Geospatial for Conservation of Aravali Hills against Urban Development in Udaipur Region, Rajasthan, India

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Keywords: Aravali Hills, Urban Development, Udaipur, FABDEM, ICESat-2, Hill Top Hill Slope.

Abstract

The city of Udaipur is situated amidst the southern Aravali hills in the state of Rajasthan in India. The State hill policy governs urban development on these hills. The policy lacks transparent, objective and verifiable criteria, and a methodology for delineating the Hill Top Hill Slope (HTHS) and ‘no construction’ zones. This has resulted in widespread construction on the hills in recent years. This study examines the chronology and status of urban development on the Aravali hills in the Udaipur Development Authority (UDA) region using the CORONA datasets, Google Earth historical imageries and ESRI satellite basemap. More than 140 development sites have been mapped, which occur from the foothill zones to slopes more than 20° and elevations more than 700 m above mean sea level. A robust geospatial workflow for delineating the HTHS has been proposed. Vertical accuracy of openly available Digital Elevation Models (DEMs) - SRTM v 3.0, FABDEM v 1-2, and ALOS PALSAR - has been ascertained using visual analytics and error metrics taking along track profile of ICESat-2 data as reference data. FABDEM has provided highest vertical accuracy in the hilly area. Overlay of slope, elevation and contour maps generated from FABDEM effectively delineates the HTHS region and identifies terrain characteristics of existing constructed sites. Decisions on proposals for new development can be taken based on overlay of cadastral boundary or coordinates of proposed site on HTHS map. The suggested geospatial workflow can aid in framing and enforcing an effective hill policy for conservation of hills.

1. Introduction

1.1 Background

The Aravali hills are relict mountains which date back to the Precambrian era (approximately 670 million years ago). These are one of the oldest geological features on the Earth. These hills traverse the western part of India for approximately 692 km from north-east to south-west through the states of Delhi, Haryana, Rajasthan and Gujarat. About 560 km of the hills lies in the state of Rajasthan forming the backbone of society, economy and ecology of the region. These hills influence the temperature and precipitation regimes thereby regulating the local climate, check the expansion of the Thar desert to the east, are home to rich floral and faunal biodiversity. Further, these are the source of major drainage networks such as Banas, Sabarmati, Luni etc. and act as watershed between the Arabian Sea and Bay of Bengal drainage systems. Moreover, these hills house rich mineral reserves of marble, granite, mica, copper, zinc, lead etc. along with abundant forest resources particularly in their southern part. Therefore, these hills are of immense significance to the economy of the region. However, in the recent decades the hills have been irreparably destroyed by anthropogenic activities such as quarrying and mining, large scale encroachment and cutting for urban development, exploitation of forest resources and deforestation. Such activities have resulted in deterioration of fragile ecosystems, degradation of forests, depletion of ground water levels, increased human-wildlife conflicts and most importantly, irreversible topographical changes in this geological heritage of the Earth.

The city of Udaipur is cradled in the Girwa basin, a saucer shaped valley surrounded by the Aravali Hills. It is located in Udaipur district in the southern part of the state of Rajasthan in India. The history of the city dates back to the medieval period over 450 years ago. Widely renowned as the ‘Venice of the East’ and the ‘City of Lakes’, it has evolved as a thriving multi-functional city, which is a hub for mining, recreational activities, tourism and education. The identity of the city predominantly rests on two unique characteristics: (1) a historical-cultural landscape with splendid architectural heritage in the form of forts, royal palaces, havelis (large residences), temples, royal gardens etc., and (2) a picturesque physiographic landscape with an inter-connected lake system and lush green Aravali ranges. This unique physio-cultural landscape draws domestic and foreign tourists in huge numbers in all seasons.

The city receives the fourth largest number of tourists in Rajasthan. In 2010, the total number of domestic tourists was approximately 0.75 million, out of which about 20 percent were foreign tourists (Town Planning Department of Rajasthan, 2013). The total tourist arrival in the city increased to approximately 0.88 million in 2014 (Tourism Department, 2015), and to 1.85 million in 2024 as per media reports. Approximately 850 properties including about 30 five-star hotels and 80 resorts cater to these tourists. To leverage the scenic beauty of the hill valley landscape, many private establishments have been developed in the foothill zone and on the hills, in and around the city. During the last decade rapid urban development has been observed primarily for housing and tourism purposes. In addition to tourism, the growing economic activities in mining, educational and commercial sectors have also led to rapid increase in population and urban sprawl in the Udaipur city. The responsibility of planning, supervising and coordinating the development of the city of Udaipur and 136 nearby villages lies under the jurisdiction of the Udaipur Development Authority (UDA) (henceforth referred to as UDA region) (Figure 1).

This contribution has been peer-reviewed. The double-blind peer-review was conducted on the basis of the full paper.
https://doi.org/10.5194/isprs-annals-X-5-W2-2025-271-2025

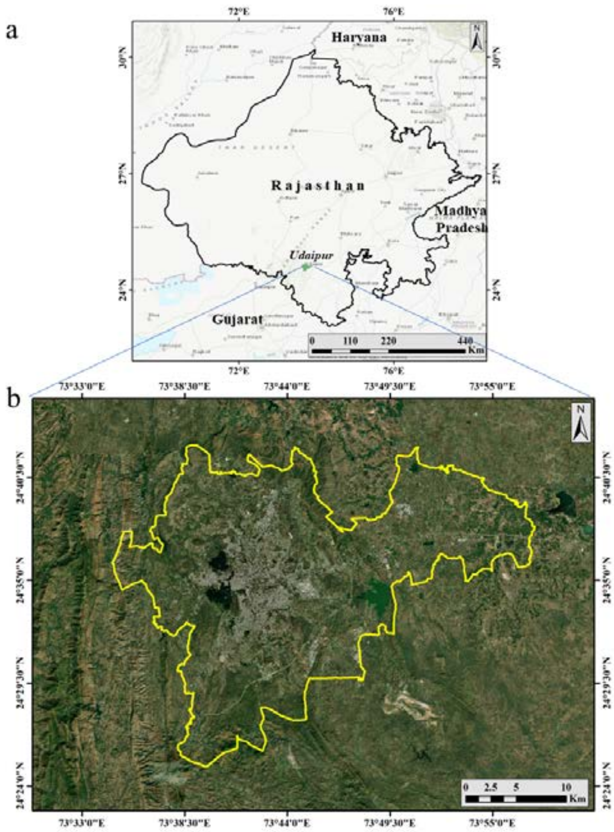

Figure 1. Location map of the study area. (a) Index map showing the location of UDA region, and (b) UDA region as seen in High-resolution satellite imagery (ESRI satellite imagery basemap).

