupta et al., 2024; Habib et al., 2025). Urban studies reveal that rooftop PV can supply 25–60% of city-scale electricity demand depending on roof geometry and climatic factors (Jakubiec and Reinhart, 2020; Li et al., 2021; Strzalka et al., 2022). In India, government institutions alone could meet 15–40% of their annual electricity needs through rooftop PV (Singh and Banerjee, 2021; Chandel et al., 2023). Integration of SPP with building infrastructure can reduce lifecycle CO_2 emissions by 30–45% (Rahman et al., 2022; Mahapatra et al., 2024). The evolution of rooftops from passive protective structures to multifunctional platforms integrating green roofs, RRWH systems, and PV installations-aligns with global trends in sustainable building design (Sheng et al., 2011). PV remains the fastest-growing power-generating technology worldwide for the 10th consecutive year, with rooftop PV contributing to 46% of the total installations (Anonymous, 2025). GIS has enabled the development of a system of integrated energy-water resource planning (Asif et al., 2024). Despite the availability of separate assessments for RRWH and SPP across different regions, integrated studies evaluating both potentials simultaneously remain limited. Addressing this research gap, the present study evaluates both rooftop rainwater harvesting potential (RTRW) and rooftop solar power potential (SPP) for the university campus. Considering the campus's recurring water shortages and frequent power cuts, quantifying these dual resources is essential for reducing dependence on external supply systems.

2. MATERIALS AND METHODS

2.1. Study area

The present study was carried out during 2023 at Dr. Y.S. Parmar University of Horticulture and Forestry, Nauni of Solan district in Himachal Pradesh, India at an elevation of 1260 m above mean sea level at 30°51'53" N latitude and 77°10'8" E longitude (Figure 1).

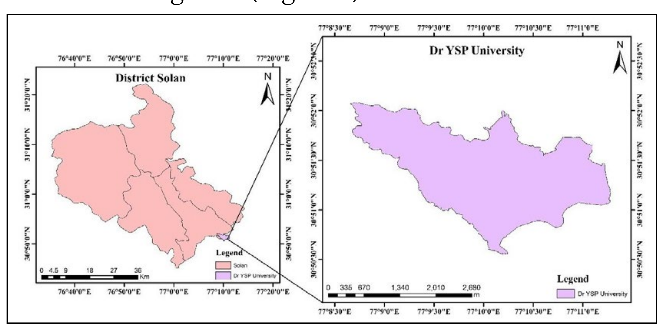

Figure 1: Study area

2.2. Climate and weather conditions

The study area falls under the sub-temperate zone with annual rainfall of 1151 mm. The maximum rainfall is observed on the campus from July to September, whereas the minimum is observed from October to December.

2.3. Software and tools used

In the present study, the following software and tools were used:

• Google Earth Pro to obtain the satellite image of the study area.

• ArcGIS Version 10.8.2

• USGS Earth Explorer

• Global Positioning System (GPS) to take geo-coordinates at the time of ground truth data collection

2.4. Methodology adopted for assessment of rooftop rainwater harvesting potential

2.4.1. Digitization and calculation of rooftop area

The boundary shape file (.shp extension) of the campus was taken from the Estate Office of the university. The polygon tool in Google Earth Pro was used to draw polygons of each roof within the study area. All the rooftops in the Google Earth Pro were imported to the ArcGIS version 10.8.2 software and were converted into digitized rooftops from kml file to a shapefile, and the total roof area was calculated. The rooftop rainwater harvesting potential was also estimated using these tools (Hari et al., 2018; Dadhich and Mathur, 2016; Hailemariam and Kumar, 2017). Google Earth is used for obtaining satellite imagery, and QGIS software for digitizing the rooftop area (Pandya et al., 2018). The rooftop area was calculated as follows:

The Polygons of the rooftops were drawn using Google Earth Pro. Exporting Polygons from Google Earth Pro to ArcGIS 10.8.2 software by adding a vector layer and converting .kml raster files of Google Earth Pro to vector files, resulting in a vector map of the polygons of the rooftop of all buildings. The kml files were converted to Shapefiles.

All the shapefiles were merged. The attributes were added to the Attribute table. The roof area was calculated using the Calculate Geometry tool in ArcGIS.

