Revealing Hidden Spatial Relationships in Urban Areas Using Remote Sensing: Functional Boundary Delineation of Dambulla

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Abstract: *Understanding urban functions is hard; understanding them spatially is even harder, particularly when their boundaries extend beyond the original administrative limits. Functional boundary of a city manifests both the configuration of the physical environment and also the socio-economic patterns of human activities. By accurately defining these boundaries, urban planners gain valuable insights into the spatial organization of the city and can effectively strategize for its long-term development. Conventionally, delineating the functional boundary relied heavily on land use/land cover classification using remote sensing data. However, this approach has proven inadequate in capturing the intricate spatial interactions within the urban fabric. Going beyond that, this study proposes a novel methodology for functional boundary delineation using connectivity analysis, Night Time Light Data (NTL), and Normalized Difference Built-up Index(NDBI), through a case study of Dambulla City, Sri Lanka. The connectivity of each node/junction indicates potential agglomeration according to urban theories. NTL is another remotely sensed source of information, indicating night-time light emission which represents activities happening even at night. The final source of information is the NDBI, calculated using Landsat 9 to get built-up area distribution representing existing agglomeration. Overlaying these three sources of information and demarcating the functional boundary of the Dambulla area has been completed. It reflects Dambulla's functional boundary while revealing hidden spatial relationships with the surroundings. According to the findings, Dambulla is the catalyst for five satellite cities, emphasizing the significance of Dambulla city and the impacted area in the event of a modification to the city. Going beyond conventional practices, revealing spatial relationships and the functional cluster will greatly influence the urban planning and development sector. The beauty of this method is that, without a single visit, it is capable of initially revealing hidden relationships that are hard to discover even by living in the area for a few days.*

Keywords: Functional Boundary Delineation; Connectivity Analysis; Nighttime Light Data; Normalized Difference Built-up Index

Introduction

Towns are emerging and growing unprecedentedly with the development of infrastructures, economic activities, population growth and invisible dynamic driving forces. Practices of urban planning and design have a close relationship with the space and its dynamic changes. Identifying space and its dynamics helps to reveal sustainable design solutions while enabling smooth operations within the system. Understanding urban context and its elements as a functioning system will minimize conflict within the system. Building a strong understanding of the entire functioning system including its components will lead to awake insights about current spatial distribution and its extent and hidden pattern of possible changes that are about to emerge.

In the urban planning and design context, cities and their relationship matter most, because if a development plan or design solution for one city negatively impacts another city, it creates conflict within the system. Understanding a functional region and observing different influential components will lead to more synergetic solutions to uplift the entire system by minimizing incompatibilities. Understanding spatial relationships and demarcating its region of impact is called functional boundary delineation. Delineating a functional boundary is the initial step to start work on planning and designing attempts by understanding the functional system with its activities. Capturing activities and their relationships sounds very complex exercise.

Understanding spatial configurations, and functioning extent is a challenging task until the right tools, parameters and methods have been discovered. Conventionally distribution of built-up areas and land use-based classification are used to segment functional areas in an urban context. Going beyond this conventional practice, incorporating socio-economic components into delineating a functional boundary, captures the spatial extent that exactly matters while unveiling relationships by understanding urban context as a system in the bigger picture.

Without having an understanding of to what extent urban activities are spread within the region will become a serious problem in urban planning and design exercise. Sometimes this can lead to unexpected outcomes, a development plan or redesign attempts that had the intention of developing a particular area can go wrong due to a poor understanding functional extent and distribution of activities. Focusing on the proper functional boundary delineation which enables capturing the spatial relationship with its extent helps planners or urban designers to concentrate on the real needy area while understanding surrounding dependencies within the system by incorporating relevant data and information. This initial step can be meaningfully utilized to extract the dynamic nature of a given urban context by its spatial relationship.

Capture all those dynamics for a plan and redesign attempt for the urban area to convert the existing setup into a more sustainable, coherent entity for the main system, requires understanding its functional region as the first step to initiate any solution, which is the primary focus of this research paper.

Functional Boundary delineation, simply understanding of spatial extent of activities spread out in a given urban context. Capturing these activities requires several parameters which capture different insights. There are three parameters which are used to delineate the boundary in this research study. The first one is the connectivity which reveals the idea of the level at which a place is connected with all other places in its vicinity. This calculates the relative connectivity value. This connectivity value positively correlates with the urbanizing potential of the place. Ultimately this gives an idea about how economic activities have been laid in real ground since highly connected places attract more activities because it is mostly connected places for their vicinity. However, relying on a single parameter does not reflect a limitation and does not give multiple dimensions to the study to make accurate delineation. To capture a more physically dimension-oriented rather socio socio-economic dimension to the study, another two parameters were incorporated. The second parameter is the Normalize Different Built-up Index (NDBI), a widely used index to visualize the distribution of built-up areas. The third parameter is the Nighttime Light (NTL), used to capture nighttime activities with the intensity of light emission at nighttime. Mostly NTL is used to capture urban areas and urbanizing levels. Combining all these three parameters functional boundary delineation has been completed. This research paper discussed each step of this delineation process in the methodology section. Then the paper goes to the result and discussion which is more focused on the results which unveiled the relationship of the Dambulla context (study area) after functional boundary delineation.