1.2 Problem Statement and Objectives

During the last decade urban development in the region has been governed by the Conservation of Hills in Urban Areas Regulations – 2018 (henceforth referred to as Regulations – 2018) framed by the Urban Development and Housing Department (UDH), Government of Rajasthan. These Regulations define a hill based on the slope of the terrain. However, the methodology for translating this criterion into transparent, objective and verifiable measurements for delineating a ‘hill’ is ambiguous and ineffective. Consequent to the lack of a precise definition of a ‘hill’, ‘development’ has overridden ‘conservation’ resulting in widespread encroachment on and destruction of the Aravalis in the UDA region, primarily for the development of hotels, resorts and other privately owned properties. This issue was considered by the Hon’ble High Court of Judicature for Rajasthan at Jodhpur, which directed the concerned State authorities to explore technology-based solutions for delineation of hills (High Court of Rajasthan, 2024). New ‘Model Regulations for Conservation of Hills in Urban Areas – 2024’ have been notified by the UDH in May, 2025. However, the precise definition of hills and methodology for delineation of permissible development zones thereon is still ambiguous. In this background, the present study addresses the need to define a geospatial technology-based workflow for delineating the hills and the ‘no construction’ zones on the hills.

The study attempts to identify suitable remote sensing-based elevation data with acceptable vertical accuracy for delineating the hills. Based on prevalent national and state level norms, the criteria for defining Hill Top Hill Slope (HTHS) have been identified. Further, the current status of urban development in the HTHS region in the UDA region has been examined. A robust geospatial workflow for delineating the HTHS has been proposed which can potentially be employed by the line government departments for the purposes of restoration/ conservation of the hills, and of planning and monitoring the future development in the Aravali hill region. For effective implementation within the technical constraints faced by government departments, priority has been given to ‘ease of use’ in terms of lower technical skill requirement, open data availability and simple processing workflow for site suitability analysis.

1.3 Study Area

Udaipur city is located at the latitude and longitude 24.58 N and 73.68 E. The study area comprises hills located within the administrative limits of the UDA region. The total area of the UDA region (formerly Urban Improvement Trust – UIT till the year 2023) from the year 1999 to 2012 was 350.9 sq km (Town Planning Department, 2013). In 2024, this area has increased by about 30 percent to 457 sq km. As per Census of 2011, the population of the UIT region was approximately 0.47 million. The population of the present-day UDA region is estimated to have increased to 0.69 million. According to the ‘India Smart City profile’ for Udaipur city, 92.4 percent of the total workers in the city were employed in secondary and tertiary sectors in the year 2011-12. Further, 40.66 percent of the total workers were employed in ‘service workers, shop and market sales workers’ and in ‘craft and related trade’. These figures underline the immense significance of the tourism and commercial sector in the economy of the city.

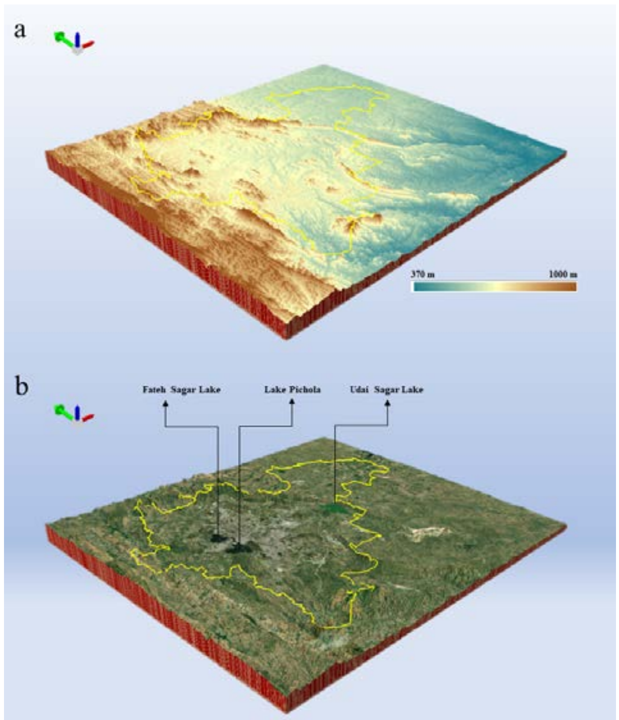

Figure 2. Perspective views of UDA region and surroundings. (a) Hillshade view generated from FABDEM v1-2. (b) 3D perspective view using FABDEM draped with high-resolution satellite imagery.

The average elevation of the UDA region is 598 m above mean sea level. The western and the eastern parts are more hilly and

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heavily forested. The central, northern, southern and south-eastern parts have scattered hills (Figure 2). Eight major lakes are located within the UDA region. The Fatehsagar, Pichhola and Badi lakes are located in the lap of the western hills, creating a picturesque hill-valley topography overlooking the interconnected waterbodies. These lakes date back to the 14th to 17th Century AD, and thus have immense historical and cultural significance. The eastern hills cradle the Udaisagar, the largest among these lakes, which dates back to the 16th century AD. The Aravali hills have high ecological significance not only as the catchment of these lakes but also as habitat for the rich bio-diversity of the forest area and wetland ecology of the region.

