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Quantification of Urban Growth Analysis using Shannon Entropy Approach for Rudrapur city

Arifa Begum[1, 2,*], P.C Tiwari[1] & Sandeep Maithani[2]

[1] Department of Geography, Kumaun University, Nainital
[2]Urban and Regional Studies Department, Indian Institute of Remote Sensing, Dehradun

Abstract

Swift and uncontrolled urban sprawl has profoundly transformed the urban landscapes. This has underscored the necessity to comprehend, monitor, and evaluate the spatial arrangements of urban growth. Relative Shannon Entropy stands as a widely utilized metric to appraise the configuration and scope of urban expansion within cities. Hence, this research article aims to quantify and oversee the forms and dynamics of urban growth through the utilization of Relative Shannon Entropy, integrated with Geospatial technology, for the city of Rudrapur, Uttarakhand. Within this study, land use and land cover maps were extracted using satellite images from LISS IV and Sentinel II, spanning the years 2009 to 2018. Subsequently, data regarding built-up areas, road networks, and the city's core were derived from satellite imagery for the years 2009, 2013, and 2018. Ultimately, Relative Shannon Entropy (RE) was calculated with respect to the city's core and main roads for the time spans 2009-2013 and 2013-2018. The results of the Relative entropy (RE) analysis indicate that the urban growth pattern in the city, which was compact in the initial period (2009), has progressively shifted to a dispersed pattern of expansion by 2018, encompassing both the city's core and road network. Consequently, this research contributes to understanding the spatio-temporal trajectory of urban expansion within the city, thereby facilitating effective land use planning to support sustainable urban development.

Keywords: *Urban Growth, Relative Shannon Entropy, Spatial Patterns*

Introduction

Cities represent intricate systems composed of interactive components (Ramachandran, 1989) encompassing factors such as population, location, and infrastructure, all intricately linked to both built-up and non built-up surroundings. The symbiotic relationships among these elements are vital for the proper operation of the urban system. Any notable alteration in the interconnected facets of urban development can disturb the entirety of the urban system. An example of such dynamic attributes is the growth of population and migration (from rural and hills to plains and cities), which lays the groundwork for urban frameworks. Swift modifications in these attribute dynamics lead to the expansion of urban areas. Uncontrolled urban expansion brings about modifications in the physical environment on various scales and extents. In truth, excessive urban growth is seen as a threat to the urban system, significantly impacting the inhabitants' quality of life. This underscores the necessity to grasp the complexities and consequences of unregulated urban expansion and to analyze how urban growth's spatial patterns unfold within the city.

The arrangement of urban expansion delineates the physical layout of constructed spaces and the populace within. This configuration reveals the evolution of urban hubs in terms of their physical, environmental, and economic attributes across time. Early identification, surveillance, and evaluation of these urban arrangements aid in productive land usage planning and efficient resource management, ultimately supporting the promotion of sustainable development.

The utilization of geospatial technology (Barnes et al., 2001) and statistical metrics (Gar-On Yeh et al., 1998) allows for the identification, tracking, and analysis of spatial urban growth patterns. Within the realm of Geographic Information Systems (GIS), methods grounded in entropy prove effective for quantifying the sprawl patterns of cities. Shannon Entropy, a significant metric for assessing spatial order, is widely applied to gauge the distribution of urban hubs (Sudhira et al., 2004; Joshi et al., 2006; Sun et al., 2007; Sarvestani et al., 2011). This metric serves as an indicator of whether concentration or dispersion characterizes spatial arrangements (Yeh and Li, 2001). In essence, it draws upon information theory and governs the level of compactness or diffusion in the expansion of urban areas (Lata et al., 2001).

Consequently, the focus of this research is to oversee and assess the urban growth patterns within the designated study area. This will be achieved by employing Relative Shannon Entropy in combination with geospatial technology, ultimately aiming to support the principles of sustainable urban development.

Study Area

The research focuses on the Rudrapur planning area, which is chosen as the study location. Rudrapur stands as one of the rapidly expanding urban centers and ranks as the second most densely populated city in the Kumaun region of Uttarakhand. Situated at the foothills of the Himalayan mountain range, Rudrapur holds a prominent status as a commercial hub within the Udham Singh Nagar district of Uttarakhand. This recognition is largely attributed to the establishment of the State Infrastructure and Industrial Development Corporation of Uttarakhand Limited (SIIDCUL).

