www.ijarp.com ISSN 2456-9992 Page 1 to 6
International Journal Advanced Research Publication

Research-Article
Volume: 2
Issue: 10

GEOSPATIAL MULTI-CRITERIA OPTIMISATION OF BLUE-GREEN INFRASTRUCTURE CORRIDORS FOR URBAN STORMWATER MANAGEMENT: HYDERABAD, INDIA

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Article Received	Article Revised	Published
12-09-2026	02-10-2026	22-10-2026

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DOI: https://doi-doi.org/101555/ijarp.6533

ABSTRACT

The process of urbanisation results in a transformation of the natural landscape into an urbanised one, which in turn increases surface runoff and reduces the recharge of groundwater, thereby causing serious instances of urban flooding. To address this issue, the concept of Integrated Blue-Green Infrastructure (BGI) offers a means of managing stormwater in a sustainable manner by combining a number of connected blue infrastructure elements, for example green roofs, rain gardens, wetlands, and urban forests, etc., these contributing to infiltration, the reduction of runoff, and improved water quality. In this study, a methodology based on geospatial technology is applied in order to produce a BGI suitability map by identifying the most appropriate locations for implementation. This methodology, which makes use of remote sensing and geographic information system techniques, examines a variety of factors such as slope, drainage density, land use/cover, and proximity to roads. Core patches are chosen to act as ecological nodes, the corridors are mapped by means of the least-cost path approach, and the networks are then refined using the gravity model.

INTRODUCTION

The Urban Blue Green Infrastructure consists of a number of interconnected components, such as parks, wetlands, water bodies, green roofs, bioswales, and similar features, which are incorporated into urban areas in order to obtain socio-ecological resilience and sustainability benefits (Pauleit et al., 2017; De Oliveira et al., 2022). By making use of natural ecological and hydrological processes, BGI offers a range of ecosystem services, such as flood protection, urban cooling, better air and water quality, carbon capture, and enhanced human well-being (Dreiseitl & Wanschura, 2016; Brown & Mijic, 2019). Furthermore, Sustainable Urban Drainage Systems, for example green roofs and retention basins, achieve resource efficiency by means of improved infiltration and reduced stormwater run-off (Ossa-Moreno et al., 2017; Liao et al., 2017).

Such techniques can only be successfully put into practice by means of remote sensing, geographic information systems, and advanced geospatial techniques concerned with spatial mapping, monitoring, and multicriteria analysis (Campbell & Wynne, 2011). It is possible to combine these techniques in order to model hydrological dynamics, to select suitable BGI sites, to monitor changes in land use, and to plan climate change adaptation strategies.

Literature Review

The integration of GIS with MCE, AHP, graph theory, least-cost path analysis and gravity models is commonly used in planning and sustainable infrastructural development. Santosh et al. (2018) utilised a GIS-based MCE methodology for the suitability analysis of urban development, considering land use/land cover, slope, distance to road, land cost, aspect, and lineaments. Using AHP and Saaty's pairwise comparison, a weighted overlay of thematic maps was done for the classification of land into five suitability classes. Likewise, Bunruamkaew & Murayama (2011) utilised GIS and AHP to identify suitable sites for ecotourism in Thailand, considering nine environmental, topographic, accessibility, and socio-economic parameters. The results were classified into four suitability classes using the FAO land evaluation framework.

When planning Blue-Green Infrastructure (BGI), Kaur and Gupta (2022) applied a combination of GIS, AHP, graph theory, least-cost pathway analysis and gravity models in order to determine suitable BGI networks for Ahmedabad. The study used factors including slope, drainage density, land cover, hydrological soil group and road distance, identifying the main blue-green areas as nodes and designing corridors to improve landscape connectivity and to aid sustainable stormwater management. In a different study, Linehan et al. (1995) suggested a graph-theory-based method for planning greenways in Central Massachusetts. In this approach, wildlife habitats were considered the nodes and ecological corridors the links. Gravity models and cost-balancing rules were employed in the connectivity analysis to establish efficient greenway networks. Overall, the examples mentioned above indicate that combining GIS with multi-criteria decision making and spatial network analysis can serve as a powerful means for achieving sustainable urban development and for planning blue-green infrastructure.