2. Material and Methods

2.1 Data

The fundamental requirement for delineating the HTHS is a Digital Elevation Model (DEM) with high vertical accuracy. The ICESat-2 data provides sub-meter vertical accuracy. However, the unavailability of required dense point cloud for interpolation for generation of high-quality DEM is a constraint. An optimal 'ease of use' approach for a government department requires the availability of an open dataset with acceptable accuracy for the given purpose. This study evaluates three openly available DEMs – SRTM v 3.0 (henceforth referred to as SRTM), FABDEM v 1-2 (henceforth referred to as FABDEM) and ALOS PALSAR - for their vertical accuracy in the study area. The geolocated photons for a stretch of 5 km subset from the ground track of the ICESat-2 Level 2A product namely ATL03 has been used to assess the vertical accuracy of SRTM, FABDEM and ALOS PALSAR DEMs. During this evaluation process it has been ensured that all the datasets are having the same vertical datum, i.e., EGM2008 geoid model.

The Forest And Building removed Copernicus DEM v 1-2 (FABDEM) has been selected owing to its reportedly high accuracy of bare earth elevation values in hilly forested terrains. Giribabu et al. (2023) have assessed the accuracy of FABDEM elevations in urban and forested areas using ICESat-2 photon elevations as reference and have found a positive bias of ~ 3 m in urban and flat forested areas. In complex mountainous terrain and rolling hills the accuracy has been found ~14 m and ~ 10 m respectively. FABDEM is freely available at the web portal - https://data.bris.ac.uk – maintained by the University of Bristol.

The Shuttle Radar Topography Mission (SRTM) is one of the most widely used global DSMs (Uuemaa et al., 2020). SRTM data is available for over 80 percent of the globe and is distributed free by USGS as 3 arc second (approximately 90 m) product. Since 2015, the Land Processes Distributed Active Archive Centre (LP DAAC) has released SRTM v 3.0 with global 1 arc second (approximately 30 m) resolution (SRTMGL1). The coverage for Asia and Australia has been released in year 2021. This data can be downloaded from Earthdata geoportal at https://search.earthdata.nasa.gov/search and LP DAAC data pool. SRTM data has been selected due to its widespread use and to assess the accuracy of the newly released version 3.0 at 30 m resolution.

PALSAR is an L-band synthetic aperture radar (SAR) sensor onboard Advanced Land Observing Satellite (ALOS) which was a mission of the Japan Aerospace Exploration Agency (JAXA). The ALOS PALSAR Radiometric Terrain Correction (RTC) product is available for the entire globe (except Antarctica, Greenland, Iceland and Northern Eurasia) at a spatial resolution of 12.5 m. The data can be downloaded freely from the web portal of Alaska Satellite Facility Distributed Active Archive Center (ASF DAAC) of the University of Alaska at https://search.asf.alaska.edu/#/?dataset=ALOS. ALOS PALSAR has been included as it provides the best spatial resolution among the freely available DEMs.

NASA's Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) hosts the Advanced Topographic Laser Altimeter System (ATLAS) sensor, which produces highly accurate elevation measurements. The accuracy of ICESat-2 photons has been found to be higher than 5 cm in various studies (Brunt et al., 2019; Li et al., 2021b). These lidar-based measurements can compensate for ground survey-based Ground Control Points (GCPs) for evaluating a DEM (Liu et al., 2020; Li et al., 2021a; Chen et al., 2022). The datasets are freely downloadable from NASA's web portal - https://openaltimetry.earthdatacloud.nasa.gov/data/icesat2/.

2.2 Identification of Suitable Elevation Data

The main criterion for measuring the quality of elevation data is vertical accuracy (ASPRS, 2004). Vertical accuracy is the accuracy of elevation at a specific location in the candidate DEM. It is measured as the discrepancy between the elevation value at a given location in a candidate DEM and the elevation value obtained from the source of greater accuracy at the same location (Mesa-Mingorance and Ariza-Lopez, 2020). Usually, highly accurate and well-distributed GCPs collected from a Differential Global Positioning System (DGPS) survey are used as reference data for evaluation of the vertical accuracy of a DEM. However, a DGPS survey is time-consuming, needs post-processing, and includes economic constraints. The use of space-borne lidar data overcomes these disadvantages. In this study, the accuracy of candidate DEMs has been ascertained qualitatively as well as quantitatively, taking the along track profile comprising 2310 locations of the ICESat-2 geolocated photons reflected from the bare Earth as reference data (Figure 3). The reference elevation values range from 594 m to 773.7 m.

Qualitative assessment has been done by comparing the elevation profiles of reference ICESat-2 and candidate DEM datasets (Figure 4). A terrain profile or an elevation profile over a surface is a two-dimensional cross-sectional view of the landscape and helps recreate the side view of the terrain relief along a line drawn between two locations. This enables a graphical representation of changes in surface heights along a particular direction. The Y-axis has the elevation in meters (orthometric heights based on the EGM2008 vertical datum), and X-axis has the latitude acquired by the ICESat-2 ground track. Zoomed views of the sections '*ij*' and '*pq*' (Figure 4a) of the ICESat-2 beam have been evaluated for assessment of elevation discrepancies in the plain (Figure 4b) and hilly area (Figure 4c) respectively.

For quantitative evaluation, elevation values from all the three candidate DEMs have been extracted at the locations of ICESat-2 photons. Based on the local along track terrain characteristics and for the purpose of DEM evaluation, 1447 locations with ICESat-2 elevation values ≤ 650 m have been used for assessment of vertical accuracy on plain area. The remaining 863 locations having reference elevation > 650 m have been used for evaluating vertical accuracy on hilly terrain. The overall vertical accuracy has been computed based on the entire profile. Standard error metrics – Root Mean Square Error (RMSE), standard deviation, and Mean Bias Error (MBE) have been used for quantitative evaluation. The difference / bias (d) between the ICESat-2 reference elevation values ($H_{ICESat\text{-}2}$) and the candidate elevation values i.e. SRTM, FABDEM and ALOS PALSAR ($H_{Candidate\ DEM}$), has been computed using Equation 1:

$$d = H_{Candidate\ DEM} - H_{ICESat\text{-}2} \quad (1)$$

Positive values of *d* imply positive bias, i.e., overestimation of elevation by the candidate DEM. A negative value implies negative bias, i.e., underestimation of elevation at the corresponding location by the candidate DEM.

