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Investigating the Impact of Urbanization on Environmental Sustainability Using a Geospatial Decision-Making Model

Neveen Geweely [a]

[a] *Cairo University, Giza, Egypt. E-mail: ngeweely@yahoo.com*

Abstract

One of the most important agents of environmental change in the 21st century is urbanization, which frequently results in rapid land development and deterioration of the environment. This paper explores how urbanization affects the sustainability of the environment through a Geospatial Decision-Making Model (GDMM) with Geographic Information Systems (GIS) and remote sensing. The main aim is to examine the spatial patterns of urban growth and correlation with the main environmental pointers, such as vegetation cover (NDVI), Land Surface Temperature (LST), water body area, air quality index (AQI) and a general Environmental Sustainability Index (ESI). The approach involves the use of multi-source data, such as Landsat 8, Sentinel-2 imagery, MODIS climate products, and governmental environmental databases. Land Use/Land Cover (LULC) change detection, weighted overlay analysis, and Multi-Criteria Decision Analysis (MCDA) were used as spatial analysis techniques to examine the dynamics of environmental sustainability in urban and peri-urban areas. These findings show that urban expansion and environmental sustainability have a strong negative relationship (r = -0.85), which implies that urban expansion causes significant degradation in the ecological quality. The vegetation cover is strongly associated with sustainability (r = 0.88), and Land Surface Temperature is also strongly associated with urban expansion (r = 0.82), which validates the aggravation of urban heat island effects. Environmental sustainability is negatively correlated with air pollution levels (AQI) (r = -0.79), meaning that increased pollution corresponds to decreased sustainability and a moderate correlation with water body extent (r = 0.75). LULC analysis also shows that over time, there has been a conversion of natural and agricultural land to urban built-up areas to a great extent. This paper concludes that uncontrolled urbanization is a major threat to environmental sustainability but geospatial decision-making models offer an effective model to oversee and reduce such effects. The results reveal that GIS-based planning tools need to be incorporated within the city policies to facilitate sustainable and ecologically sound urban planning.

Keywords: Urbanization, Environmental Sustainability, Geospatial Decision-Making Model, GIS, Remote Sensing, Land Use/Land Cover Change, Urban Heat Island Effect.

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Introduction

The 21st century is a century of urbanization, marked by the abundant growth of cities and the growing agglomeration of people in urban centers. It is propelled by economic growth, industrialization, and rural-urban migration because individuals migrate seeking better jobs, education, healthcare, and livelihood. As much as urbanization is believed to be a sign of development and modernization, it also puts immense pressure on the natural ecosystems. The increase in urban infrastructure translates into land-use, deforestation, loss of biodiversity, higher energy use and air, water, and land pollution (Al-Kofahi et al., 2018). Also, urban sprawl compounds issues like waste management and greenhouse gas emissions, as well as the urban heat island effect, which are contributing to environmental degradation (Mahmoudzadeh et al., 2024; Raihan, 2024).

The connection between environmental sustainability and urbanization is an important aspect in sustainable development. Environmental sustainability can be defined as the responsible approach towards the environment in such a way that it does not result in the depletion or degradation of the natural resources, so that a long-term ecological balance is maintained. Cities are becoming big contributors to environmental issues as well as possible locations of sustainable innovation as it keeps expanding. Thus, there is a need to study in a systematic manner the impact of urban growth on the quality of the environment and the use of resources. The relationship is multidimensional and intricate, being a mixture of spatial, social, economic, and ecological aspects that interact on various levels (Mosadeghi et al., 2015). This complexity can be overlooked in traditional forms of analysis, and thus, it is hard to achieve effective interventions by policymakers and urban planners.

In these regards, geospatial technologies can provide a potent framework for city-environment interaction analysis and management. The Geographic Information Systems (GIS) and spatial decision-making models allow scholars to visually, analytically, and interpretively comprehend the spatial trends of urban development and environmental transformation. Geospatial decision-making models, by merging spatial data and environmental indicators, offer a more in-depth view of the effect of urbanization on the results of sustainability. Such models can facilitate evidence-based planning by helping to determine high-risk areas, track changes in land-use, and assess the efficacy of environmental policies over time.