Materials and Methods

Data

This research has integrated multi-spectral satellite images including LISS IV and Copernicus Sentinel II for the period spanning from 2009 to 2018. The acquisition of LISS IV and Sentinel II data was accomplished through the National Remote Sensing Centre (NRSC) and the European Space Agency, respectively. The LISS IV data features a spatial resolution of 5.8 meters, operating across three spectral bands: B2 (Green), B3 (Red), and B4 (Near Infrared). In contrast, Sentinel 2 imagery offers a spatial resolution of 10 meters and comprises four spectral bands: B2 (Blue), B3 (Green), B4 (Red), and B8 (Near Infrared). The delineation of the planning boundary was extracted from the Master Plan of 2031 sourced from the Town and Country Planning Organization (TCPO), Uttarakhand.

Methodology

Gaining insight into the dynamic nature of urban growth and the resultant patterns stemming from expansion underscores the importance of initially grasping the specifics of land use land cover (LULC) within the study area. Subsequently, an assessment of the patterns that have emerged over time becomes imperative. The flowchart outlining the methodology is presented in Figure 1.

Land Use Land Cover Characterization

Land Use Land Cover (LULC) classification serves as the foundational step in conducting geospatial analysis. This process entails the assignment of pixels to specific classes. Within this study, the LISS IV and Sentinel II data underwent classification into primary categories, including built-up areas, vegetation, agricultural and fallow lands, open spaces, road networks, and river and water bodies. Consequently, LULC maps were generated for the years 2009, 2013, and 2018, utilizing the Maximum Likelihood Classification (MLC) algorithm.

The delineation of the planning boundary was derived from the Master Plans of 2031. The individual LULC maps were created, attaining an overall classification accuracy rate of 89%, 91%, and 90% for the images of 2009, 2013, and 2018, respectively. The Kappa statistics extracted from the resulting maps were 0.87 (2009), 0.85 (2013), and 0.89 (2018) respectively.

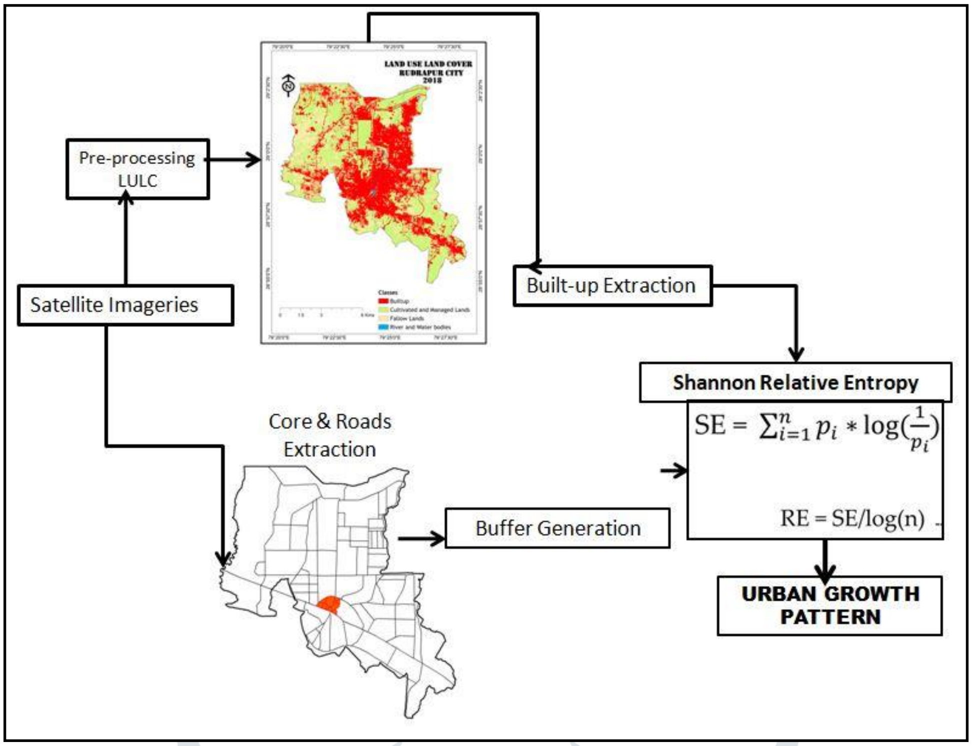

Figure 1 Methodology flowchart for the study undertaken

An important metric for gauging urban growth is the percentage of an area occupied by impermeable surfaces, or built-up areas (Barnes et al., 2001). A greater extent of built-up coverage signifies more pronounced urban expansion, and conversely, a lower proportion indicates less expansion. Consequently, two primary categories, namely Built-up and Non-Built-up, were delineated for the study area across the years 2009, 2013, and 2018.