Equation 2, 3 and 4 have been used to calculate the MBE, standard deviation and RMSE respectively (after Mesa-Mingorance and Ariza-Lopez, 2020 and Giribabu et al., 2023):

$$MBE = \frac{1}{N}\sum_{i=1}^{N} d_i \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} {d_i}^2}{N}} \quad (3)$$

$$\sigma_d = \sqrt{\frac{\sum_{i=1}^{N}(d_i - \mu)^2}{N-1}} \quad (4)$$

Where d_i = difference/bias in elevation at location *i*
N = number of sample locations
μ = mean value of difference/bias
σ_d = standard deviation of difference/ bias

Here, the value of *N* is equal to 2310 for computation of overall vertical accuracy for the entire profile, 1447 for plain area and 863 for hilly area.

MBE measures the net bias inherent in the dataset across the reference locations. Positive MBE implies more overestimations than underestimations. The magnitude and direction of MBE of a DEM over different types of terrain or topography (hilly, plain, dissected etc.) can be a parameter of its performance and utility for the respective types of terrain. Small values of overall MBE must be interpreted as indicator of overall performance of the dataset only after the magnitude of positive and/or negative bias across all the reference locations has been accounted for. RMSE measures the gross bias in terms of the average of both overestimations and underestimations. The RMSE quantifies only the magnitude of the overall bias, without differentiating between positive and negative values, and thus provides an estimate of overall performance of the dataset across all the reference locations. RMSE does not differentiate between overestimations and underestimations of elevation values across the reference locations. It is used to express the vertical accuracy of a DEM in most cases (Mesa-Mingorance and Ariza-Lopez, 2020). The smaller the value of RMSE, the more accurate is the DEM. The standard deviation (SD) measures the variability in distribution of the bias with reference to the MBE. A low value of SD implies more uniformity in magnitude and direction of bias across the reference points. This indicates that the dataset records similar bias across the different types of terrain. A DEM is considered more accurate if both MBE and SD are low.

2.3 Delineation of Hill Top Hill Slope region

The criteria for delineation of various categories of HTHS have been determined on the basis of norms laid down by the Bureau of Indian Standards (BIS, 1995), the National Building Code of India (NBC) (BIS, 2005), the National Green Tribunal (NGT) (NGT, 2015), and by the Pune Municipal Corporation (PMC) in pursuance to the Unified Development Control and Promotion Regulations for Maharashtra State (UDCPR, 2020). Pune city is located in southern India having similar topography as Udaipur and well-defined norms for defining and delineating the HTHS.

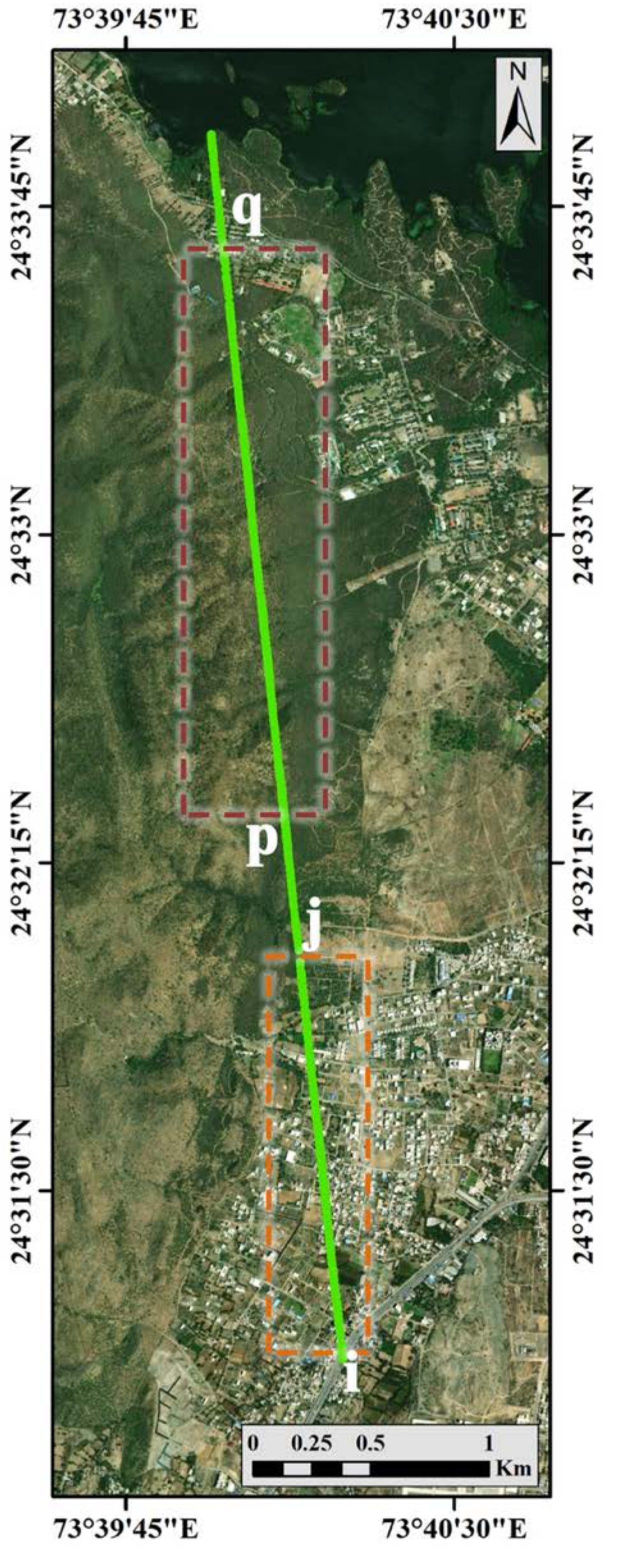

Figure 3. Satellite imagery showing a subset of UDA region draped with ICESat-2 beam.