The thematic layers were integrated using the Analytical Hierarchy Process (AHP) method, a technique widely employed in multi-criteria decision making which was proposed by Saaty in 1977. This method determines the priority of the various criteria by means of pairwise comparisons on Saaty's nine-point scale (Saaty, 2001; Kumar & Shaikh, 2012). A comparison matrix is used to establish the priorities of the criteria in relation to their importance for BGI suitability (Murali et al., 2013; Mahapatra et al., 2015; Rajakumari et al., 2022). The output map – the BGI suitability map (which serves as the cost layer in the following step of the methodology) – was produced as a result of the weighted overlay analysis (Fig. 2). The cost layer is then combined with the blue and green core patches identified from the integrated LULC map in order to identify potential ecological corridors using least-cost path analysis and, subsequently, the gravity model is applied to select the most feasible BGI network.

Study Area and Datasets

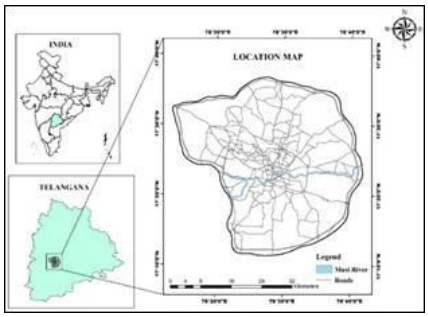


Fig.1 Location of the study area.

The study area is Hyderabad, which is situated along the Nehru Outer Ring Road (ORR) in the state of Telangana, India, and it is bordered on the north by 17°10′00″ to 17°40′00″ N and on the east by 78°20′00″ to 78°40′00″ E.

The city of Hyderabad is surrounded by the 158 km long eight-lane Nehru Outer Ring Road, this road encircling the metropolitan area which is situated at an average altitude of 549 metres above sea level on the undulating Deccan Plateau; it consists of granite hills, a number of lakes—both natural and man-made, such as Hussain Sagar—and the Musi River system.

Table 1. List of Input Data and Source.

Input data	Source
DEM	NRSC Cartosat DEM
LULC	NRSC database
Soil	NRSC database
Roads	Open Street Map

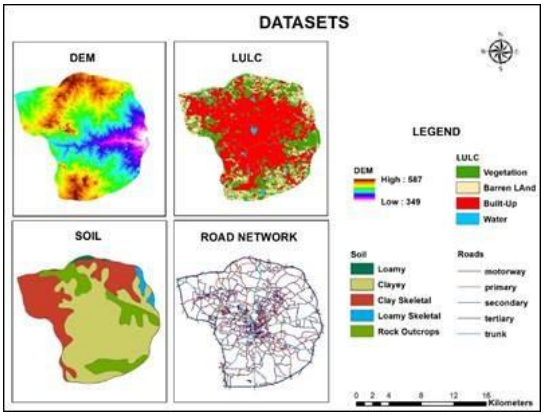


Fig. 2 Datasets of the study area.

METHODOLOGY

A BGI network was developed using suitability analysis, land-use/land-cover-derived core patches, least-cost path analysis, and a gravity model. The first stage of the methodology (Fig. 2) focuses on developing a Blue-Green Infrastructure (BGI) suitability map using a GIS-based multi-criteria suitability analysis—a spatial decision-making technique that integrates multiple thematic layers to identify locations best suited for specific interventions. In this study, the analysis aims to identify optimal locations for BGI installations to enhance stormwater management and groundwater recharge. Five key criteria representing geophysical, land-use, and infrastructure characteristics were selected: slope, drainage density, land-use/land-cover (LULC), soil type, and proximity to roads. Each criterion was processed separately in the GIS environment, classified into suitability classes, and combined using the Analytical Hierarchy Process (AHP) to generate the Biodiversity and Green Infrastructure (BGI) suitability map. This map is then used as the cost layer in corridor analysis.