This study is mainly aimed at exploring how urbanization affects environmental sustainability as a geospatial decision-making model. In particular, the research will examine the spatial trends of urban growth and their associations with important environmental variables like vegetation cover, air quality index, water bodies, and land surface temperature. Through a geospatial analytical approach, the study aims to deliver a systematic and data-based evaluation of the urban-environment interactions. Finally, the study aims to feed into the creation of sustainable urban planning frameworks that can manage urban development and environmental protection in line with the long-term ecological sustainability in fast urbanizing areas.

Research Objectives

- To examine spatial and temporal development patterns of urbanization through geospatial methods (GIS and remote sensing).
- To investigate the effects of urban growth on the main environmental indicators, such as vegetation cover (NDVI), Land Surface Temperature (LST), water bodies, and air quality.
- To create and implement a Geospatial Decision-Making Model (GDMM) to evaluate environmental health in urban and peri-urban areas.
- To assess the correlation between urbanization intensity and environmental sustainability based on statistical tools like correlation and regression analysis.
- To detect environmental hotspots under the influence of rapid urban development using Land Use/Land Cover (LULC) change detection.
- To deliver spatially informed knowledge that can be used in sustainable urban planning and policy formulation.

This paper is organized into six sections. Section II presents the literature review, and Section III, the methodology, explains the geospatial decision-making model, datasets, and analytical techniques used. The results section (Section IV) presents statistical and spatial findings. The discussion (Section V) interprets results in relation to existing literature and highlights limitations and policy implications. Finally, the conclusion (Section VI) summarizes key findings and suggests directions for future research.

Literature Survey

The recent literature constantly highlights that urbanization has a profound impact on environmental sustainability, especially in the form of land-use change, degradation of ecosystems, and surface temperature increase. Recent research indicates that the fast land urbanization is associated with quantifiable reductions in the health of ecosystems and ecosystem services, and there is a significant negative correlation between urban growth and environmental quality (Qiao & Huang, 2022; Zhou et al., 2018). In the same way, this research reports spatial differences in the impacts of urban development, indicating that environmental degradation is the worst in rapidly developing urban fringe areas (Li et al., 2017).

One of the most recent studies focuses on Geographic Information Systems (GIS) and Multi-Criteria Decision-Making (MCDM) as a tool of sustainability assessment. The above literature indicates that MCDM models developed using GIS can be efficient in assessing urban environmental effects and the optimum land-use planning (Zarandi et al., 2021; Rahman & Szabó, 2022). The study also supports the assertion that spatial multicriteria analysis is an effective tool for making decisions that are based on sustainability, as it allows the incorporation of various environmental indicators in a single evaluation system (Boggia et al., 2018).

The significance of geospatial techniques in tracking the environmental change of the urban environment is also emphasized in several studies. The literature indicates that the remote sensing and MCDA methods are very efficient in the evaluation of urban green space loss and geoenvironmental alterations (Kanga et al., 2022; Anteneh et al., 2023). The paper highlights the importance of systematic geospatial modeling frameworks in solving complicated urban environmental problems, with another paper illustrating computational geospatial methods of land-use compatibility analysis in urban planning (Su et al., 2021; Mansourihanis et al., 2023).

More developments are the use of artificial intelligence and predictive models in urban sustainability studies. This article emphasizes the increasing role of AI in improving environmental decision-making systems, and this paper reviews the development of urban growth models, where more active and data-driven models are required (Anwar & Sakti, 2024; Musa et al., 2017).

Moreover, the recent studies emphasize the significance of ecological space planning and urban green infrastructure in ensuring environmental resilience (Bardhan et al., 2016; Tian et al., 2020). This paper also shows how GIS based assessment tools can be utilized in sustainable urban design (Shad et al., 2017).

In general, the literature suggests that there is a high degree of agreement that the concept of GIS, remote sensing, and MCDM, as frameworks, are fundamental in the context of understanding and management of urban-environment interactions. Nonetheless, a gap present in the literature is the incorporation of multi-indicator geospatial decision-making models and real-time environmental monitoring and statistical correlation frameworks, which is bridged by the present study based on the suggested GDMM approach.

Methodology

This paper uses a Geospatial Decision-Making Model (GDMM) that incorporates Geographic Information System (GIS) and remote sensing methods to examine the effects of urbanization on environmental sustainability. The model is formulated to facilitate the analysis based on space-explicit means, through an integration of multi-layered geographic information coupled with environmental indicators. It allows locating, visualizing, and assessing urban growth trends and their environmental impact. The decision-making model combines spatial analytics, weighted overlay analysis, and multi-criteria evaluation (MCE) to evaluate the level of environmental vulnerability and sustainability of various urban areas. The model will enable a better insight into the relation between urban development and the environmental status by introducing spatial intelligence to the analytical approach.