The BIS (1995) primarily prescribes the standards for selection of building sites in mountainous terrains. It prohibits building sites on slopes more than 30° in general. The NBC (2005) prescribes any area above 600 m from mean sea level or having average slope of 30° as hilly. The State Governments have been provided the discretion of identifying and notifying an area to be designated as 'hilly', which needs to be provided special consideration while undertaking developmental activities. The NGT (2015) has defined a hill as a rounded natural elevation of land which has a distinct summit, is lower than a mountain and rises less than 305 m above the surrounding area. The UDCPR (2020) considers slope having gradient equal to or more than 1:5 (11.33°) as HTHS. No construction is permissible on HTHS and 100 feet area from the hill boundary. The Regulations-2018 of Rajasthan define the hill as an area which rises in elliptical or conical form from the surrounding area, has a crestline and has a slope more than 15° measured from the centreline of the nearest connecting road. Summarily, based on the above criteria, an ideal HTHS region can be defined as having three major characteristics: (1) Elevation more than 600 m from mean sea level, (2) relative relief less than 305 m, and (3) slope equal to or more than 11.33°. Since Aravali hills are relict mountains, the threshold of slope of 30° may exclude major part of the eco-sensitive zone. Measurement of slope from the road centreline is bound to underestimate the slope because of the extended baseline. Therefore, slope derived using this method would not be a robust parameter for delineating HTHS.

The FABDEM has been cropped to the extent of UDA region. The Hills have been delineated using parameters - contours, slope and relative relief - derived from the DEM having highest vertical accuracy. The HTHS has been delineated for 04 slope categories (> 11.33°, 15°, 30° and >30°). The Slope map has been generated with slope measured in degrees, and has been reclassified into the 04 categories (Figure 6a). The FABDEM has also been reclassified into 05 elevation categories (Figure 6b). Contour map has been generated at 10 m interval (Figure 6b).

The state forest boundary shape file acquired from the Forest Department, Government of Rajasthan has been cropped to the extent of UDA region and overlaid on the slope and hill boundary map for identifying the protected hill forest area. A shape file has been created containing lake boundaries, and has been overlaid with other layers for assessment of ecological significance of the hills as catchment for the lakes and wetlands of the region. Entire data generation and analysis has been implemented in ArcGIS v10.8.2 (henceforth ArcGIS).

2.4 Chronology and Status of Urban Development

The CORONA imagery and ESRI satellite basemap have been used to visually compare the urban landscape of the UDA region before commencement of urbanization in the city and at present. The type and chronology of construction after 2014 till date has been mapped as point vector file using Google Earth Pro. Urban development sites on and near the hills were marked on Google Earth, using historical imageries for years 2014 and 2017, and exported as .kml files and imported as shape files in ArcGIS. Extensive field verification has been done for data validation. The sites have been classified as government and non-government (private) constructions. The private sites have been further classified into 03 broad categories - settlements/farm houses/ academic institutions, hotels/resorts/guest houses, and industrial/ commercial establishments. The nature of some sites could not be identified. Some others are under construction. These have been included as a separate category. The slope and elevation characteristics of each site have been determined by extracting the respective raster values to the point layer. The distribution of sites across different classes of HTHS indicate the spatial pattern and intensity of destruction of the hills.

3. Results and Discussion

3.1 Accuracy Evaluation of Elevation Data

Figure 4 shows the distribution of bias through superimposed elevation profiles of all three candidate DEMs and the reference ICESat-2 data for the entire track, and subset of plain and hilly area (Figure 4b & c). Out of the 03 candidate DEMs, the accuracy of FABDEM has been found to be highest in hilly as well as plain areas. The elevation profiles of FABDEM and ICESat-2 closely overlap in major part of the terrain along the selected track. At higher elevations and forested areas, the elevations are overestimated at some places. While all the three DEMs provide fairly accurate elevations in the plain area, the FABDEM has provided the best vertical accuracy in the hilly area of the region.

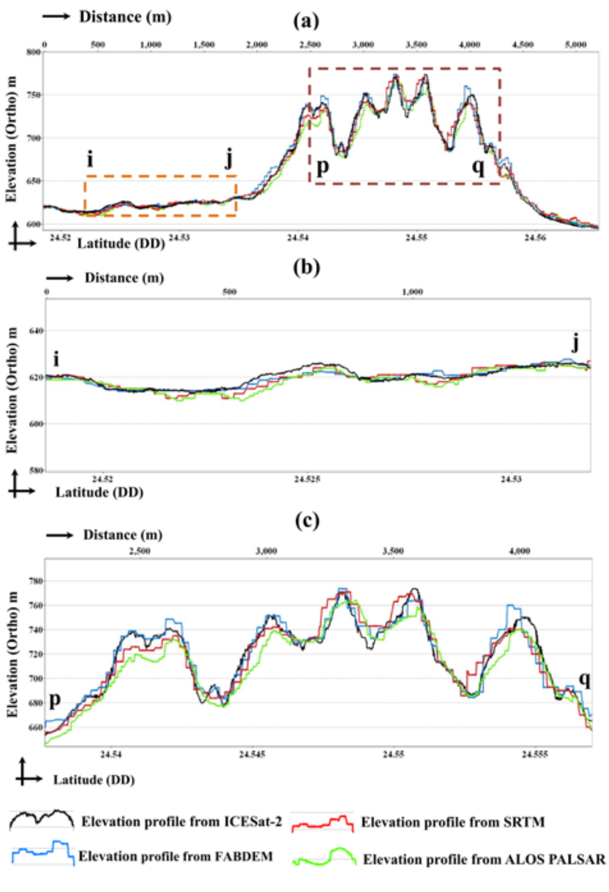

Figure 4. Comparison of elevation profiles generated from ICESat-2, FABDEM, SRTM, and ALOS PALSAR (a) entire beam, (b) plain area with dense urban cover, and (c) hilly terrain including forested area.

The accuracy statistics for the three candidate DEMs have been given in Table 1. The MBE of all three DEMs is within ± 1 m and SD is less than 3 m. All the three DEMs record significantly larger bias in hilly area as compared to the plain area. However, FABDEM records least bias (RMSE = 7.72 m) in the hilly area as compared to the other 02 DEMs. The MBE (1.22 m) and

RMSE value of FABDEM for the hilly region along with the SD (7.62 m) suggests lesser variability in bias with respect to the MBE across the hilly terrain. For SRTM, the low MBE but high SD value (9.52 m) and high RMSE (9.54 m) indicate larger biases in hilly area.