For this research purpose, the city of Dambulla in Sri Lanka has been selected, which was identified as a potential area to develop as an urban centre in the future in terms of accessibility through A-roads, especially being in the east-west corridor, away from natural disasters and tourism aspects by the National Physical Plan (NPP 2017-2050). The City of Dambulla located in the northern central province of Sri Lanka known to be a critical area of water catchment. The City of Dambulla is not a highly populated town (83000) but according to the National Physical Plan 2050, it is recognized as a significant city which expected to be populated in future. Dambulla area has its cultural values since it is home to two UNESCO world heritages. With these significances Understanding the Dambulla region in terms of its spatial configuration while unveiling spatial relationships to demarcate the functional boundary is the purpose of this research study.

Literature Review

Urban functional boundary delineation in an urban context was a critical exercise, and finding suitable criteria was a challenging task. The broader subject of boundary delineation incorporates various parameters depending on the specific matters at hand. Specifically, functional boundary delineation requires capturing the activities and movements that define the dynamics of the area. This was a data-intensive operation aimed at tracing the functional region. Urban boundary delineation has significantly evolved with the advent of remote sensing. Conventional practices have transitioned to more data-driven approaches. The use of nighttime light data and point-of-interest (POI) data has significantly altered the methods and parameters previously employed for boundary delineation.

Urban areas were extracted from Land Use Land Cover (LULC) classification using a combined classification technique to delineate the urban core boundary (Sridhar & Sathyanathan, 2022). The "Travel to Walk" (commuter pattern) method is very data-intensive yet comprehensive for delineating functional boundaries by tracing people's movements. This method maximizes a fitness function that measures intra-region interactions while maintaining inter-region separation and other constraints (Flórez-Revuelta, Casado-Díaz, & Martínez-Bernabeu, 2008). However, delineating functional boundaries with limited and readily available data was the core of this research study.

Nighttime light data provided a novel approach to tracing urbanizing patterns with a single data source, though it was enriched through fusion methods for more accurate results. Traditional methods relied solely on nighttime light (NTL) data, which often overlooked spatial differences between urban and rural areas. This study introduces a new approach by fusing NTL data with point-of-interest (POI) data using wavelet transform, followed by multiresolution segmentation for boundary delineation (Zhang, Yuan, Tan, & Zhan, 2021).

Although various studies have captured functional boundaries with different dimensions, they often missed potential areas that remained untouched. Consequently, these studies did not capture the entire system but only parts of it, including existing functional boundaries utilizing land uses, points of interest, and NTL data. To fully understand the entire functioning system, it is essential to capture potential areas alongside existing ones. Integrating spatial configuration theories, such as connectivity analysis, into conventional practices can provide better insights into functional boundaries as functioning systems. This research study focused on spatial configuration theories and remotely sensed data to capture functional boundaries and aimed to uncover the hidden spatial relationships within the study area of Dambulla.

Methodology

For this study, Dambulla town of Sri Lanka, which is located north of Matale District was selected. It is the second most populous and urbanized city in Matale District (Figure 1). Dambulla is a critical crossroads where the A0 and A9 roads intersects, representing not just geographical convergence but also a nexus of economic vitality and cultural diversity. Dambulla thrives as a hub of trade and opportunity, with specialized economic centers that provide a unique value to its context.

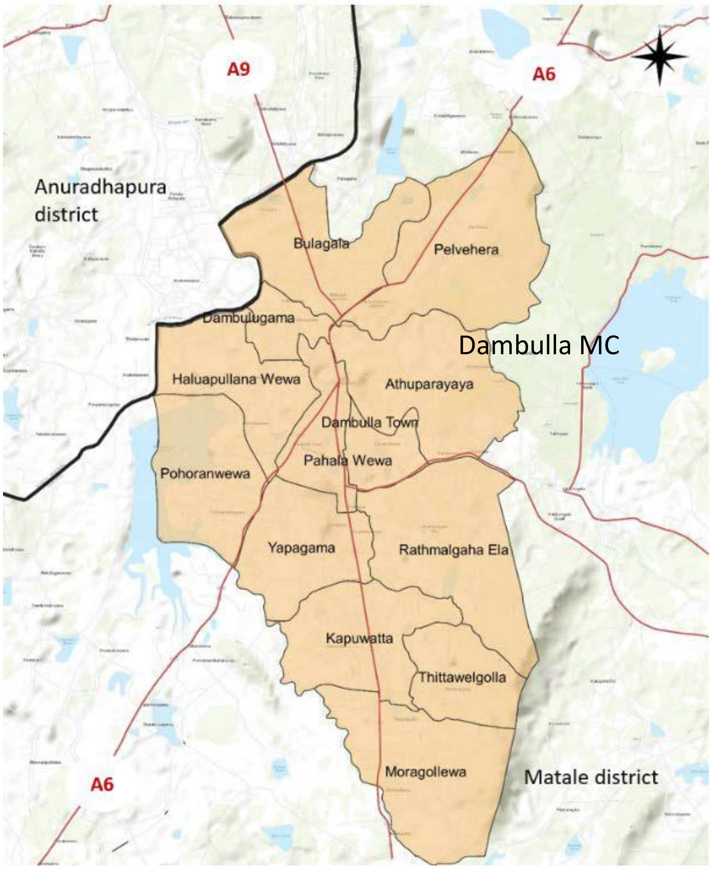

Figure 1: Location of Dambulla Municipal Council

For this study, an area with a 50 km radius from the Dambulla City Center was selected to obtain relevant data, allowing for a broader coverage and minimizing potential errors from edge effect. Conventionally delineating a functional boundary is data intensive and requires careful observation for a longer period to capture the activity pattern in its spatial distribution. It will be even harder if the area becomes an unfamiliar place with little or no experience. Going to the basics of spatial configuration theories combined with geospatial data can delineate potential a functional boundary for any given area even without prior experiences or familiarization. In this study, a novel approach is presented based on the road connectivity, Nighttime Light (NTL) data and Normalized Difference Building Index (NDBI). The road network was the fundamental data that was required to examine the connectivity (the level at which a place connected with all other places in its vicinity as data about the spatial configuration). None of these data can be borrowed from somewhere, it requires retrieval from different sources as data after that with necessary computation those data was converted into meaningful information.

