Sustainable Cities and Society 143 (2026) 107365

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Morphological and fractal diagnostics for sustainable transport planning in sensitive tourism landscapes

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ARTICLE INFO

Keywords:
Fractal analysis
Spatial diagnostics
Sustainable transport
Tourism accessibility
Urban-Rural Connectivity
Urban Morphology

ABSTRACT

Managing sustainable transport access to pristine natural heritage sites without triggering ecological degradation is a critical planning challenge for tourism-driven regions within complex landscapes. This study focuses on morphological and fractal diagnostics for sustainable transport planning to unravel challenges associated with accessibility in sensitive tourism landscapes. Specifically, it investigates the severe inaccessibility of Cala Mariolu, a globally renowned beach in Sardinia, Italy, by developing a novel diagnostic framework that integrates fractal analysis of road networks with quantitative topographic assessment. Using GIS-based spatial analysis, the structural connectivity and terrain constraints of the municipalities of Nuoro and Baunei were quantified and compared. Results reveal a significantly more fragmented and less connected road network in the coastal city of Baunei compared to the urban hub of Nuoro. Crucially, this disparity is driven primarily by steeper average slopes rather than general terrain ruggedness. This relationship was synthesised into a new Terrain Connectivity Constraint Index (T_i), quantifying the landscape's inherent limitation on network development. The findings provide a robust, context-sensitive diagnostic methodology for diagnosing the root causes of transport inequity. This study quantifies that the terrain in high-constraint coastal areas can reduce the geometric potential for creating well-connected transport pathways by 46% compared to adjacent urban hubs, providing critical insight for targeting adaptive infrastructure and fostering equitable access in environmentally sensitive regions.

1. Introduction

The global pursuit of urban sustainability is increasingly confronted by the complex challenge of managing the interface between evolving urban systems and fragile peripheral landscapes (Bibri & Krogstie, 2017). As cities expand their functional regions, the demand for accessible recreational and natural heritage sites grows, placing immense pressure on ecologically sensitive areas that often lack robust transport infrastructure (Zhang et al., 2023). This tension is acutely felt in sustainable tourism, where the imperative to provide equitable access must be carefully balanced against the paramount need for environmental conservation (Tehseen et al., 2024). The United Nations' Sustainable Development Goals (SDGs), particularly SDG 11, emphasise making cities and human settlements inclusive, safe, resilient, and sustainable, a goal that inherently includes fostering sustainable connections between urban and natural spaces. However, conventional urban planning models, often rooted in Euclidean geometry and top-down approaches, struggle to conceptualise and optimise transport systems within the irregular, organic, and topographically complex landscapes that characterise many of these precious peripheries (Jeličić et al., 2021).

The Mediterranean region, with its world-renowned coastal destinations, manifests this conflict. Islands like Sardinia, Italy, experience intense seasonal tourism, leading to a spatial concentration that overwhelms coastal hotspots while leaving rural and ecologically pristine areas underdeveloped and inaccessible via public transport (Garau et al., 2022). This paradox is starkly visible in the Gulf of Orosei on Sardinia's eastern coast, home to Cala Mariolu—a globally recognised beach celebrated for its stunning beauty yet infamous for its inaccessibility. The cove remains cut off from the public transport network, accessible only by private vehicle, challenging trekking, or private boat tours, which themselves contribute to marine ecosystem degradation (Wang et al., 2023). This shifts the focus from normative debates on access

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https://doi.org/10.1016/j.scs.2026.107365
Received 14 November 2025; Received in revised form 31 March 2026; Accepted 1 April 2026
Available online 2 April 2026

towards the need for spatial diagnostics capable of revealing how terrain governs transport network structure.

The current state of the art in sustainable urban mobility planning has advanced with integrating Geographic Information Systems (GIS) and multi-criteria decision analysis to model transport routes and their environmental impacts (Emami et al., 2022; Singh et al., 2019; Song et al., 2021). Yet a significant gap remains in methodologies that can quantitatively diagnose the intrinsic spatial structure and connectivity of existing transport networks in relation to the specific, constraining features of the landscape. This is where fractal geometry offers a promising, yet underutilised, lens. Fractals, mathematical sets exhibiting self-similarity across scales, provide a robust framework for analysing the complex patterns of natural and human-made systems. When applied to street networks, fractal dimension (D) serves as a diagnostic metric for quantifying network complexity, connectivity, and spatial efficiency (Alam et al., 2025; Alam & Garau, 2025; Batty & Longley, 1994; Frankhauser, 2021). However, the application of fractal analysis remains largely siloed in theoretical urban morphology, with limited translation into practical, sustainable transport planning, particularly in contexts where tourism drives spatial development pressures.