Subsequently, the road network and the urban core were extracted within the study area, serving as the foundation for estimating urban growth. The significant roads encompass National Highway 9, establishing connections with state and national capitals from Rudrapur. Additionally, National Highway 109 traverses the city, while other notable roads comprise the Rudrapur-Kaladhungi-Ramnagar road and National Highway 309. The city's core lies within the municipal limits, serving as the pivotal point where the major city roads converge.

Shannon Entropy Estimation

Shannon entropy is defined as a metric that quantifies the extent of spatial concentration or dispersion of an urban growth element across various zones. The foundation of Shannon entropy is established on the concept of concentric circles or buffers, which are constructed within urban areas. These circles have a radius of 500 meters centered on the city's core, and an additional radius of 100 meters is established around the major roads.

The Shannon entropy was calculated using the Equation 1 and Equation 2 respectively.

$$SE = \sum_{i=1}^{n} p_i * \log(\frac{1}{p_i}) \text{------------------------------------Equation 1}$$

$$RE = SE/\log(n) \text{ -- Equation 2}$$

The relative entropy was calculated to normalize the values of Shannon entropy and was calculated using the following equation 2.

Here, pi refers to as the probability of a variable/entity occurring in the i^{th} zone. The entropy values ranges from zero (0) to log (n). The value of zero (0) indicates that the urban expansion is of compact or concentrated whereas the value of log (n) indicates that the urban growth pattern is of dispersed or disseminated type.

Results and Discussion

The land use land cover (LULC) maps of the study area illustrate a significant observation: the rate of expansion for built-up areas has doubled its speed (as shown in Figure 2). Analyzing the LULC map from 2009, it's evident that built-up areas were primarily concentrated within the core and municipal region of the city. However, by 2013, the built-up regions had become more densely clustered around the city center and had begun to extend outward, covering the outer municipal boundaries.

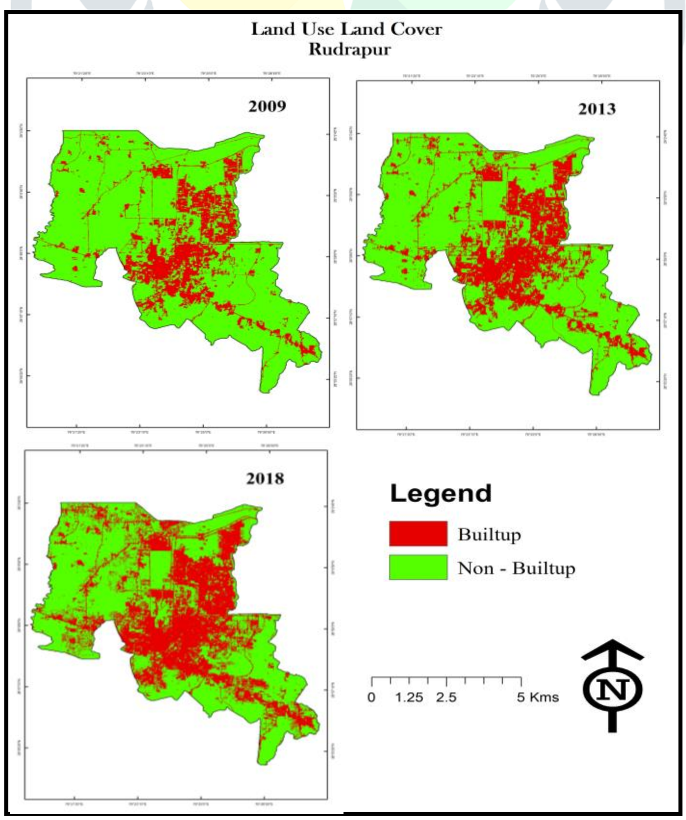

Figure 2 Land Use Land Cover Map

The urban expansion is notably prominent in the southern, northern, and northeastern sections of the city, as evident in the LULC maps of 2009 and 2013. This trend continues in the same direction, with urban sprawl predominating in the LULC map of 2018.

The extent of built-up areas, serving as a marker for urban growth, has exhibited significant expansion, increasing from 20.24 square kilometers in 2009 to 38.42 square kilometers in 2018. This equates to a substantial 38.1% change in built-up area over the 2009-2018 timeframe. In contrast, the proportion of non-built-up areas has experienced a stark decline, dropping by 61.8% during the same period. Non-built-up areas encompassed 80.43 square kilometers in 2009, diminishing to 62.29 square kilometers by 2018 (as depicted in Table 1).