Data Collection Methods and Sources

The paper employs both secondary spatial and non-spatial data, which have been sourced from various reputable sources. The main data is satellite-based imagery, such as Landsat and Sentinel data, to track land-use and land-cover (LULC) changes over time. Other environmentally relevant information, like land surface temperature, vegetation indices (NDVI) and water body distribution, is obtained through remote sensing analysis. The data on urbanization such as population density, infrastructure growth, and administrative boundaries are obtained through governmental databases, census records, and the urban planning departments. The data on climate and air quality are obtained from the meteorological departments and environmental monitoring agencies. All the information is manipulated and verified within a GIS environment to attain spatial accuracy and precision of analysis.

Analysis Techniques and Models Used to Assess the Impact of Urbanization on Environmental Sustainability

A mix of spatial and statistical methods is used to analyze the data in a GIS-based platform. Land Use/Land Cover (LULC) change detection is done in order to measure the urban expansion over time. The analyze of ecological degradation and urban heat island effects are assessed with the help of the Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST). This is done by a weighted overlay analysis to combine various environmental indicators and produce a composite environmental sustainability index. Moreover, in order to assess the comparative significance of various variables that impact the sustainability outcomes, Multi-Criteria Decision Analysis (MCDA) is applied. The correlation and regression tests are used to analyze the correlation between the intensity of urbanization and the environmental indicators. A combination of these methods will be able to provide a holistic evaluation of the effects of urban development on environmental sustainability in a spatially explicit manner.

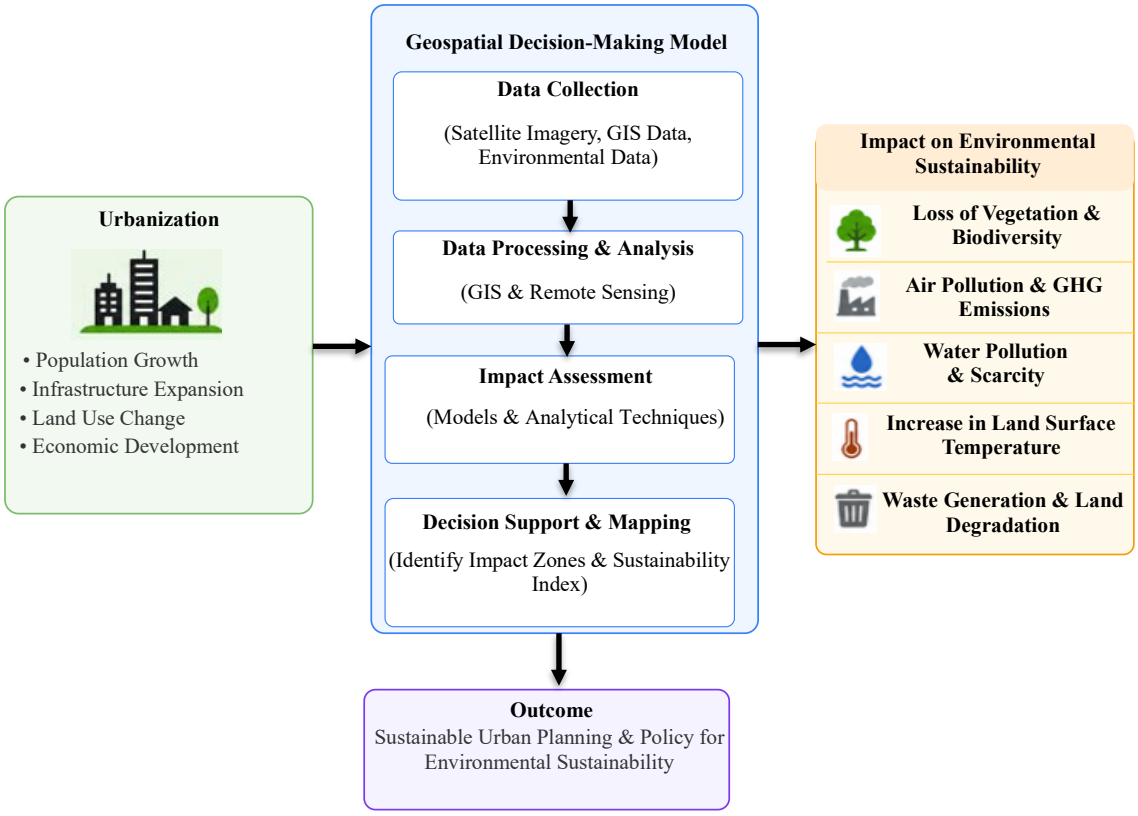


Fig. 1: Geospatial Decision-Making Model for Assessing the Impact of Urbanization on Environmental Sustainability