This study addresses this gap by developing a spatial diagnostic framework that integrates fractal analysis of street networks with topographic metrics to inform sustainable mobility planning. Three core objectives guide the research: first, to quantitatively assess and compare the connectivity of the road networks in Nuoro and Baunei using fractal dimension; second, to analyse the underlying topography using slope and ruggedness indices; and third, to correlate these findings to diagnose the root causes of accessibility issues and derive evidence-based, context-sensitive policy recommendations. The significance of this work is threefold. Methodologically, it merges fractal geometry—a tool adept at handling urban complexity—with established GIS-based terrain analysis, providing a new, integrated diagnostic framework. Substantively, it offers a quantifiable, evidence-based assessment of how topographic constraints contribute to transport inequity in sensitive tourism landscapes, which directly informs policy debates on sustainable development and spatial justice. Finally, it introduces a novel and transferable tool, the Terrain Connectivity Constraint Index (T_i), which provides a direct and practical metric for planners to assess accessibility constraints a priori and target adaptive infrastructure.

To achieve these objectives, this study is guided by three primary, testable Research Questions. RQ1: Does the road network of the urban centre (Nuoro) exhibit a significantly higher fractal dimension (D) compared to the coastal tourism area (Baunei)? RQ2: Is the disparity in network connectivity between the two regions more strongly correlated with average local slope than with general terrain ruggedness? RQ3: Does the novel Terrain Connectivity Constraint Index (T_i), derived from the synthesis of fractal dimension and topographic metrics, accurately quantify the geometric limitation imposed by terrain on potential transport network development?

The following section of this study provides a comprehensive review of the literature, synthesising concepts from sustainable tourism, fractal geometry in planning, and sustainable urban mobility. Section 3 details the study areas and the methodological framework for the fractal and topographic analysis. Section 4 presents the results and their implications for sustainable transport planning. Section 5 discusses these findings into specific, actionable recommendations and reflects on broader applications. Finally, Section 6 concludes by summarising the key findings and suggesting directions for future research.

2. Literature review

2.1. The sustainable mobility and tourism dilemma in sensitive landscapes

The paradigm of sustainable tourism is fundamentally intertwined with mobility, positing that tourism development must balance a triad of objectives: economic viability, environmental protection, and socio-cultural equity (Taneja, 2025). While widely endorsed, this tripartite model often encounters its most severe test at the practical intersection of accessibility and conservation. Central to this is accessibility, a key determinant of a destination's spatial equity and inclusivity (Garau et al., 2025), which governs who can benefit from tourism's economic opportunities and who can experience a region's natural and cultural heritage (Flego & Tei, 2025). However, in ecologically sensitive landscapes adjacent to urban areas, a critical dilemma emerges improving physical access can trigger a cascade of environmental degradation, undermining the foundational sustainability principles it seeks to promote. This creates an "accessibility paradox," where the means to enjoy a resource threaten its existence.

This paradox is particularly acute in Mediterranean coastal regions and islands, where tourism economies dominate and urban centres exert significant pressure on pristine peripheries. The geographical configuration of islands like Sardinia, with their highly valued coastlines and often rugged, inaccessible interiors, intensifies this dynamic (Garau et al., 2022). Tourism demand becomes spatially concentrated, leading to a phenomenon where iconic but fragile sites, such as the coves of the Gulf of Orosei, experience intense, temporally compressed visitor pressures. The prevailing model for accessing these sites often relies on private vehicles or unregulated private boat services. This creates a vicious cycle of carbon dependency, traffic congestion in gateway communities, habitat fragmentation from roadside parking and informal trails, and direct marine pollution (Davenport & Davenport, 2006). The environmental cost of access is thus externalised onto the landscape itself.

The challenge transcends mere infrastructure provision; it involves designing mobility systems that are inherently low-impact, spatially judicious, and harmonised with the ecological fabric of the destination (Correa et al., 2024). It forces a re-evaluation of the very purpose of transport planning in such contexts. The question for planners and policymakers becomes not just how to connect, but how to connect responsibly—how to facilitate movement without facilitating degradation. Thus, it requires moving beyond simply mapping roads to understanding their relationship with the terrain: Do the routes follow the path of least ecological resistance? Does the network's structure inherently limit or encourage high-impact, private vehicle use? These are questions that traditional, Euclidean-based planning tools, focused on movement efficiency alone, have proven insufficient to answer, creating a critical impasse at the heart of sustainable tourism development.