A ground truth survey was carried out to get the position information of the building rooftops in the form of distinctive geographic coordinates using a GPS. The area of the digitized rooftops was also verified by the manually obtained data of the area of some of the buildings selected randomly in the university campus. The digitized area and the actual area of the buildings were compared, and the error efficiency of the buildings was calculated using Equation (Gilmore et al., 2020).

Error percent=(Actual value-Estimated value)/(Actual Value)×100

2.4.2. Rooftop rainwater harvesting potential

The RTRW harvesting potential was calculated using the following Equation (Gould and Nissen, 1999)

S=R×A×Cr

where,

S is RTRW harvesting potential (m^3)

R is the average annual rainfall (mm)

A is the roof area (m^2)

Cr is the runoff coefficient

The rainfall data of the University for the last 40 years (1982–2022) was obtained from the conventional agrometeorology observatory situated on the university campus. The rooftop area was computed using the area calculated. The runoff coefficient for any catchment is defined as the percentage of water that runs off of the total amount of rain that falls on the roofs.

2.4.3. Water demand analysis

A sample calculation of demand analysis was done for four different categories of buildings existing on the campus, i.e., College, Hostel, Residential Quarters, and Offices. The daily water requirement for college was taken as 45 l capita^{-1}, whereas for the hostels (18 l capita^{-1} day^{-1}), residences (55 l capita^{-1} day^{-1}), and offices (13 l capita^{-1} day^{-1}) were taken[26]. The annual water demand and the annual water harvested by rooftops were analysed, and the amount of water demand met by the rainwater from the rooftops was calculated. The annual water demand for different categories was calculated by using the following Equation (Hari et al., 2018)

Water demand=Per capita demand×Population×Number of days

2.5. Methodology adopted for assessment of rooftop solar power potential

The DEM, which was obtained from the Shuttle Radar Topography Mission (SRTM), having a resolution of 30 m, was used as an input file. The input was further interpolated to a DEM with a resolution of 5m using the Inverse Distance Weighting (IDW) Interpolation technique of the Spatial Analyst tool of ArcGIS for better precision and analysis. The aspect map of the university was generated using the DEM. Out of the total building rooftops digitized, only the rooftops facing true South, South-East, and South-West were selected to estimate rooftop SPP in the campus, as the north-facing rooftops in the northern hemisphere receive less sunlight (Fitriaty and Shen, 2018; Maniatis et al., 2022). The total rooftop SPP was estimated assuming solar panels of one kW peak can be installed within an area of 10 m^2 (Kouhestani et al., 2019) as described in the following equation.

Solar power potential (kW)=Rooftop area (m^2)/10

The average solar power potential received in a year was then estimated using the equation following

Solar power (MWh)=Rooftop area (m^2)×Average solar radiation (kWh/10 m^2/day)×No. of sunny days

2.5.1. Electricity demand analysis

The annual electricity consumption and the annual electricity produced by the already installed 640 kW PV plant on the campus were analysed. The data for the electricity consumption of the campus was obtained through the Estate Office of the university, whereas that for the residential colonies was obtained through the Himachal Pradesh State Electricity Board, Solan. The amount of electricity demand that could be fulfilled by calculating the rooftop PV power of panels on the campus was also analysed.

3. RESULTS AND DISCUSSION

3.1. To assess the rooftop rainwater harvesting potential

A total of 151 buildings were digitized across the study area. The total building rooftop area in the study region was 38,318 m^2. Two types of roofing materials were found in the campus buildings: Galvanized Iron Sheets (GI) and Cement Concrete Roofs (CC). Out of the 151 buildings digitized, the Galvanised Iron rooftops covered an area of 29,120 m^2 (72%) while cement concrete covered 9,198 m^2 (25%). About 97% building roofs on the campus were inclined, and 3% had flat roofs.