As shown in Table 1, three major input datasets were utilized in this study: the road network, directly obtained from OpenStreetMap (OSM), and the Nighttime Light Data and NDBI data, which were processed from satellite images using the Google Earth Engine (GEE) platform. Only the Nighttime Light (NTL) data was resampled to 30 meters from its native resolution of 463.83 meters. No auxiliary data was fused; the data was resampled to 30 meters by clipping the larger 463.83-meter tiles using the nearest neighbor method.

Table 1: Input data used

Input data	**Type**	**Source**
Road network	Vector	OSM (Open Street Map) - https://www.openstreetmap.org/#map=8/7.879/80.767
Nighttime Light Data	Raster (463.83 m resolution)	Earth Observation Group, Payne Institute for Public Policy, Colorado School of Mines. - https://eogdata.mines.edu/products/vnl/#monthly
NDBI	Raster (30m resolution)	Landsat 9 data from USGS - https://www.usgs.gov/landsat-missions/landsat-collection-2-level-2-science-products

All these three data represent different variables that potentially contribute to delineating a functional boundary by adding different dimensions and filling data gaps by mutually combining data sets to provide more reliable output. These three data layers brought different dimensions to the boundary delineation study. Which were able to extract the physical component as well as the socio-economic aspect of the study. As shown in Figure 2, Connectivity levels of major transportation nodes, NTL intensity and NDBI are the computed inputs from various data sources for the delineation of functional boundary in the study area. Data was acquired during the first half of 2024 (1st of January to 1st of July) and the get the median of all data to get a more accurate answer while capturing temporal variations.

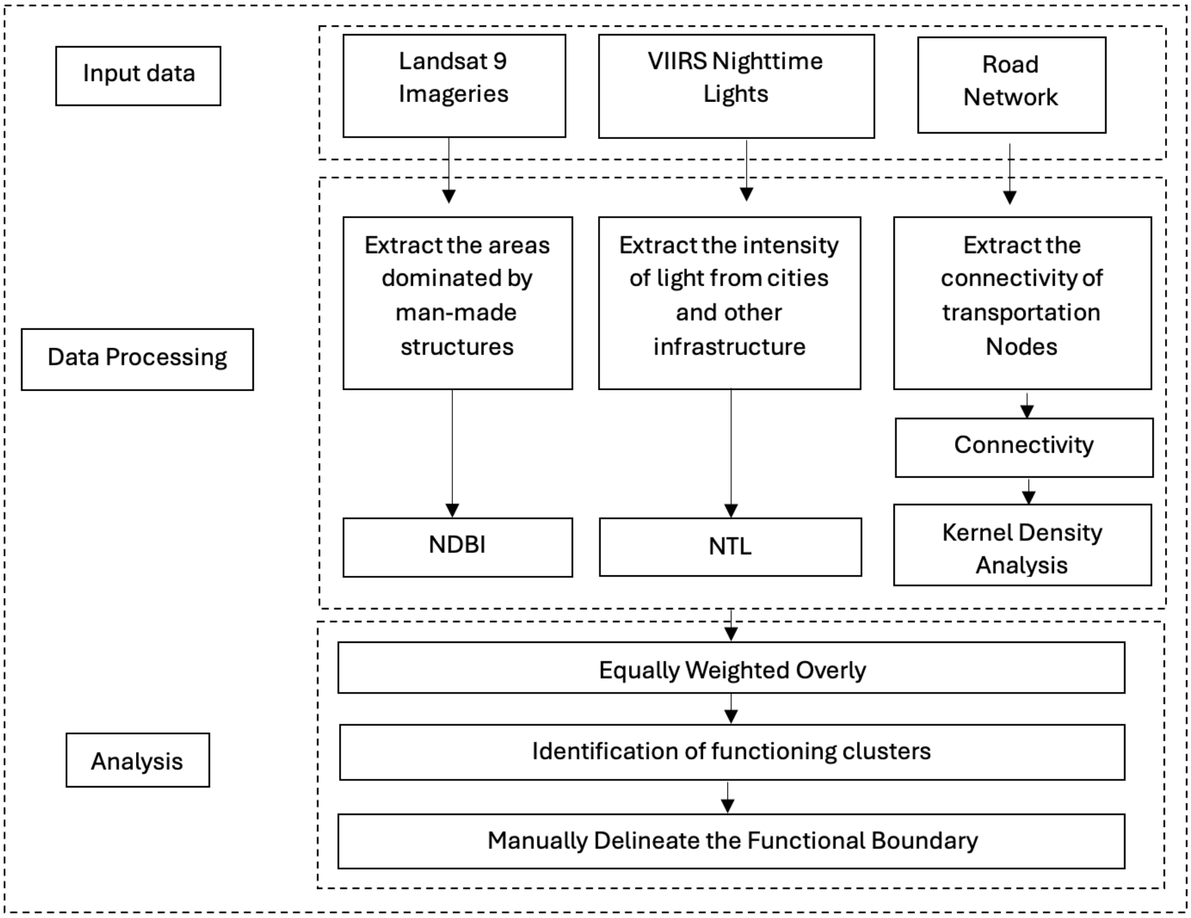

Figure 2: Methodology

Connectivity is the key criterion which reveals the idea of the level at which a place is connected with all other places in its vicinity. Correlations between the Connectivity value and the urbanizing potentials have shown a positive correlation (Jayasinghe & Munasinghe, 2013). Connectivity plays a key role in urbanization. Areas with higher connectivity have greater potential for urbanization, while areas with lower connectivity have less potential. Calculating the connectivity value to capture the urban agglomeration potential requires a proper road network. Extracting a node from each intersection in the road network and calculating the relative connectivity was the key process to obtain connectivity value for each node. Even though the computation and extracting seemed to be complicated since a tool is used here to extract nodes from the road network and calculate the connectivity value (closeness centrality value). This tool is the Connectivity Tool developed by the Department of Town and Country Planning, University of Moratuwa, Sri Lanka for network centrality analysis.