2.2. Beyond euclidean planning: the need for complex systems approaches

Euclidean principles have long guided conventional transport planning, favouring hierarchical, centrally oriented networks and simplified spatial representations. This paradigm, effective for designing new towns or grid-based urban expansions, reveals significant shortcomings when applied to organic landscapes that have evolved over centuries in response to complex terrain Alam and Garau (2025); Shi et al. (2025). While tools like Geographic Information Systems (GIS) and network analysis have brought significant computational power to the field, their application often remains within a deterministic framework. They are adept at modelling flows and identifying shortest paths based on distance or travel time (Sowmiya Narayanan & Manimaran;, 2024). Still, they are less proficient at quantifying a transport network's intrinsic, multi-scalar spatial structure and organic connectivity (Askarizad et al., 2024). For instance, standard GIS network analysis can calculate the shortest route from point A to B. Still, it cannot easily quantify whether the overall network pattern is robust, resilient, or efficiently integrated with the landscape's morphology (Rouhana & Jawad, 2021).

In topographically complex regions—such as the rugged hinterlands of Sardinia—the landscape negotiates the organic evolution of route networks. These networks do not conform to rigid grids and are complex, adaptive systems shaped by gradients, barriers, and historical pathways. Traditional metrics like network density or connectivity indices provide a static, aggregate snapshot but fail to capture the network's scaling behaviour and spatial efficiency across distinct levels of detail (Lau et al., 2017). A network might have a high density of roads in a valley but no connectivity to the surrounding plateaus, a critical nuance lost in a single, average value. This represents a significant methodological shortfall for sustainable planning (Sarkar et al., 2019). If the goal is to design transport solutions that "work with the land," minimising environmental impact while maximising access, first the structural relationship between the existing network and the terrain must be diagnosed. This requires a fundamental shift from a Euclidean, reductionist view to a complex systems perspective that can manage non-linearity, scale-variance, and emergent patterns, inherent to natural landscapes and the networks that traverse them.

2.3. Fractal geometry as a diagnostic tool for urban systems

Fractal geometry provides a robust mathematical framework for describing the irregular, complex, and self-similar patterns throughout nature and human settlements. A fractal pattern appears similar at different scales, a property known as scale-invariance. The Fractal Dimension (*D*) is a quantitative measure that characterises this complexity, indicating how completely a fractal pattern fills the space in which it resides (Ahmed, 2024). This has been instrumental in moving beyond qualitative descriptions of city shape to quantitative, comparable metrics in urban form.

In urban studies, fractal analysis was applied to decipher the morphology of cities, from the distribution of built-up areas to the structure of street networks. The application typically falls into two categories: the analysis of urban form (the patchiness of development) and the analysis of urban networks (the connectivity of streets) (Al-Dabbagh & Ismail, 2024). The fractal dimension serves as a potent diagnostic metric for a transport network for this latter category. A higher fractal dimension (closer to a value of 2 in a two-dimensional plane) suggests a more complex, well-connected, and space-filling network, indicative of a dense, integrated system with multiple route choices available at different scales. This is characteristic of well-developed urban cores. Conversely, a lower fractal dimension (closer to a value of 1, resembling a simple line) often points to a simpler, more fragmented, or tree-like network, typical of rural, suburban, or topographically constrained areas with limited connectivity (Li & Hu, 2022). The power of this approach lies in its ability to reduce the intricate visual complexity of a network to a single, comparable metric that comprises its connectivity and spatial efficiency across scales (Alam & Banerjee, 2023). It allows planners to move from asking, "Is this network connected?" to a more nuanced question: "How is this network connected across different spatial scales, and what does its fractal dimension reveal about its capacity to support efficient and resilient mobility?" This is particularly valuable for assessing the potential of a network to integrate new public transport routes, which rely on a certain threshold of connectivity and redundancy to be effective.