Class	Area (in Square Kilometers)					
	2009	2009 (in %)	2013	2013 (in %)	2018	2018 (in %)
Built-up	20.24	20.11	27.81	27.6264166	38.42	38.1491411
Non-built-up	80.43	79.89	72.87	72.3735834	62.29	61.8508589

Table 1: Built-up Statistics of Study Area (2009-2018)

An analysis was undertaken to examine the directional growth of built-up areas within the study area. The most substantial urban expansion in 2009 was observed in the southeast-south direction, accounting for 4.4 square kilometers (22.1%). This directional expansion then increased to 5.9 square kilometers in 2013 and further to 8.06 square kilometers in 2018. Following this, expansion in the north-northeast direction emerged as the second highest, with built-up areas experiencing percentage growth shares of 17.5%, 16%, and 15.6% in 2009, 2013, and 2018, respectively. This growth was attributed to the establishment of the State Infrastructure and Industrial Development Corporation of Uttarakhand Limited (SIIDCUL).

The visualization in Figure 3 distinctly reveals the significant expansion of Rudrapur city, which has notably extended alongside the major roads and the central core of the city. With this configuration as the foundation, it is foreseeable that the city's growth will persist in radial directions from this central point.

Subsequently, the computation of Shannon entropy was undertaken for the study area. The initial step for entropy calculation involved dividing the study area into concentric circles. These circles, or buffers, were established with a radius of 500 meters emanating from the city's core and continued to expand into several successive buffers until encompassing the entirety of the study area. The largest buffer spanned a distance of

8500 meters, encircling the city's outskirts. Notably, the core, with a radius of 500 meters, exhibited the highest concentration of built-up areas, whereas the buffer farthest from the city center had the least built-up coverage.

Similarly, additional buffers were generated along the major roads at a distance of 100 meters, extending outward to cover the study area, with the farthest buffer reaching up to 1000 meters from the road.

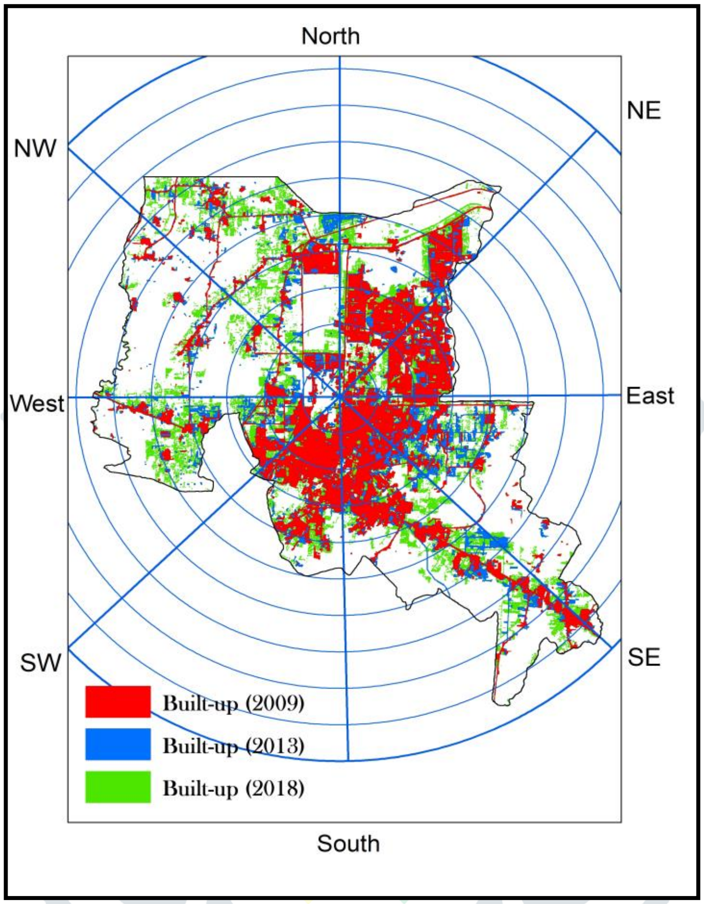

Figure 3 Directional Urban Expansion of the Study Area

The calculation of Shannon entropy was performed employing the provided Equation 1. To streamline and enhance the comprehensibility of the outcomes, the Shannon entropy results underwent normalization through the utilization of Equation 2, referred to as Relative Entropy. The outcomes of the relative entropy (RE) values for the study area are presented in Table 2.