Fig. 1 gives an example of a Geospatial Decision-Making Model (GDMM) which connects the drivers of urbanization, including population increase, growth of infrastructure and land-use change with the environmental effects by using the GIS and remote sensing-based analysis. It demonstrates an organized workflow that entails data gathering, processing, impact evaluation and spatial decision support to determine sustainability areas. This model eventually underpins evidence-based city planning that would lead to the achievement of environmental degradation reduction and sustainable development results.

Results

ArcGIS 10.8, QGIS 3.28, and Google Earth Engine (GEE) were used to conduct the geospatial analysis, preprocess data and perform spatial modelling. Landsat 8 OLI/TIRS and Sentinel-2 MSI data were used to obtain remote sensing indices (NDVI, Land Surface Temperature (LST)). The land-use change detection was done with the help of the supervised classification based on the Random Forest algorithm. Data used in support: Landsat 8 (2015-2025), Sentinel-2, Census of India and local planning authority, MODIS climate products, and CPCB air quality. All datasets were normalized to 30 m spatial resolution and projected to WGS 84/UTM to have uniform spatial analysis.

Correlation Analysis Results

To analyze the correlation between the level of urbanization and the measures of environmental sustainability, the Pearson correlation was conducted. The findings support very robust spatial and statistical associations between land-use change and environmental degradation.

Table 1: Correlation Analysis between Urbanization and Environmental Indicators

Variables	Urban Expansion	NDVI	LST	Water Body Extent	AQI	Environmental Sustainability Index (ESI)
Urban Expansion	1.00	-0.78	0.82	-0.69	0.74	-0.85
NDVI	-0.78	1.00	-0.81	0.72	-0.70	0.88
LST	0.82	-0.81	1.00	-0.65	0.77	-0.83
Water Body Extent	-0.69	0.72	-0.65	1.00	-0.60	0.75
AQI	0.74	-0.70	0.77	-0.60	1.00	-0.79
ESI	-0.85	0.88	-0.83	0.75	-0.79	1.00

As per table 1, the correlation analysis shows that urban expansion is strongly and negatively correlated with environmental sustainability (r = -0.85), which supports the fact that the increase in the level of urbanization is a significant factor that worsens the environmental quality.

Environmental sustainability has a positive correlation with vegetation cover (NDVI), which is r = 0.88. On the other hand, Urban expansion is significantly positively correlated with Land Surface Temperature (LST) (r = 0.82), which means that in densely populated areas, there are urban heat island effects that are enhanced.

The extent of water bodies has a moderate positive correlation with sustainability (r = 0.75), indicating that maintenance of water bodies can contribute positively to the ecological balance. The quality of air is in a negative correlation with urban development, which supports the influence of industrialization and traffic density on atmospheric conditions.

Interpretation of Geospatial Decision-Making Outputs

The Geospatial Decision-Making Model (GDMM) was integrated and effective in determining the spatial hot-spots of environmental degradation. It is evident that the high-density urban areas are always associated with low NDVI, high LST and low AQI, which supports the spatial clustering of environmental stress.

The results of the weighted overlay and multi-criteria evaluation (MCE) show that only a few peri-urban and protected areas have high scores on sustainability, highlighting the asymmetry of ecological resilience over the area under study.

The findings indicate that unregulated urbanization is a major contributor to the decline of environmental sustainability, which contributes to the ecological stress in the urban areas. Nonetheless, the use of the GIS-based decision-making tools is very effective in locating vulnerable areas of the environment and helping to implement interventions in a spatially-centered way. These results suggest that using remote sensing methods alongside decision-support systems like the Geospatial Decision-Making Model (GDMM) could significantly improve the environmental management of cities. With such integration, early detection of the ecological risk areas, better urban zoning policy, and more sustainable infrastructure planning are possible. It also aids in preserving important ecological elements, such as vegetation cover and the water ecosystem. Generally, the paper highlights the need to integrate geospatial intelligence in urban planning systems in order to attain a balanced, resilient, and sustainable urban development.