Therefore, it allows planners to ask: 'Does the structure of this network suggest efficiency and integration, or isolation and fragmentation?' However, a critical limitation persists where fractal dimension describes the network's form but does not, by itself, diagnose the topographical causes of that form. The literature reveals a gap for a synthesised metric that can directly couple a key topographic driver like slope with the potential for network connectivity, providing a predictive diagnostic tool for planners in landscape-sensitive contexts. This study, therefore, fills the lacuna by proposing a framework that moves beyond merely describing the network's structure to quantitatively diagnosing the landscape constraints that preclude optimal network development, providing a crucial, predictive diagnostic tool for planners in landscape-sensitive contexts.

Previous research has examined strategies for improving accessibility in environmentally sensitive and tourism-intensive regions through a range of applied interventions. These include the optimisation of public transport services and seasonal shuttle systems in coastal and island destinations (Cavallaro et al., 2019; Garau et al., 2022; Ranjitha et al., 2025), multimodal integration combining land–sea transport to reduce private vehicle dependence (Miravet et al., 2021; Makarova et al., 2023), and regulatory approaches such as access caps, pricing mechanisms, and demand management to mitigate ecological pressure while maintaining visitor access (Fleming, 2017; Laarman & gregersen, 1996; Leung et al., 2018). Recent studies have also emphasised the role of spatial analytics and GIS-based accessibility modelling in identifying service gaps and improving last-mile connectivity in protected landscapes (Boonprong et al., 2025; Yadav et al., 2025).

While these approaches provide valuable operational and policy insights, they largely focus on optimising transport provision within existing spatial configurations. Far less attention has been paid to diagnosing the intrinsic structural capacity of landscapes to support connected transport networks in the first place, particularly in regions characterised by complex terrain. By integrating fractal network analysis with quantitative topographic diagnostics, the present study addresses this gap and complements existing accessibility-improvement strategies by providing a prior structural assessment of feasibility before service design or infrastructure investment is undertaken.

3. Materials and methods

3.1. Study area

The selection of the adjacent municipalities of Nuoro and Baunei in central-eastern Sardinia, Italy, is strategic, as the two sites represent a clear and measurable urban-rural gradient, a central concern in sustainable urban systems research. This gradient embodies the core tension between developed infrastructure and pristine, yet inaccessible, natural assets. The rationale for this comparative approach is rooted in providing a controlled investigation into the role of topography and urbanisation on network structure.

Nuoro (population: ∼36,000) is a provincial capital and a primary urban hub. Its road network has evolved to support administrative, commercial, and residential functions, exhibiting characteristics of a planned, hierarchical system. It serves as a robust benchmark for a well-connected, semi-urban network. In contrast, Baunei (population: ∼3600) is a rural municipality characterised by a dramatic and rugged topography (ISTAT, 2021). This municipality contains the core case study focus, Cala Mariolu, whose status as a globally recognised beach (ranked among the best in Europe and the world) makes its severe inaccessibility a high-stakes problem for regional sustainability and tourism policy. It stretches from the high plateaus of the Supramonte down to the renowned coves of the Gulf of Orosei, including the case study focus, Cala Mariolu. Its transport network is not a product of centralised planning but an organic adaptation to severe topographic constraints, resulting in a sparse and fragmented structure.

By holding the regional context constant (eastern Sardinia) while varying the degrees of urbanisation and topographic harshness, the study can isolate and precisely quantify the influence of these factors on transport network structure. The geographical context of the study area, highlighting the comparative road network densities in the municipalities of Nuoro and Baunei, is shown in Fig. 1.

3.2. Data acquisition and pre-processing

The analytical framework of this study is grounded in high-resolution, standardised geospatial datasets to ensure internal consistency and reproducibility across all spatial metrics. Two primary data sources were employed: road network data and topographic elevation data.

Road network data for the municipalities of Nuoro and Baunei were obtained from OpenStreetMap (OSM) using the Geofabrik regional extract for Italy, reflecting the database status as of May 2025. This