3.1.2. Estimation of rooftop rainwater harvesting potential

Since the major roofing materials were found to be galvanized iron and cement concrete, the runoff coefficients were taken to be 0.98 and 0.95, respectively (Rande, 2000). The average annual rainfall during the study period was found to be 1151.4 mm (Figure 2). The month-wise rainwater harvesting potential from the rooftops is described in Table 1. The total rainwater harvesting potential from Cement Concrete roofs was found to be 10,061.05 m^3 and

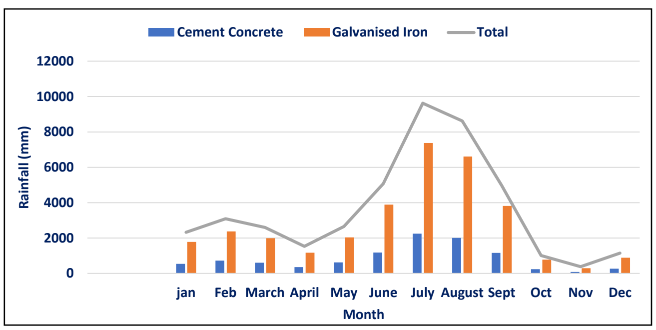

Figure 2: Monthly rooftop rainwater harvesting potential of the university campus

from Galvanised Iron roofs was found to be 32,858.19 m^3. The rooftop-wise total rainwater harvesting potential was found to be 42,919.24 m^3 (Table 2). With regards to the seasonal rooftop rainwater harvesting potential, the southwest monsoons contributed to a maximum rainwater

Table 1: Monthly rooftop rainwater harvesting potential of the university campus

Month	Average rainfall (mm)	Rooftop rainwater harvesting potential (m³)		
		Cement concrete	Galvanized iron	Total
January	62.1	559.77	1772.18	2,331.957
February	82.8	723.51	2362.91	3,086.428
March	69.4	606.42	1980.50	2,586.934
April	40.9	357.38	1167.18	1,528.338
May	71.0	620.40	2026.17	2,646.575
June	135.7	1185.76	3872.55	5,058.312
July	257.5	2250.06	7348.43	9,598.493
August	230.7	2015.88	6583.62	8,599.504
September	133.3	1164.78	3804.06	4,968.851
October	27.1	232.43	759.10	991.5336
November	10.1	88.25	288.22	376.4846
December	30.8	269.13	878.95	1,150.925
Total				42,917.74

harvesting potential volume of 23,166.85 m^{3,} and the minimum rainfall would be harvested in the post-monsoon season, accounting for a volume of 1386.66 m^3.

3.1.3. Water demand analysis

According to the previously indicated standards, the demand was determined based on the numerous sources of consumption. The daily water demand from the entire university campus was found to be 154.22 m^3 and the annual water demand was found to be 56,291.77 m^3 (Table 3).

3.2. Rooftop solar power potential

The building rooftops facing South, South-West, and South-East were extracted, and the total required rooftop area was calculated. Figure 3 indicates the aspect of the digitized rooftops in the university campus.

The 30 m resolution data of DEM was interpolated into 5 m resolution data using the interpolation tool of ArcGIS software. Google Earth Pro and ArcGIS software were used for the estimation of rooftop solar potential[33]. The aspect map of the campus was created using the spatial

Table 2: Rooftop type-wise rainwater harvesting potential of the university campus

Sl. No.	Roof type	Area (m²)	Runoff coefficient	Rainfall (mm)	Rainwater harvesting potential (m³)
1.	Cement Concrete	9,198	0.95	1,151.4	10,061.04
2.	Galvanized Iron	29,120	0.98	1,151.4	32,858.19
	Total	38,318			42,919.24

Table 3: Category-wise water demand at the campus

Sl. No.	Category	Demand (l Capita^{-1} Day^{-1})	Type of water used	No. of person	Water demand of campus (m^3)	
					Daily	Annual
1.	Hostel	18	Drinking, cooking, washing utensils, and premises	1250	22.5	8,212.5
2.	College	45	Overall	1669	75.105	27,413.33
3.	Residential	55	Drinking, cooking, bathing, washing utensils and house, toilets, washing clothes	972	53.46	19,512.9
4.	Office	13	Drinking, sanitation, miscellaneous	243	3.159	1,153.04
	Total				154.224	56,291.77