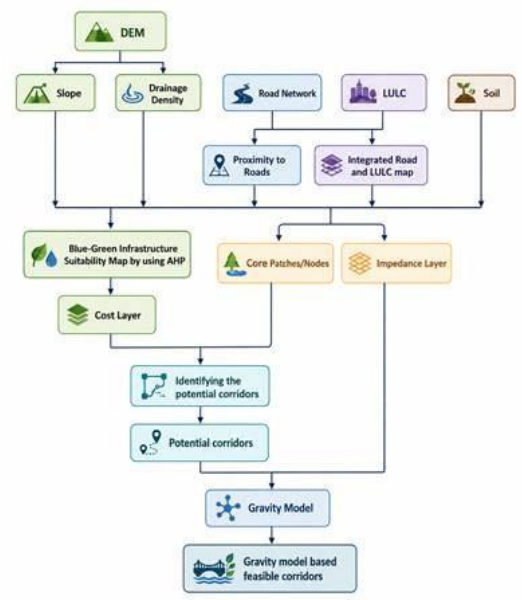


Fig. 3. Flow chart of the overall methodology.

Slope: The slope layer was generated from the Cartosat DEM (10 m) by GIS surface analysis tools. The slope layer directly affects runoff velocity and infiltration, making it an important parameter in BGI planning. Flat slopes (below 5%) are preferable for permeable pavement, bioswale, and rain garden installation; however, slopes of 10-15% can be applicable depending on the situation (NVSWCD, 2009; Hinman, 2013; Kaur & Gupta, 2022). The final slope layer was reclassified into five suitability classes.

Drainage density— a measure of the concentration of drainage channels and the tendency for water to accumulate—was calculated from the Cartosat DEM by means of hydrological analysis and then by estimating line density using GIS; areas exhibiting a higher drainage density are more prone to runoff accumulation and are therefore identified as priority areas for the placement of BGI (Kwak, 2016; Kaur & Gupta, 2022). The map produced was divided into five categories ranging from very low to very high density.

Land Use / Land Cover (LULC): The LULC layer was obtained from the NRSC Soil Resources and Land Use Mapping & Monitoring Group (55 m resolution). To accurately capture urban conditions, original classes were reclassified into water, vegetation, built-up, barren land, and roads, with the road network fully integrated. This classification maps the ratio of pervious to impervious surfaces, which heavily dictates runoff generation and infiltration capacity (Buchholz, 2013; Northeast Ohio Regional Sewer District, 2011; Kaur & Gupta, 2022).

The soil type is loam, clay, clay skeletal, loam skeletal and rock outcrop, as obtained from the vector soil layers produced by the NRSC Soil Resources and Land Use Mapping & Monitoring Group at a scale of 1:250,000. The vector soil layers have been converted into raster format and reclassified into their respective suitability classes in GIS since soil permeability controls the rate at which natural infiltration and recharge take place in the groundwater system.

The distance from the roads was determined by using the Euclidean Distance tool on the OSM road network, in order to identify potential sites which could house linear BGI measures such as bioswales, green corridors, and pervious pavements; sites located within 30 metres of major transportation networks were considered to be ideal for implementation (Kaur & Gupta, 2022).

Blue-Green Infrastructure Suitability Map

The method suggested is in agreement with Saaty's (1977) technique, a technique which stresses the need for consistency in the comparison matrix; the consistency ratio was calculated in order to verify its validity by means of the following formula:

$$Consistency\ Ratio(CR) = \frac{CI}{RI}$$

Where,

CI is the consistency index, while RI is the randomness index. CI is calculated as follows:

$$Consistency\ Index(CI) = \frac{\lambda\ max - n}{n - 1}$$

Where,

λmax is the largest matrix eigenvalue, and n is the criterion number.

The Random Index (RI) is defined as the average of the obtained consistency indices, which depend on the matrix order.

Table 3. Random Index matrix. (Santosh et al., 2018)

n	1	2	3	4	5	6
RI	0.00	0.00	0.58	0.90	1.12	1.24

If the consistency ratio is under 0.1 then the weights assigned to the parameters in the pairwise comparison are adequately consistent with the aim of the study and the parameter criteria weights can be used for further analysis and decision-making within the study.

The ultimate BGI suitability map is subsequently produced through the multiplication of each reclassified raster map by its designated weight, followed by their summation according to the specified formula within the realm of GIS.