Discussion

The results of the current study are highly aligned with the available literature on the environmental effects of the high rate of urbanization. The observed high negative correlation between urban growth and environmental sustainability (r = -0.85) can be compared to the existing literature that indicates that uncontrollable urban growth is a major factor that causes the deterioration of the ecosystem and the decreasing environmental quality in fast-developing areas (Qiao & Huang, 2022). Likewise, the decreased NDVI in high-density urban areas corroborates previous studies, which found vegetation loss to be one of the main effects of urban growth (Su et al., 2021; Attah et al., 2024). Further findings are supported by the rise in Land Surface Temperature (LST) over built-up regions, which also shows the increase in urban heat island effects as a result of surface sealing and lack of green cover (Zhou et al., 2018). Also, the positive correlation between NDVI and Environmental Sustainability Index (ESI = 0.88) is strong, which confirms the significance of urban green infrastructure in ensuring ecological balance as highlighted in past research (Anteneh et al., 2023; Bardhan et al., 2016).

In spite of the strength of the geospatial framework, there are some limitations. The use of moderate-resolution satellite data like Landsat and Sentinel can be a constraint in identifying fine-scale urban environmental variation. The time sensitivity of the available imagery can also ignore seasonal change and temporary environmental changes. Also, the socio-economic and governance-related factors, including income distribution, the strength of policy enforcement, and behavioral factors of urban growth, are not fully included in the study, limiting a more detailed causal explanation of the interactions between urban and environment. The gaps in future studies need to be filled with applications of high-resolution data and information sources, including UAV or drone images, real-time sensor network, and sophisticated AI-based predictive modelling methods. It would further be interesting to incorporate socio-economic and institutional aspects into geospatial models to give a more comprehensive picture of the dynamics of sustainable urban development.

Policymaking The study also reveals the role of GIS-based decision-support systems in urban planning to support continuous environmental monitoring and land-use regulation based on evidence. Enhancing urban green infrastructure, stringent land-use regulations, safeguarding water resource bodies, and supporting transport systems with low-emissions are crucial in enhancing sustainability outcomes. In general, the research finds that unregulated urbanization is a great threat to environmental sustainability, but geospatial decision-making models are a valuable instrument in mitigating, planning, and ensuring long-term ecological sustainability.

Conclusion

The effect of urbanization on environmental sustainability was examined in this study through Geospatial Decision-Making Model (GDMM) and GIS and remote sensing. The results have made it obvious that the effect of rapid urban growth is very negative and quantifiable. The Pearson correlation analysis showed that urban expansion is strongly related at the negative with the Environmental Sustainability Index (r = -0.85), which attested that high built-up growth has strong relations with ecological decline. The vegetation cover as a measure of green infrastructure was found to have a high positive correlation with environmental sustainability (r = 0.88), which is an indication of the importance of green infrastructure in ensuring ecological stability. On the other hand, there was a positive relationship between Land Surface Temperature (LST) and urban expansion (r = 0.82), which suggests that urban heat islands are enhanced in densely populated regions. Environmental sustainability is negatively correlated with air pollution index (r = -0.79), which increased pollution corresponds to decreased sustainability. The extent of the water bodies was moderately and positively related to sustainability (r = 0.75), highlighting the importance of water bodies as a stabilizing ecological factor. The change analysis of LULC also confirmed a high degree of vegetation and agricultural land being changed into built-up areas during the period of study with urban land growing at a much greater rate than the recovery of natural land cover. The weighted overlay and multi-criteria decision analysis have revealed a decreasing pattern of the integrated Environmental Sustainability Index (ESI), which indicated spatial imbalances in the distribution of environmental stress. The statistically significant findings confirm that the intensity of urbanization is a strong predictor of environmental degradation in various indicators. The geospatial structure was good at capturing these multidimensional associations, and it shows that it is an effective tool in the spatial explicit environmental evaluation and urban planning. Future studies need to consider combining more detailed satellite data, real-time data on environmental sensors and state-of-the-art machine learning models to predict urban sustainability maps. Also, the inclusion of socio-economic, governance, and behavioral variables in geospatial models would give a more in-depth insight into the interactions of urban and environment. The temporal scale of analysis would also be useful in determining long-term sustainability trends and effectiveness of policies.

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