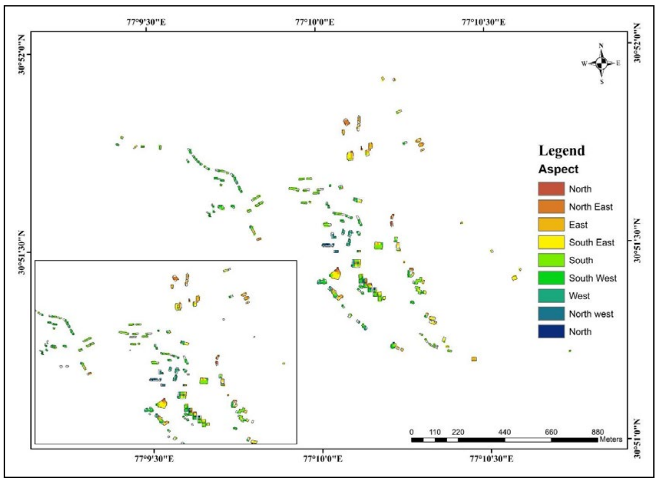

Figure 3: Aspect of the digitized buildings in the university campus

analyst tool of the ArcGIS software. The total south-facing area of the rooftops was found to be 20,261.47 m^2, which corresponded to the usable area available for PV panel installation. The daily total solar power potential of the area was estimated to be 2026.14 kW. The last 20 years' worth of sunshine hour data was obtained from the Conventional Agro-meteorology Observatory of the Department of Environmental Science and revealed that, on average, each day receives 6.4 hours of sunshine annually, averaging 280 sunny days. The total solar power potential of the campus through the application of sunshine hours was found to be 2269 MWh. The average annual electricity consumption at the campus is 2279 MWh. It was found that about 99.59% of the electricity demands of the campus can be fulfilled through the installation of rooftop PV panels.

The buildings for accuracy assessment were randomly chosen owing to their easy accessibility and were compared with the digitized data, and the error efficiency was calculated. The accuracy of the digitization method was found to be about 99%. The small error was mainly due to parallax error, tree obstruction, roof confusion, the shadow from trees, etc. A 95% accuracy was found in the methods of digitization, making the procedure quite reliable (Pandya et al., 2018).

It was found that about 76% of the annual water demand of the campus (56291.77 m^3) can be fulfilled by the water harvested from the rooftops (42,919.24 m^3). It was found that through the use of RTRW harvesting, at least 60% of the basic needs of drinking and cooking could be fulfilled. The rooftop rainwater harvesting systems at the city level could cover 28% of the daily water demand of the city. The southwest monsoons contributed to a maximum rainwater harvesting potential volume of 23,166.85 m^3, and the minimum rainfall would be harvested in the post-monsoon season, accounting for a volume of 1386.66 m^3.

The annual rooftop rainwater harvesting potential in Bharathiar University (Duraiswamy et al., 2025) was found to be 4,90,28,274 litres from a rooftop area of 96,839 m^2. In another study, the estimated rooftop rainwater harvesting potential was 662,273.4 m^3 from a rooftop area of 68,195.74 m^2, conducted in Addis Ababa Science and Technology University (Godana et al., 2025). A study was also conducted in rural areas of the Philippines (Mabbin and Reyes, 2025) and found that the estimated rooftop RWHP was 69.53 m^3 from a GI rooftop area of 36.25 m^2. The annual total rooftop RWHP was estimated to be 141.21×10^8 l, capable of meeting the domestic water requirement of 32.75% and 29.47% of standard urban water demand in Hyderabad, reducing municipal water demand (Hari and Kasa, 2025). Various studies indicate that rooftop area can be estimated using GIS, and rainwater harvesting potential can also be calculated accurately, which can be utilized for meeting municipal water requirements if stored properly by constructing an appropriate water tank.

A study was conducted to get the people's perception in Ahmedabad, Gujarat, and found that most of the respondents felt that the reduction in electricity cost is the main benefit of installing solar panels (Dave et al., 2025). The studies revealed that the rooftop area can be utilized for generating solar power, thus meeting the electricity requirements of the campus and saving fuel bills. A 640-kW rooftop solar power plant has already been installed at the university campus (Aggarwal, 2023), reducing not only the electricity bill of the campus also reducing carbon emissions.

5. CONCLUSION

The study area had a RTRW harvesting potential of 42,919.24 m^3, which, if harvested, could have met 76% of the campus's total water demand, including irrigation, thereby reducing dependence on external sources. The rooftop solar power potential was estimated at 2026.14 kW day^{-1} and 2269 MW h^{-1}, which would have supplied 99.59% of the campus's energy demands. The solar photovoltaics installation would have lowered fuel expenditures, supported other developmental activities, and contributed to achieving Sustainable Development Goals (SDG) 7 and 13.

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