Area	MBE (m)	RMSE (m)	SD (m)
SRTM			
Plain	-0.32	2.78	2.76
Hill	-0.66	9.54	9.52
Overall	0.04	6.23	6.23
FABDEM			
Plain	0.45	2.06	2.01
Hill	1.22	7.72	7.62
Overall	0.74	4.99	4.94
ALOS PALSAR			
Plain	-0.48	2.58	2.54
Hill	-6.16	10.78	8.85
Overall	-2.60	6.90	6.39

Table 1. Error statistics for the vertical accuracy of FABDEM, SRTM, and ALSO PALSAR DEMs

ALOS PALSAR with high MBE (-6.16 m), high RMSE (exceeding 10 m) and high SD (8.85 m) indicates large negative bias and high variability in discrepancy of elevation values given by ALOS PALSAR. The statistical results validate the qualitative assessment indicated by the elevation profiles.

3.2 Delineation of HTHS Region

The DEM derived elevation in UDA region ranges from 455 m to 980 m with a mean elevation of 596.5 m and standard deviation of 69.3 m. The entire hilly region of UDA region has elevation higher than 600 m. Slope in the region ranges between 0° to 54.7° with a mean of 6.6° and standard deviation of 8.82°. The contours and the slope map effectively delineate the HTHS region as per the criteria of elevation > 600 m, slope > 11.33° in 04 categories, and relative relief < 305 m. Steepest slopes and highest elevations are found in the hills located to the west of the lakes located in the western part of the city, and in the north and north-eastern part of the UDA region. Through empirical observations, study of toposheets and Google Earth, 45 hills have been identified in UDA region. The hills mapped using FABDEM closely coincides with the observed topography.

3.3 Chronology and Status of Urban Development

Temporal changes in the urban landscape can effectively be identified by comparing the current satellite data with historical CORONA datasets. Figure 5 (a) shows the status of urban development on the hills located west of Pichhola lake in the year 1972 as revealed in the CORONA image of the region. Figure 5 (b) shows the status in year 2024 as observed in the high-resolution satellite imagery (ESRI satellite basemap). Box A and B show the construction on the Nayakhera and Burja hills respectively. Box C illustrates the urban development on the hill and in the foot hill zone of Gourela and nearby hills.

Total 160 construction sites have been identified on the hills and the foot hill zones in the UDA region. Excluding the government establishments and historical heritage sites, there are 144 privately owned establishments. Approximately 50 percent (64) of these sites are hotels/ resorts, 22.3 percent (33) are academic institutions/residential settlements/ farm houses etc., about 10 percent are industrial/ commercial establishments, and the remaining sites are unnamed or under construction. Majority of the development has occurred after the year 2014. Approximately 50 percent of these have been constructed after the year 2017 and 40 sites have been developed in 2023 – 2024. Development on the western hills started in 2014 while it is a relatively recent phenomenon in the eastern part of the region.

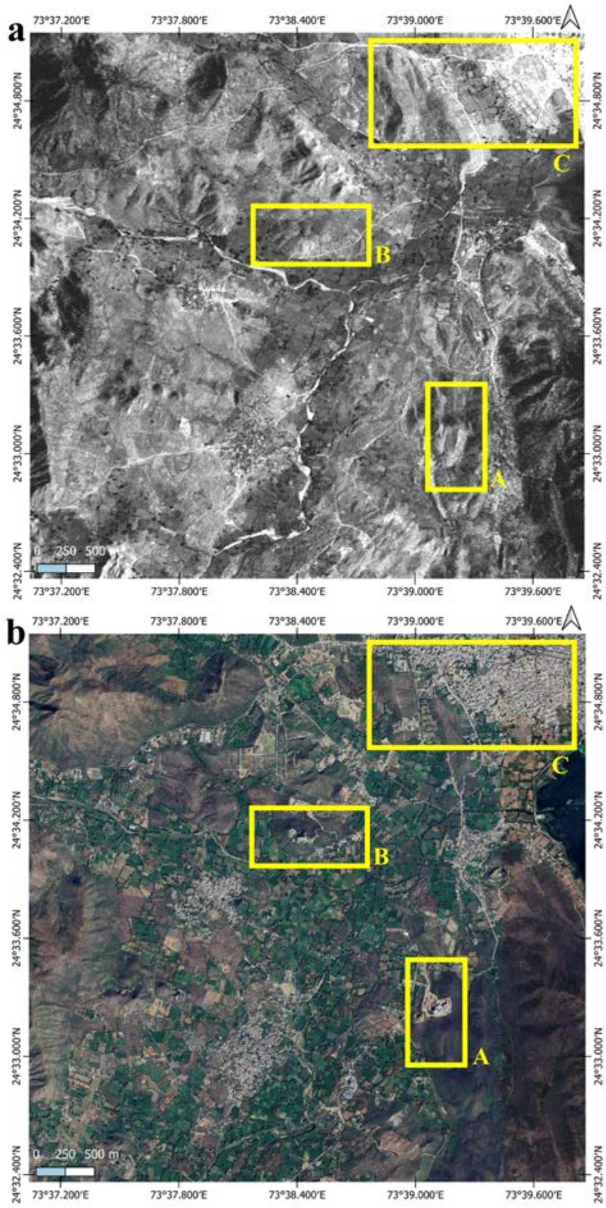

Figure 5. Urban development on hills on the west of Pichhola lake and surroundings (1972 and 2024). (a) CORONA imagery of the year 1972. (b) ESRI Satellite basemap of the year 2024.

Figure 6 shows the location and type of urban development in the UDA region in context of elevation and slope, and distribution of forest and lakes. It is evident that the slope is > 15° in major part of the hilly area of the region. Majority of the construction in HTHS region comprises of hotels and resorts, predominantly near the lakes or on the hills to the west of the lakes (Figure 6b). About 60 percent (86) establishments are located on the hills or in the foothill region in the north-western, western and south-western part of the UDA region. Apparently, the scenic beauty of the hills, and proximity to forested areas and the lakes has been a strong pull for the hospitality industry and posh residential colonies. Another region of high concentration of hotels and resorts are the eastern hills.