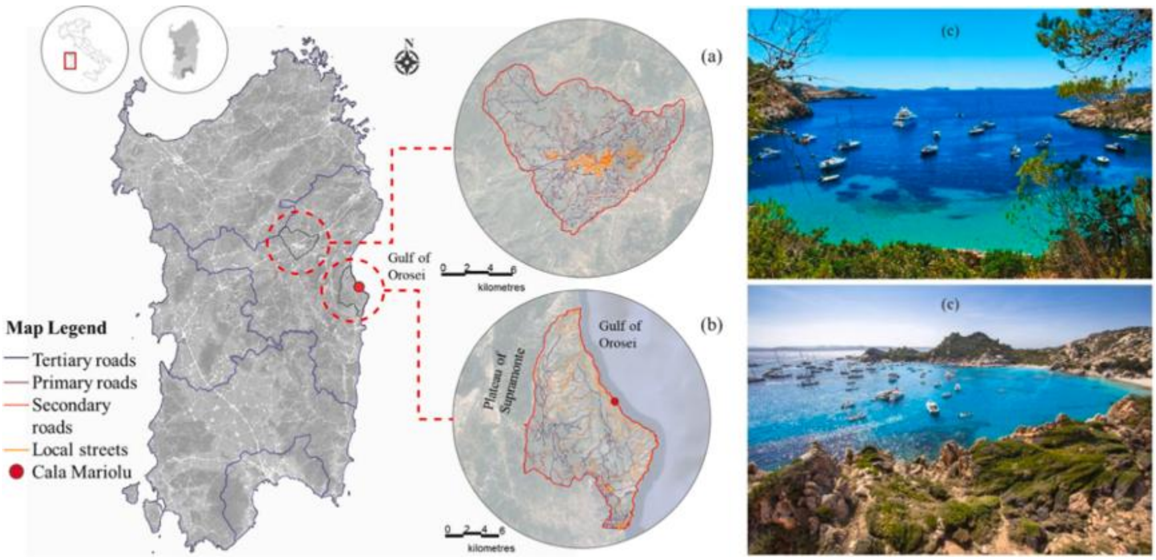

Fig. 1. Geographical location of the study areas (a) Nuoro municipality; (b) Baunei municipality, with their different degrees of roads; (c) Cala Mariolu natural landscape.

temporal consistency is critical, as variations in network updates can directly influence fractal dimension estimation. The extracted dataset was filtered to retain only motorable road classes (including motorway, trunk, primary, secondary, tertiary, unclassified, and service roads), thereby excluding pedestrian paths and informal tracks not relevant to transport network structure. The resulting vector networks were subjected to topological cleaning procedures, including node snapping within a 5 m tolerance and segmentation at all intersections, to ensure network continuity and analytical robustness. The processed networks were stored in a unified GeoPackage format and used consistently for fractal dimension analysis.

Topographic characteristics were derived from the Shuttle Radar Topography Mission Digital Elevation Model (SRTMGL1, Version 3), with a spatial resolution of 1 arc-second (approximately 30 m). The DEM was reprojected to the local Universal Transverse Mercator coordinate system (EPSG:32,632) to ensure metric accuracy and spatial compatibility with the road network data. Prior to analysis, elevation artefacts and sinks were corrected using a standard filling algorithm to maintain surface continuity. From the corrected DEM, slope and topographic ruggedness metrics were computed uniformly across both municipalities.

Municipal boundary data were obtained from official administrative sources and used to clip all raster and vector datasets, ensuring that spatial statistics were calculated within consistent zonal extents. All preprocessing steps were carried out using QGIS (version 3.28), providing a transparent and replicable workflow. This harmonised data preparation ensured that all subsequent fractal and topographic analyses were based on spatially and temporally consistent inputs, allowing observed differences in network structure and terrain constraints to be attributed to morphological conditions rather than data artefacts.