The spatial distribution of connectivity values was analyzed using Kernel Density Analysis, which captured the extent of the areas influenced by these values. This analysis revealed an approximate boundary with the potential for agglomeration. The Kernel Density (D) was computed based on the connectivity values to extract the spatial distribution pattern (Equation 1).

$$Kernel\ Density(D) = \frac{\sum wi.K(\frac{di}{r})}{\pi r^2}$$

Equation 1

Where;

wi is the weight assigned to each point (or line). The weight could represent things like the population of that point, the sales value at a location, or any other factor that makes certain points more important than others.

$K(\frac{di}{r})$ is the kernel function which determines how much influence each point has based on its distance di from the center of the radius r

r is the search radius

Here wi is the calculated connectivity value used as weighted in kernel density.

Nighttime Lights (NTL) data is a powerful tool for representing urbanization within urban areas. Nighttime Light data represent the emitted light during nighttime. Which gives an idea about nighttime activities happening or active areas at night times. Since urban areas usually have nighttime activities NTL data can be utilized to understand urbanizing levels by analyzing the intensity. If certain urban areas are active at night, they are likely to have even more activity during the daytime. Furthermore, a highly functional area usually emits more lights which indicate the core area of the urban context with more activities. Overall, NTL data enables the mapping of urban extent and the assessment of economic activity levels based on the distribution of luminosity and light intensity. Ultimately this can be utilized to get an idea about the most active and functioning part of a given urban context.

NTL data was extracted from the Google Earth Engine (GEE) platform using the data source of VIIRS Nighttime Day/Night Band Composites Version 1**.** Data was acquired during the first half of 2024 (1st of January to 1st of July) and the get the median of all data to get a more accurate answer while capturing temporal variations.

Normalized Difference Built-up Index data is computed by normalized difference between the Shortwave Infrared (SWIR) band and Near Infrared (NIR) band of Landsat 9 satellite images (NDBI = (SWIR – NIR) / (SWIR + NIR)). NDBI is used to identify and map built-up or urban areas computed using multispectral satellite imageries. It is particularly effective in distinguishing between built-up land and other types of land cover, such as vegetation and water bodies due to the reflection and absorption of SWIR and NIR from different surface materials. Identifying built-up areas is important because, in an urban context, activities and functions are more integrated with the built-up area. NDBI becomes an indicator to identify the spatial extent of distribution of activities in terms of built-up environment. However, there may be some exceptional cases like some built-up areas becoming abandoned where no activities are happening only remaining as ghost cities. To capture this kind of instance NTL data can be utilized to identify activities in suspicious urban environments to verify whether it is abandoned or not. NDBI data was extracted from the Google Earth Engine (GEE) platform using a data source of Landsat 9 satellite images and the data provider is USGS.

After preparing the three layers—connectivity analysis, NDBI, and NTL—they were clipped to the same extent to ensure consistency for further analysis. Equally weighted overly method was used to composite the three layers using Raster calculator using ESRI ArcGIS Pro software. Subsequently, the functional boundary was manually delineated from the composited output by analyzing the clustering pattern and the distribution of urban fabric observed in the Google Earth base map.

Results and Discussion

Figures 3, 4, 5, and 6 display the connectivity values of transportation nodes, the level of connectivity based on Kernel Density Analysis, and the NDBI and NTL layers of the study area, respectively.