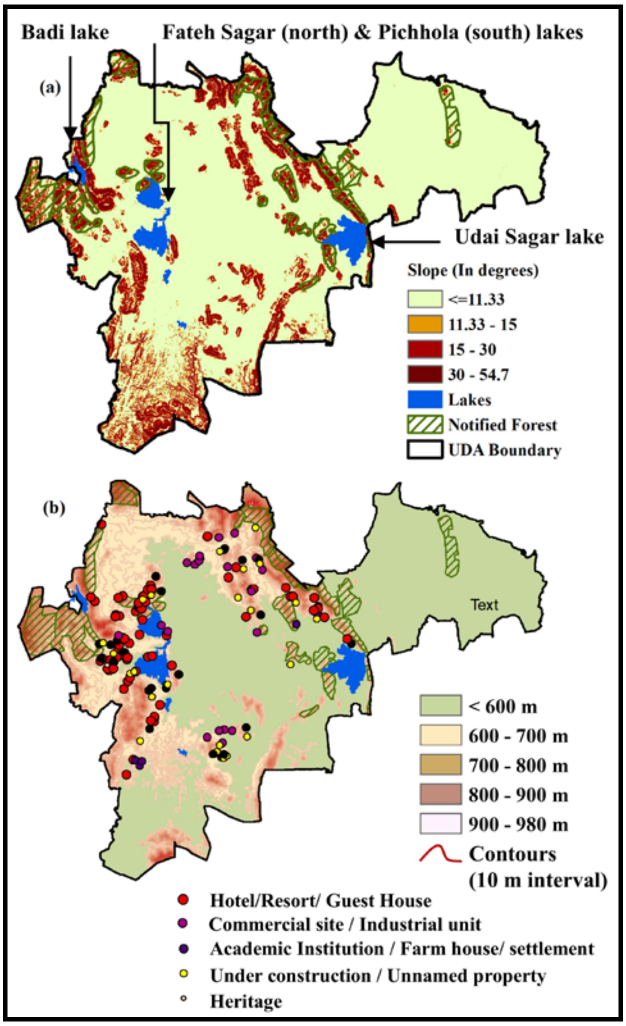

Figure 6. Locational analysis of urban development and terrain characteristics in UDA region. (a) Slope map derived from FABDEM (b) classified elevation map based on FABDEM overlaid with contours at 10 m interval.

Approximately 30 percent (42) developed sites are located primarily in the foothill zone in the northern, eastern and north-eastern part of the UDA region. However, in recent years, new establishments have developed on the hills as well. The industrial units are more confined to the north-east and the south-central UDA region. Some new hotels/ resorts have been constructed on the southern hills since 2023. The hills in extreme south and south-eastern part of the region are the least affected.

Locational analysis of the developed sites in context of the HTHS reveals that 37 establishments including 16 hotels/ resorts and farm houses are located on slopes > 11.33° and elevation > 600 m. Out of these. 14 sites are located on the western hills including Gaurela, Burja, Sajjangarh hills. Eight sites are located in north-western and south-western hills. Mixed types of establishments including 04 hotels and resorts have been developed in the northern and north-eastern HTHS region. If the threshold slope is considered as > 15° and elevation > 600 m, 11 developed sites including 08 hotels/ resorts are located on the hills of the west, north west and south west. Hotels and resorts are located upto the slopes > 20° and elevation upto 700 m. Ongoing construction has been observed on slopes > 30° and elevation > 700 m also. Thus, in the UDA region the hills located in the western, north-western and south-western part of the region have undergone severe destruction.

It may be inferred that the HTHS maps derived from FABDEM enable effective analysis of the terrain characteristics of developed sites in the hilly area of UDA region. The status, pattern and intensity of destruction of the hills, and violation of norms prescribed in the Regulations-2018, can be identified using the proposed geospatial workflow. This methodology can also be used for site suitability evaluation of sites proposed for new construction.

3.4 Geospatial Workflow for Conservation of Hills

The workflow proposed in this study has been summarized in Figure 7. The workflow is based on freely available high accuracy FABDEM. However, another DEM may be used which provides equivalent or better accuracy. The cadastral maps or point coordinate location of proposed sites can be overlaid on the HTHS maps to determine the permissibility of urban development in hilly regions. Zonal Statistics tool can be used to determine the average elevation or slope, or any other terrain parameter for the area under consideration.

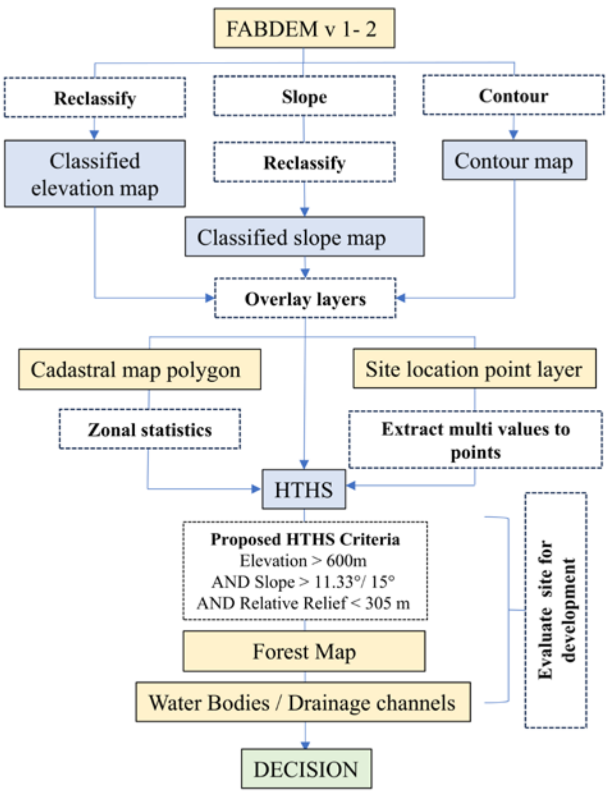

Figure 7. Proposed geospatial workflow for delineating HTHS and site suitability evaluation for existing and proposed urban development sites.