3.3. Analytical framework: an integrated fractal-topographic workflow

The methodology's core is a three-stage analytical workflow,

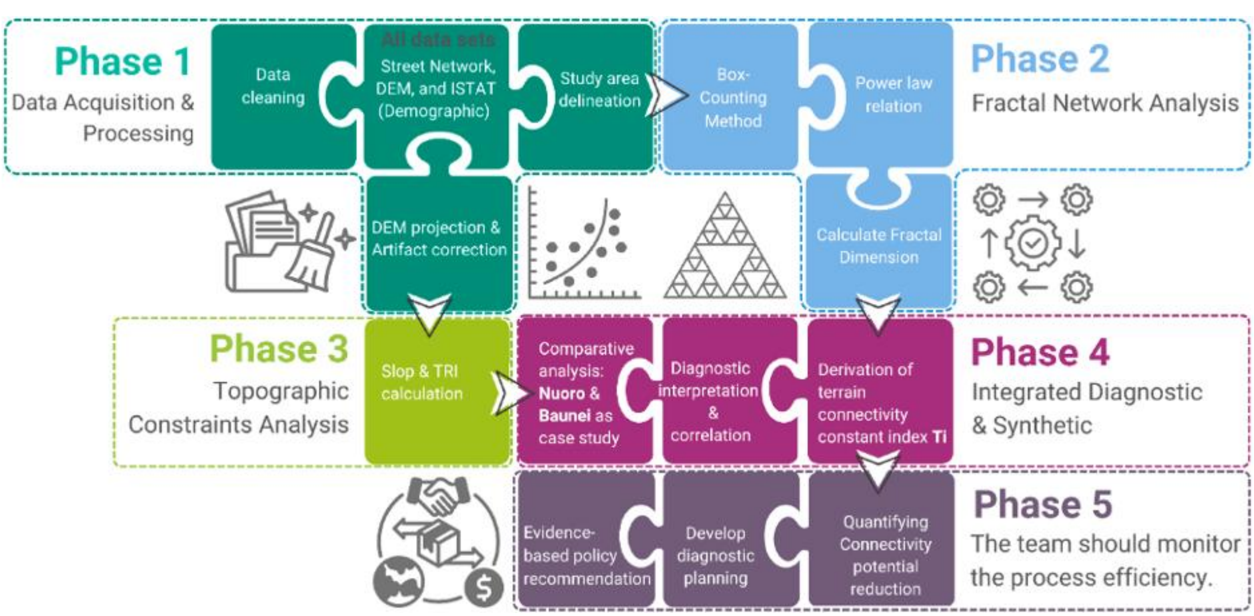

Fig. 2. Integrated analytical workflow for the fractal-topographic diagnosis of transport constraints in this study.

strategically designed to move the analysis from descriptive mapping to diagnostic quantification. The workflow first quantifies network complexity (Fractal Dimension Analysis), then characterises terrain constraints (Topographic Constraint Analysis), and finally synthesises these results to diagnose transport inequity (Integrated Diagnostic and Validation).

It is executed through a systematic, multi-stage workflow, designed to integrate independent geospatial and fractal analyses (Fig. 2). The initial stage involves rigorous data pre-processing, where street network, DEM, and official boundary data (ISTAT) are acquired and cleaned. This includes topological correction of the network, and the projection and artefact correction of the DEM. The cleaned street networks are then subjected to Fractal Dimension (D) Analysis. This is performed via the Box-Counting Method, which establishes a Power Law relation to calculate the Fractal Dimension (D), a quantitative metric of network complexity. Concurrently, the DEM is used to calculate the Average Slope and the TRI, with zonal statistics applied to derive average values for each municipality. The final, diagnostic stage involves the Comparative Analysis of Nuoro versus Baunei, where the fractal dimension and topographic metrics are correlated to perform a Diagnostic Interpretation. This is followed by the Derivation of the Terrain Connectivity Constraint Index (T_i), which quantifies the connectivity potential reduction due to terrain. The entire process culminates in the development of a diagnostic planning framework and the formulation of evidence-based policy recommendations. The following subsections detail each component of this framework, including fractal network analysis, topographic assessment, and the derivation of the Terrain Connectivity Constraint Index (T_i).

3.3.1. Fractal dimension analysis of street networks

The complexity and connectivity of the road networks were quantified using the fractal dimension (D), calculated via the box-counting method (BCM). The BCM is a widely adopted technique for characterising the space-filling capacity of complex, irregular shapes and proceeds through a series of steps. Initially, the cleaned vector road networks for Nuoro and Baunei were converted into a binary raster format. In this raster, a pixel value of 1 represented the presence of a road, and a value of 0 represented its absence. A resolution of 5 m was chosen to accurately capture the detail of the road lines without introducing excessive computational load.

The fundamental principle of the BCM is then applied by overlaying the rasterised network with a series of square grids of decreasing side length (ε). For each grid size (ε), the number of boxes ($N(\varepsilon)$) that contain at least one part of the road network is counted. The fractal dimension (D) is mathematically derived from the power-law relationship between $N(\varepsilon)$ and ε:

$$N(\epsilon) \propto \epsilon - D \tag{1}$$

Taking the logarithm of both sides linearises the relationship:

$$log(N(\epsilon)) = -D \cdot log(\epsilon) + C \tag{2}$$

where C is a constant. Therefore, the fractal dimension (D) is the negative slope of the regression line fitted to the data points in the log-log plot of $N(\varepsilon)$ against ε.