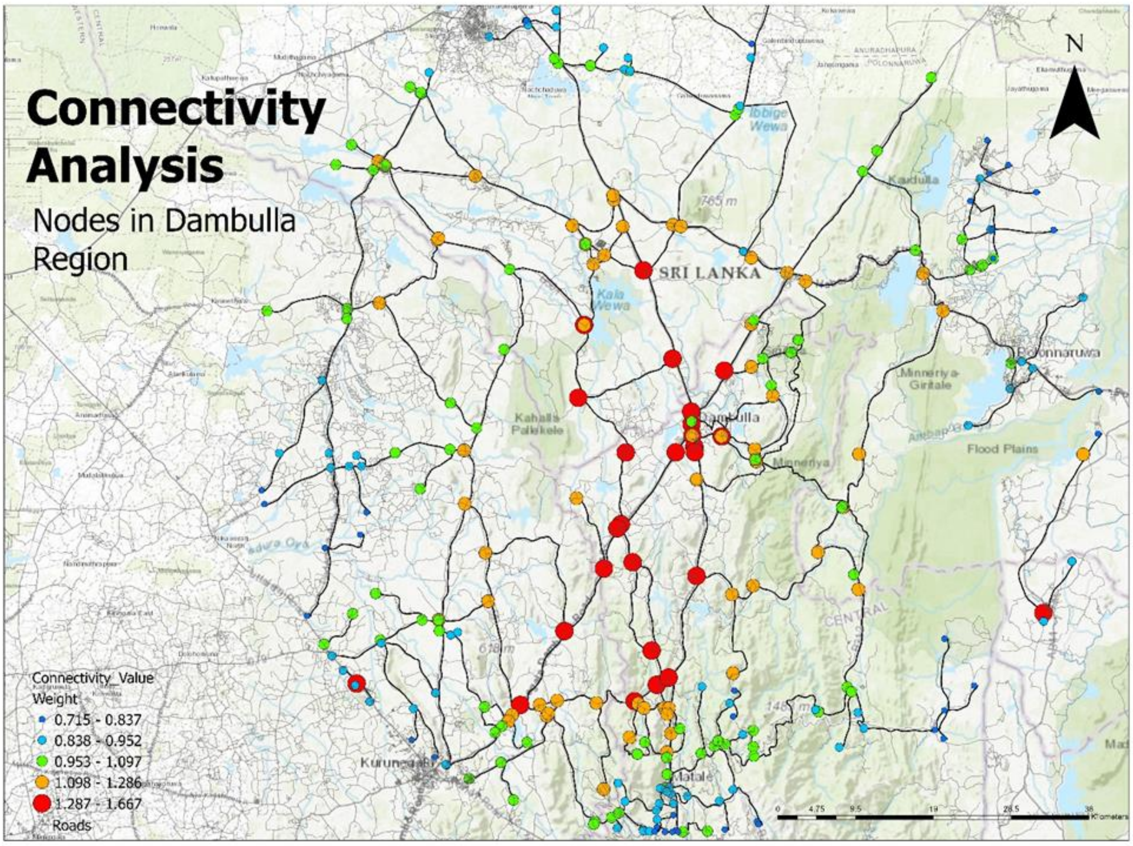

Figure 3: Connectivity values of the transportation nodes

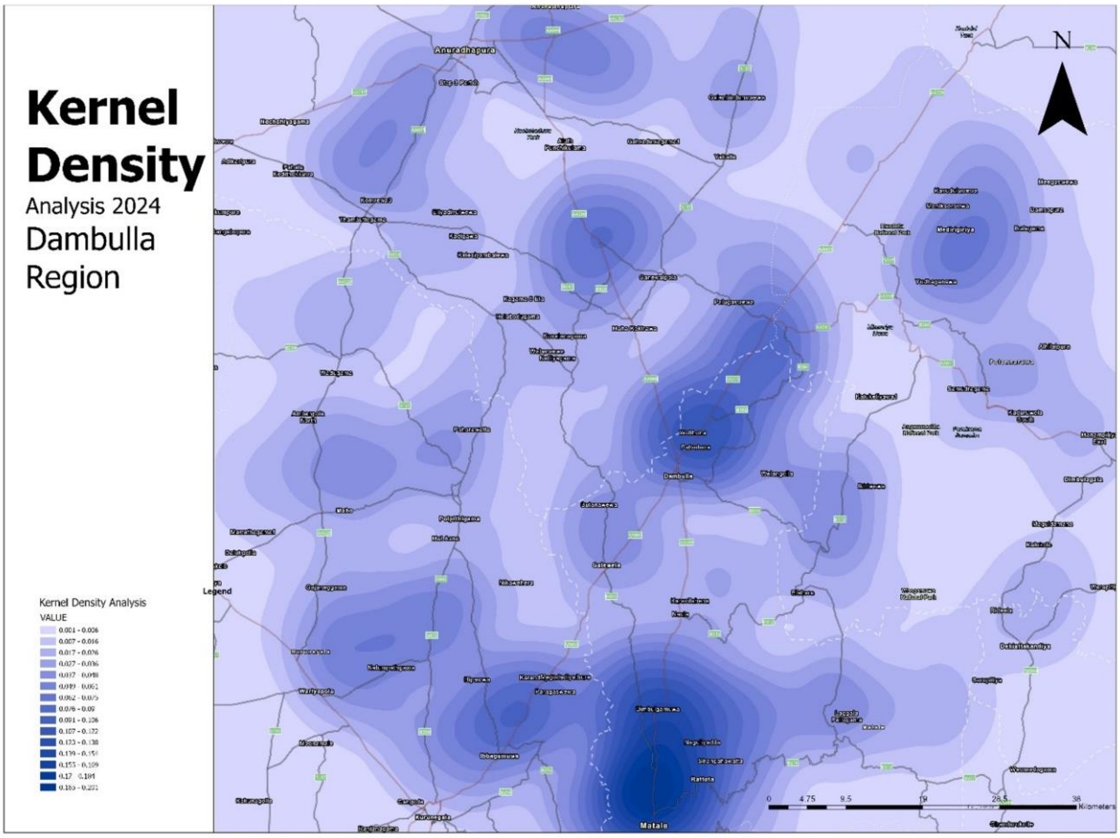

Figure 4: Level of connectivity obtained from the Kernel Density Analysis

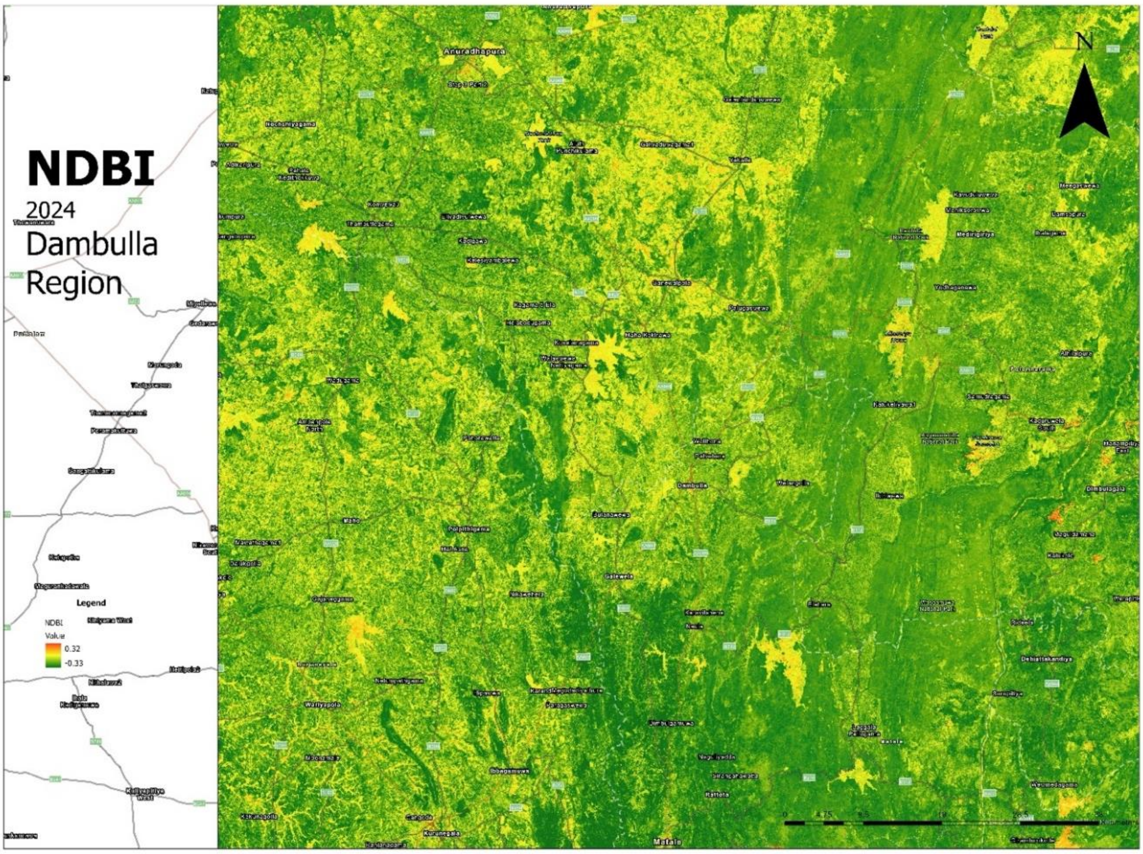

Figure 5: NDBI layer

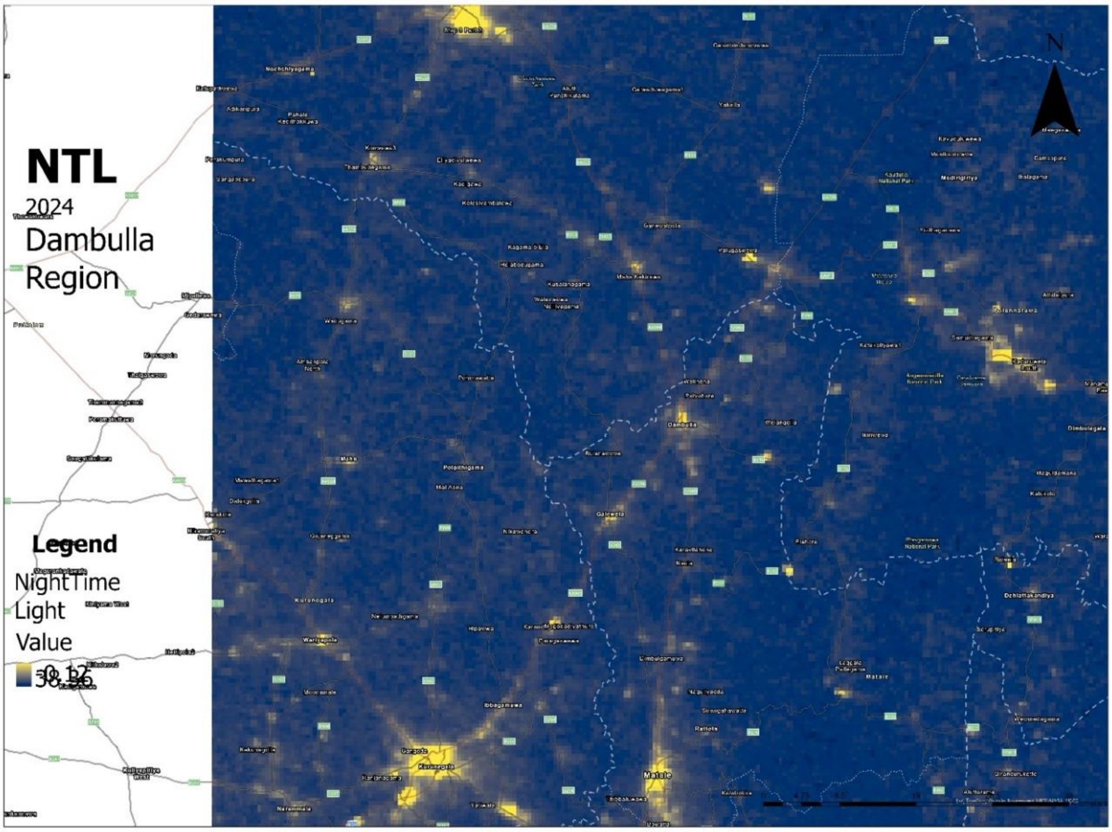

Figure 6: NTL layer

The kernel density analysis of each node's connectivity, overlaid with Nighttime Light (NTL) and the Normalized Difference Built-up Index (NDBI), produced the functional boundary of the given urban context. Figure 7 illustrates the functional boundary of Dambulla city obtained through this method.