Time-period	Entropy along roads	Entropy alone city core
2009-2013	0.64	0.94
2013-2018	0.66	0.95
2018-2019	0.70	0.96

Table 2: Shannon Entropy Values along the Core and Roads of the City

The relative (RE) values for the study area, considering both the core and the roads, during the time span of 2009-2018, are visually depicted in Figure 4. The relative entropy (RE) values along the city's core were 0.94 (2009), 0.95 (2013), and 0.96 (2018). Notably, the highest and lowest RE values along the core were recorded in the years 2018 and 2009, respectively. Similarly, the entropy values (RE) along the roads followed a similar trend; the lowest and highest RE values were observed in 2009 and 2018, respectively. Specifically, the RE values along the major roads were 0.64 (2009), which progressively increased to 0.66 in 2013 and 0.70 in 2018.

The RE values along both the core and roads exhibited a consistent upward trajectory, reflecting the ongoing urban expansion within the city over the examined period. This trend underscores that the city demonstrated a more compact pattern in 2009, which has gradually evolved into a dispersed configuration over time. In essence, the present urban layout displays a higher degree of dispersion compared to its earlier counterpart.

Furthermore, it's noteworthy that the RE values along the major roads remained consistently lower than the RE values along the city's core throughout the 2009-2018 timeframe. This observation strongly indicates that the distribution of built-up areas follows a more compact pattern along the roads compared to the built-up pattern observed along the central core of the city.

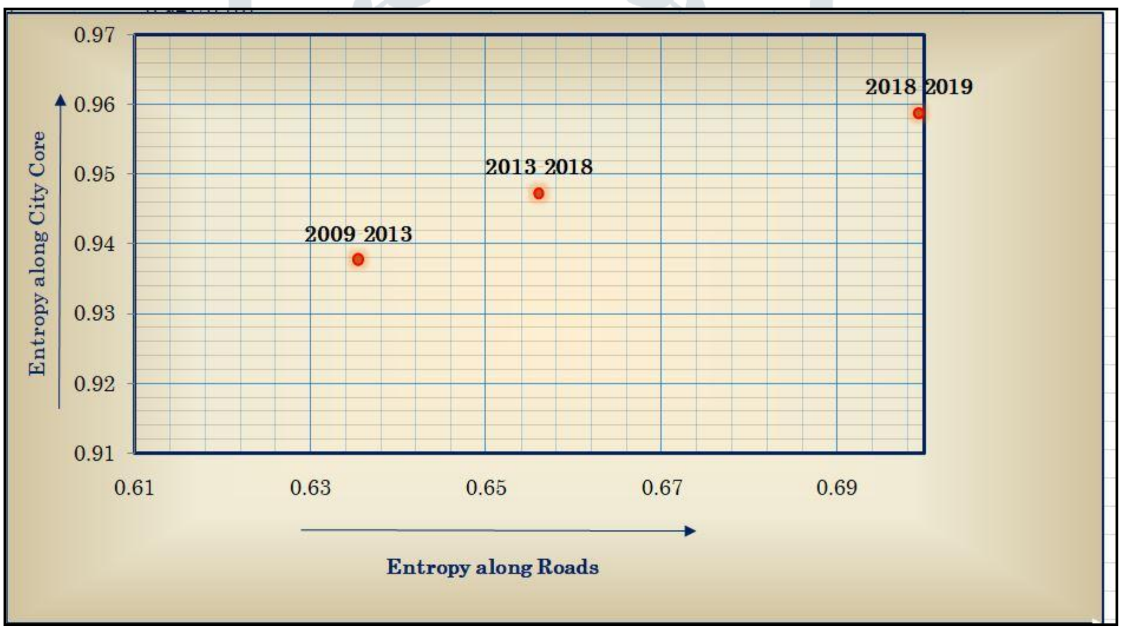

Figure 4 Shannon Relative Entropy Values along the core and major roads (2009-2018)

Conclusion

The research work undeniably establishes that the integration of Shannon entropy and geospatial technology holds considerable importance in analyzing urban growth and patterns within a city. The findings from this study vividly illustrate that higher entropy values correspond to more significant urban expansion or sprawl, and conversely, lower values signify the opposite trend. Furthermore, similar to the approach adopted in this research, where road networks and the city's core/CBD were considered, other influential factors could also be incorporated into entropy-based analyses for a comprehensive understanding of urban growth patterns.

Consequently, this study plays a crucial role in offering a holistic perspective of the city, revealing the 'where' and 'how' of its growth and the pace at which this expansion occurred for Rudrapur city between 2009 and 2018. The insights provided by this research serve to elucidate the current growth pattern of the city and lay the groundwork for a future direction framework. Such a framework ensures effective planning strategies for the city's sustainable urban development.

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