Suitability map = Σ [criteria map * weight]

Identification of potential corridors using least-cost path analysis

The technique known as the least-cost path is a highly efficient approach in Geographic Information Systems (GIS) used to identify least-cost corridors. These corridors indicate the optimal route between two nodes by defining the landscape as a cost surface. The least-cost path analysis can be utilised to determine a potential corridor with the minimum impedance value between a single source and multiple destinations. In this study, the initial stage of the least-cost path analysis involves identifying core patches that serve as either sources or destinations. The BGI suitability map serves as a cost surface in a GIS context for executing the least-cost path function. Finally, cost distance, backlink, and cost path tools within a GIS environment are employed to create the least-cost corridors linking the designated nodes in the study area.

Refining corridors using a gravity model

The gravity model is the most commonly utilised approach for evaluating interactions between pairs of nodes. The cost path tool is used in a GIS environment to identify potential corridors that connect blue and green spaces. These corridors offer the most suitable connection between two nodes, meaning they are the least-cost paths. However, there are multiple corridors, and it is not possible to complete all of them. In this instance, the gravity model is utilised to determine the most appropriate corridors between the nodes (Kaur & Gupta, 2022). For the determination of the most appropriate corridors, the equation of the gravity model is modified from Linehan et al. (1995) as mentioned below.

The level of interaction between nodes i and j along the corridor is calculated as follows:

$$G_{ij} = \frac{N_i N_j}{D_{ij}^2}$$

Where,

$\boldsymbol{G_{ij}}$ **is** the level of interaction between node i and j and i,j = 1,2,3,……, n.

$\boldsymbol{N_i}$ **and** $\boldsymbol{N_j}$ represent the corresponding weight values

$\boldsymbol{D_{ij}^2}$ **represents** the cumulative impedance values between nodes 1 and 2.

To calculate N_i , N_j, and D_{ij} , the following formula is used

$$N_i = \frac{S_i}{P_i} \qquad N_j = \frac{S_j}{P_j} \qquad D_{ij} = \frac{L_{ij}}{L_{max}}$$

Where,

S_i and S_i represent the area of the nodes i and j

P_i and P_j represent the node weight of i and j

L_{ij} represents the cumulative impedance value of the corridor between nodes i and j

L_{max} represents the maximum impedance value of all L_{ij} (Kaur & Gupta, 2022).

RESULTS AND DISCUSSION

The following five thematic layers—slope, drainage density, land use/land cover (LULC), soil type, and proximity to roads—were created and combined by means of the Analytical Hierarchy Process (AHP) in order to determine the best locations for implementing Blue-Green Infrastructure (BGI) along the Outer Ring Road in Hyderabad. The slope map, derived from a 10 m Cartosat DEM, is divided into five classes, and it was discovered that approximately 79.68% of the study area belongs to the two least steep categories (42.91% and 36.77%), indicating that the land is appropriate for the development of BGI. The drainage density map highlights areas prone to the accumulation of runoff; those with high and very high densities cover about 30.05% of the total area and are therefore designated as priority areas. According to the LULC map, 49.49%, 22.19%, 14.83%, 10.04%, and 3.41% of the study area is covered by built-up areas, vegetation, barren land, roads, and water bodies respectively. It is therefore evident that the present blue-green spaces and road corridors can act as focal points for the expansion of BGI. The main soil types in the region are clayey (53.96%) and clay skeletal (27.87%), although loamy soils are preferred due to their good infiltration capacity. A 30 m buffer zone around the OpenStreetMap network defines the roadside areas. The weights for the thematic layers were determined using the AHP method developed by Saaty, with the resulting Consistency Ratio (CR) remaining below 0.1. In the priority ranking, the slope layer was given the highest weight, followed by drainage density, LULC, soil type, and proximity to roads. The weighted overlay eventually yielded a suitability map, showing that 2.84% and 39.41% of the study area fall into the very high and high suitability categories, respectively.