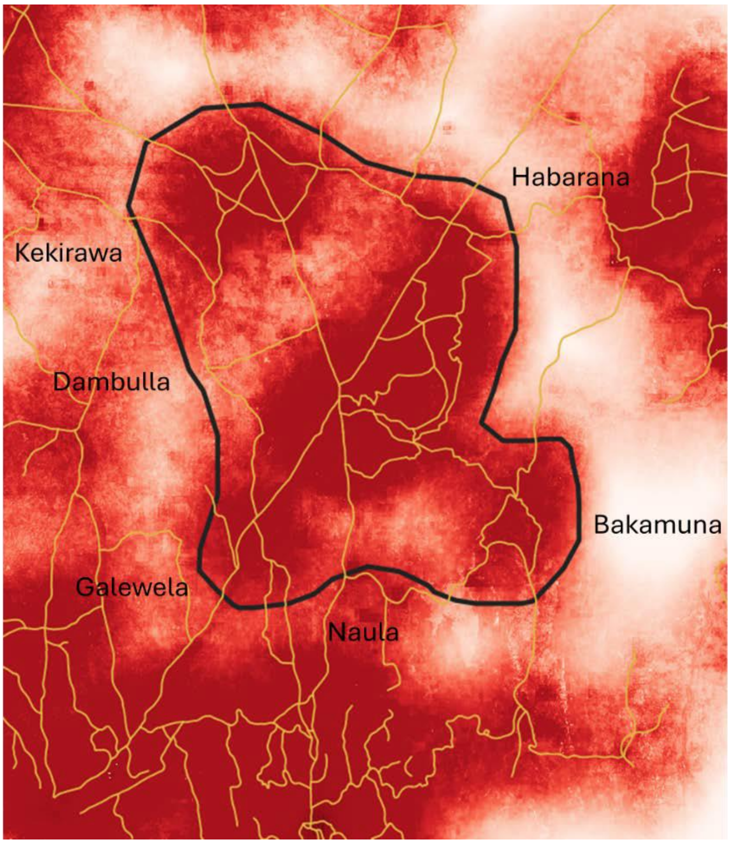

Figure 7: Functional boundary of the Dambulla city

Upon examining the clustering pattern at a macro scale, a hidden relationship became apparent within the same composited output. Dambulla acted as a catalyst for five satellite towns and was operationalized as part of a larger system. The towns of Naula, Bakamuna, Habarana, Kekirawa, and Galewela were not identifiable through conventional methods of functional boundary delineation (Figure 8). A combination of Connectivity analysis, NTL and NDBI made the platform reveal hidden spatial configurations by delineating a functional boundary. The resultant output at the macro level is similar to the regional-level functioning clusters in the Dambulla region.

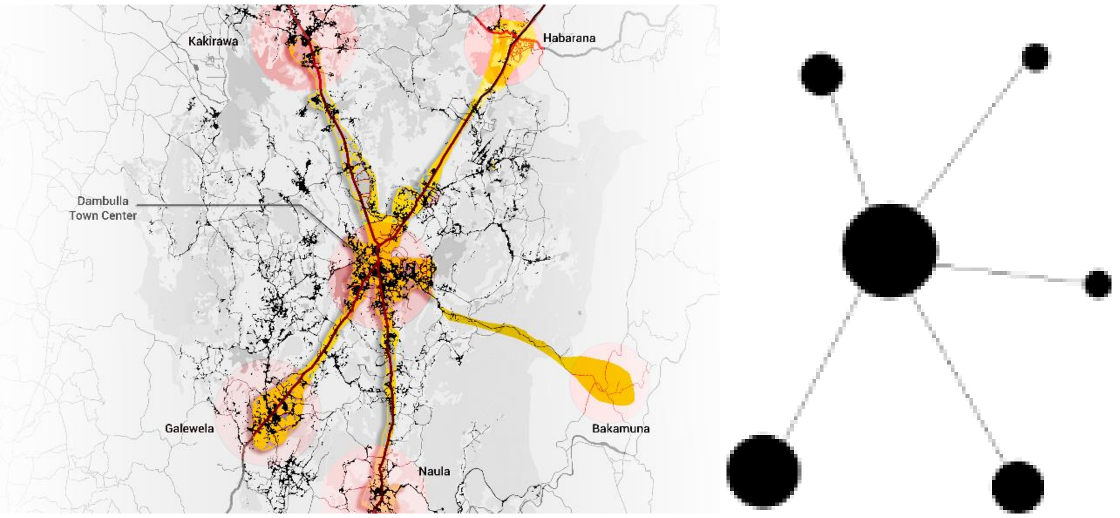

Figure 8: Connectivity of Dambulla City to Surrounding Areas at the Macro Level

Conclusion and Recommendation

Understanding the location and its dynamics through remote sensing and GIS technology is a significant achievement for urban planners and researchers. The ability to demarcate functional regions of an urban context without conducting physical site visits is an impressive feat. This process provides a foundational understanding of the spatial relationships within an area and its functional regions, which are essential for initiating effective planning and redesigning projects for any given environment.

One of the key advancements in urban analysis is the integration of connectivity theory with remotely sensed data, such as Nighttime Light Data (NTL) and the Normalized Difference Built-Up Index (NDBI). This combination enables us to gain initial insights into how urban spaces are configured and how they interact spatially. Connectivity theory helps to identify critical nodes of activity and the strength of relationships between them, while NTL data provides information on areas that are active at night, often indicating economic or social hubs. NDBI, on the other hand, focuses on the presence of built-up areas, allowing the identification of physical structures and their distribution within a region.