Another alternative method is to vectorize the reclassified elevation and slope maps to generate vector shape files with different categories of elevation and slope, in accordance with the respective criteria for defining HTHS, and the criteria adopted for defining the hills to be conserved 'as they are'. The elevation and slope shape files may be exported as .kml/.kmz files. The coordinates or polygon boundary of the existing/ proposed site can be overlaid in Google Earth environment on the slope and elevation maps. These layers, along with .kml polygon files of other significant considerations like forest and water bodies, can be readily used for site suitability evaluation, and ensuring objectivity, transparency and verifiability in the decision-making process.

4. Conclusion

The Aravali hills under the UDA region have witnessed widespread development on the hill top, hill slope and the foothill zones during the past decade. In view of the geological, ecological and economic significance of the hills, it is essential to conserve them against indiscriminate urban development. The existing regulations lack precise criteria and clear methodology for delineating the HTHS region, which is a pre-requisite for determining the hilly areas to be conserved 'as they are'. Application of geospatial technology is imperative for objective, transparent and effective decision making by the line government departments regarding issue of permissions for proposed urban development.

This study proposes a geospatial workflow with a 'ease of use' approach for delineating the HTHS using openly available FABDEM v 1-2. Accuracy of the FABDEM v 1-2 subset of UDA region has been evaluated using the reference elevation derived from ICESat-2 geolocated photons. The chronology, typology and spatial pattern of urban development in the UDA region has been easily and effectively mapped using historical imageries of the Google Earth. The CORONA historical imageries provide useful baseline data to map the change in landscape over time. FABDEM has been found to be suitable for moderate accuracy applications requiring large-scale cost-effective mapping of regional topography. Slope, elevation and contour maps generated from FABDEM effectively delineate the HTHS region. Overlay of the layers has provided the terrain characteristics of existing constructed sites. Overlay of cadastral maps can unambiguously guide the decision-making regarding permission for construction on a given piece of land. The proposed geospatial workflow can effectively aid in framing effective regulations, ensuring stringent enforcement, identifying violations, monitoring future development, and implementing corrective measures for restoration and conservation of hills.

Acknowledgement

The authors acknowledge the help extended by Darshna Nagar and Anmol Soni, students of MLS University, Udaipur for generating data relating to urban development sites and water bodies, and conducting the field work for the study.

References

ASPRS, 2004. Vertical Accuracy Reporting for LiDAR Data; Martin Flood; ASPRS LiDAR Committee (PAD): Bethesda, MD, USA.

Brunt K.M., Neumann T.A., Smith B.E., 2019. Assessment of ICESat-2 ice sheet surface heights, based on comparisons over the interior of the Antarctic ice sheet. *Geophys. Res. Lett.*, 46(22),13072–13078. https://doi.org/10.1029/2019GL084886.

Bureau of Indian Standards, 1995. Indian Standard - Selection and Development of Site for Building in Hill Areas – Guidelines. Part 2: Selection and Development. New Delhi.

Bureau of Indian Standards, 2005. National Building Code of India. New Delhi.

Chen W., Yao T., Zhang G., Li F., Zheng G., Zhou Y., Xu F., 2022. Towards ice-thickness inversion: an evaluation of global digital elevation models (DEMs) in the glacierized Tibetan Plateau. *Cryosphere*, 16(1),197–218. https:// doi. org/ 10. 5194/ tc- 16- 197- 2022.

Giribabu D., Hari R., Ghosh K., Bera A.K., Srivastav S.K., 2023. Accuracy assessment of digital bare-earth model using ICESat-2 photons: analysis of the FABDEM. *Modeling Earth Systems and Environment*, 9, 2677-2694. https://doi.org/10.1007/s40808-022-01648-4.

National Green Tribunal, (Western Zone) Bench, Pune, 2015. *Aam Aadmi Lokmanch Versus The State of Maharashtra and ors* Application No. 04 of 2014 (Order dated 19 May 2015).

Li B., Xie H., Liu S., Tong X., Tang H., Wang X., 2021a. A method of extracting high-accuracy elevation control points from ICESat-2 altimetry data. *Photogramm. Eng. Remote Sens.*, 87, 821–830. https:// doi. org/ 10. 14358/ PERS. 21- 00009 R2.

Li R., Li H., Hao T., Qiao G., Cui H., He Y., Hai G., Xie H., Cheng Y., Li B., 2021b. Assessment of ICESat-2 ice surface elevations over the Chinese Antarctic Research Expedition (CHINARE) route, East Antarctica, based on coordinated multi-sensor observations. *Cryosphere*, 15, 3083–3099.

Liu Z, Zhu J, Fu H, Zhou C, Zuo T (2020) Evaluation of the vertical accuracy of open global dems over steep terrain regions using ICESat data: a case study over Hunan province. China Sens 20:4865. https:// doi. org/ 10. 3390/ s2017 4865

Mesa-Mingorance J.L., Ariza-López F.J., 2020. Accuracy assessment of digital elevation models (DEMs): A critical review of practices of the past three decades. *Remote Sens.*, 12 (16), 2630. https://doi.org/10.3390/rs12162630.

High Court of Judicature for Rajasthan at Jodhpur, 2024. *Jheel Sanrakshan Samiti Versus State of Rajasthan and ors* D.B. Civil Misc. II (Writ) Stay Application No. 19428/2023 connected with D.B. Civil Writ Petition (PIL) No. 1374/2019 (Order dated 9 May 2024).

Tourism Department, 2015. *Progress Report 2014-2015*, Tourism Department, Government of Rajasthan.

Town Planning Department of Rajasthan, 2013. *Master Plan of Udaipur (2011-2031)*, Govt. of Rajasthan, Jaipur.

Unified Development Control and Promotion Regulations for Maharashtra State, 2020. Urban Development Department. Government of Maharashtra.

Urban Development, Housing and Self Governance Department, 2018. Regulations for Conservation of Hills in Urban Areas – 2018, Urban Development, Housing and Self Governance Department, Government of Rajasthan.

Uuemaa E., Ahi S., Montibeller B., Muru M., Kmoch A., 2020. Vertical accuracy of freely available global digital elevation models (ASTER, AW3D30, MERIT, TanDEM-X, SRTM, and NASA-DEM). *Remote Sens.*, 12 (21), 3482. https://doi.org/10.3390/rs12213482.