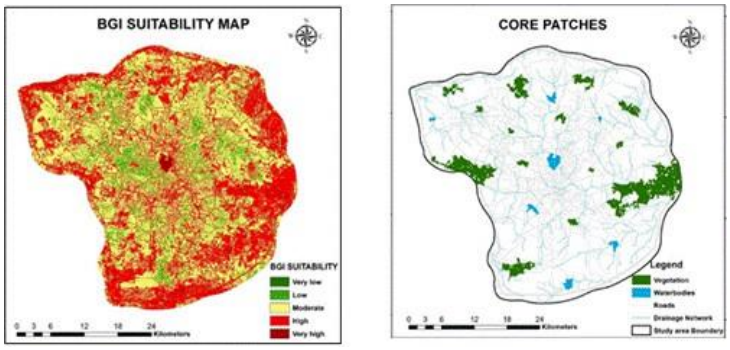


Fig. 4. The Map shows the most suitable BGI corridors by using the Gravity model.

All urban blue and green spaces having areas over 30 hectares were selected from the LULC map to form the core patches. The significance of the 30-hectare criterion is that large patches have a much higher capacity to absorb rainfall and reduce runoff, which is essential for highly populated urban areas such as Hyderabad because of high impervious surface cover and, consequently, the risk of floods. In addition, focusing on large patches is a more economically feasible approach for ecological connectivity and provides other benefits, including regulation of the urban microclimate, improved air quality, and recreational use. According to the above-described criteria, a total of 21 urban blue and green spaces were selected as core patches (Figure 4). Least-cost path analysis was carried out to link all the selected core patches using the BGI suitability map as the cost surface within a GIS framework, resulting in a network of 229 corridors.

The gravity model is applied in order to rank the 229 corridors, with the aim of establishing a sustainable network in which the nodes are linked so as to guarantee landscape connectivity and effective stormwater management. The interaction value between the nodes within each corridor, as calculated by the gravity model, is used to decide which corridors—those with an interaction value G less than 0.005—should be included in the network. Finally, 40 of the 229 corridors will be part of the network.

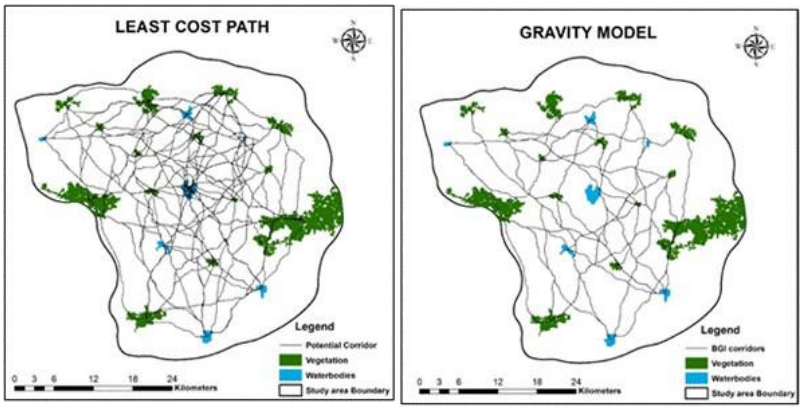


Fig. 5 Derived corridors using Least cost Path and Gravity model.

CONCLUSION

The study looks at the efficiency of applying a geospatial model when planning green infrastructure networks in order to enhance sustainable stormwater management on the Outer Ring Road in Hyderabad. Remote sensing techniques and Geographic Information System (GIS) were combined with the Analytical Hierarchy Process (AHP) so as to integrate a number of environmental and infrastructure factors, including slope, drainage density, land use/land cover, soil type, and distance from the road, allowing a suitability map for BGI to be produced. Furthermore, a method was developed for designing a network comprising 21 core patches and 229 optimal corridors by means of core patch identification (over 30 ha), along with least-cost path analysis and gravity modelling.

There is clearly a great deal of potential with regard to BGI development since a large part of the study area is appropriate for this type of development. Using blue-green resources in cities aids in reducing urban flooding, helps to restore nature's hydrological functions, and offers ecological and social services such as climate regulation and better citizen well-being. It is also evident from this study that the inclusion of data-based BGI planning in urban areas is important, particularly in the rapidly urbanising regions of developing countries.

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