The Dambulla urban area was carefully analyzed using this remote sensing approach to better understand its functional region and spatial configuration. During this study, a hidden relationship emerged—Dambulla was found to act as a catalyst for five other nearby towns, functioning as part of a cluster rather than an isolated urban area. This discovery emphasized that Dambulla is not an independent urban entity; instead, it has strong interdependencies with these five satellite towns. These towns collectively form a regional system in which Dambulla plays a central role.

Overall use of this method was simple in terms of its process, but it was equipped with rich data which were able to capture different dimensions relevant to functional boundary delineation. This method covered several important parameters which enabled us to understand the actual functioning area. If it breakdown down dimensions associated with the study, NTL which gives data about nighttime activities at higher intensity shows a higher level of functionalities. This functioning aspect cannot directly be captured in the NDBI data, since it does provide the building index, some of the buildings may be abandoned, dilapidated or out of use for a longer period. Combining both NTL and NDBI can reveal real functioning areas by mitigating unforeseen circumstances like abandoned built-up areas.

Connectivity is another vital parameter which indicates the potential for urbanization or urban activities to happen. Connectivity as spatial configuration theory shows impactful nodes and their impact on the surroundings. Using connectivity combined with kernel density analysis can capture the extent of the potential areas for urban agglomeration. A more realistic idea of functional boundary is a combination of the potential functional areas and existing functioning areas to see the urban area in a bigger picture. This approach really helps when it comes to zoning and regulations or controlling development at the phase of extreme consideration.

Most of the conventional functional boundary delineation lacks the aspect of potential areas, which is a vital indicator of socioeconomic activities. Some of the underutilized projects have shown they did not capture the connectivity and agglomeration potential at the initial planning stage. On the other hand, well-functioning informal structures(street vendors) popping up in some area unintentionally using this connectivity aspect and operate successfully. At first glance, this connectivity has appeared to be the invisible hand of guiding things. Once it is revealed it can be utilized to avoid projects getting obsoleted but to reach success.

Additionally, if some development becomes a threat to the spatial configuration, it can be also controlled by rearranging the road network and getting the most connected nodes into somewhere else.

This method of boundary delineation is equipped with various levels of parameters from physical to hidden parameters like connectivity that can not be captured and quantified at first glance, which enable to capture wide scope in terms of the functional region of a given urban context. Studies matter with location and its possible influential extent would be benefited by this functional boundary delineation study.

This method of functional boundary delineation can be used for various applications in the most effective manner. In administration’s purpose, monitoring urban activities, zoning and regulation as well as a development guide to make cohesive developments without destroying the spirit of any given urban environment.

However, the scalability of this approach has its limitations as well. For instance, upscaling this approach to the local level brings the problem of limited resolution (30 m) resolution of NTL data as the most matter, high-resolution images directly from the sensor can bring more insight with clear dynamic changes which is the fundamental required on a local scale exercise like extracting spatial relationships within a small town. Using resolution-enhancing methods like data fusion can give answers to this problem but it requires careful dedicated study.

References

Jayasinghe, A. B., & Munasinghe, J. (2013). *A study of the urbanizing pattern in Kegalle District, Sri Lanka with connectivity analysis*. University of Moratuwa.

Abedini, A., Ebrahimkhani, H., & Abedini, B. (2016). Mixed Method approach to delineation of functional urban regions: Shiraz Metropolitan Region. *Journal of Urban Planning and Development*, *142*(3). https://doi.org/10.1061/(asce)up.1943-5444.0000298

Gajović, V. (2023). Comparative analysis of different methods and obtained results for delineation of functional urban areas. *www.academia.edu*. https://www.academia.edu/105084574/Comparative_analysis_of_different_methods_and_obtained_results_for_delineation_of_functional_urban_areas

Yu, Y., Zhang, C., Ma, W., Xu, Y., & Gao, X. (2022). Urban Growth Boundaries Delineation under Multi-Objective Constraints from the Perspective of Humanism and Low-Carbon Concept. *Sustainability*, *14*(23), 16100. https://doi.org/10.3390/su142316100

Liu, J., Zhang, G., Zhuang, Z., Cheng, Q., Gao, Y., Chen, T., Huang, Q., Xu, L., & Chen, D. (2017). A new perspective for urban development boundary delineation based on SLEUTH-InVEST model. *Habitat International*, *70*, 13–23. https://doi.org/10.1016/j.habitatint.2017.09.009

National Physical Planning Department. (2017). *National physical planning policy & the plan — 2017-2050*. Ministry of Megapolis and Western Development, Sri Lanka.

Flórez-Revuelta, F., Casado-Díaz, J. M., & Martínez-Bernabeu, L. (2008). *An evolutionary approach to the delineation of functional areas based on travel-to-work flows*. University of Alicante.

Zhao, C., Li, Y., & Weng, M. (2021). *A fractal approach to urban boundary delineation based on raster land use maps: A case of Shanghai, China*.

Flórez-Revuelta, F., Casado-Díaz, J. M., & Martínez-Bernabeu, L. (2008). *An evolutionary approach to the delineation of functional areas based on travel-to-work flows*. Department of Computing Technology, University of Alicante; Institute of International Economics, University of Alicante.

Zhang, J., Yuan, X., Tan, X., & Zhan, X. (2021). *Delineation of the urban-rural boundary through data fusion: Applications to improve urban and rural environments and promote intensive and healthy urban development*

Sridhar, M. B., & Sathyanathan, R. (2022). Assessment of urban expansion and identification of sprawl through delineation of urban core boundary. SRM Institute of Science and Technology