This entire process was automated using the dedicated spatial analysis software Fractalyse (v2.4). The software was fed the binary road rasters and performed the box-counting across a predefined range of scales. The correlation coefficient (r^2) of the linear regression in the log-log plot served to validate the scaling behaviour; a high (r^2) value (typically > 0.95) indicated a strong fractal relationship over the measured scales. The output for each municipality is a single, comparable metric: its fractal dimension (D).

To translate the fractal dimension into a measure of realised network potential, the utilised geometric potential (P) was calculated. This expresses the observed fractal dimension as a percentage of the theoretical maximum for a complex, plane-filling network ($D = 2.0$), discounting a baseline of 1.0 representing a simple line. The utilised potential (P) for a given area is calculated as:

$$P = D - 1 \tag{3}$$

The percentage reduction in potential between a high-constraint area and a low-constraint area was then calculated as:

$$R_d = \left(1 - \frac{P_{high-constraint}}{P_{low-constraint}}\right) \text{ x } 100\% \tag{4}$$

The influence of scale selection on the estimation of fractal dimension was explicitly considered. Box-counting was performed across a predefined range of box sizes, selected to span from fine to coarse spatial resolutions while avoiding both pixel-level noise at very small scales and saturation effects at very large scales. The selected scale range was defined to capture the stable linear scaling region of the log–log relationship, ensuring that the estimation of fractal dimension is based on scale-invariant behaviour. This range was verified through inspection of regression stability ($r^2 > 0.95$), thereby avoiding distortions associated with pixel-level noise at finer scales and saturation effects at coarser resolutions.

To verify robustness, fractal dimensions were recalculated using alternative subsets of box sizes within the same scale range. Across these tests, variations in absolute D values were minimal and did not affect the relative comparison between municipalities. This confirms that the reported fractal dimensions are not artefacts of a particular box-size selection but reflect stable, scale-consistent network characteristics.

In practical terms, the fractal dimension (D) of a street network reflects the degree to which the network fills space and offers multiple routing possibilities across scales. Higher D values indicate dense, well-connected, and spatially redundant networks, typically characterised by multiple alternative paths, shorter average detours, and greater resilience to local disruptions. Such configurations are commonly associated with urban centres where accessibility is supported by grid-like or web-like street structures. Conversely, lower D values correspond to sparse, tree-like or corridor-based networks, where movement is channelled along a limited number of linear routes. In these contexts, accessibility is highly sensitive to terrain constraints and network interruptions, and opportunities for route choice and service redundancy are structurally limited. Accordingly, fractal dimension provides a diagnostic measure of the intrinsic capacity of a street network to support connected and resilient accessibility, rather than a direct measure of travel time or demand.

3.3.2. Topographic constraint analysis

Two complementary topographic metrics were derived from the clipped Digital Elevation Models (DEMs) to objectively characterise the terrain: Average Slope and the Topographic Ruggedness Index (*TRI*).

A. **Average Slope:** Slope, defined as the elevation change rate, is a primary determinant of road construction feasibility and routing. The QGIS algorithm calculates the maximum rate of change in value from each cell to its neighbours, computing the first derivative of the elevation surface. For a detailed cell at coordinates (i, j), the slope (S) is calculated as:

$$slope_{i,j} = \arctan\left(\sqrt{\left(\frac{\delta_z}{\delta_x}\right)^2 + \left(\frac{\delta_z}{\delta_y}\right)^2}\right) \tag{5}$$

where $\frac{\delta_z}{\delta_x}$ and $\frac{\delta_z}{\delta_y}$ are the rates of change in the east-west and north-south directions, respectively.

B. **Topographic Ruggedness Index (TRI):** The *TRI* quantifies the elevation difference between adjacent cells of a DEM, providing a measure of terrain heterogeneity and ruggedness independent of slope direction. The TRI for a central cell (z_0) is calculated as the square root of the sum of the squared differences between the central cell's elevation and the elevation of its eight surrounding cells (z_k).

$$TRI = \sqrt{\sum_{k=1}^{8} (z_{k-} z_0)^2} \quad (6)$$

where z_0 is the elevation of the central cell and z_k are the elevations of the eight neighbouring cells.

C. **Zonal Statistics for Municipal Averages:** To obtain a single representative value for each municipality, the Zonal Statistics tool (QGIS) was employed. This tool calculates the statistics of a raster layer (either Slope or *TRI*) within the zones defined by a polygon layer (the municipal boundaries). The key output for each municipality and each metric was the MEAN value, representing the average slope in degrees and the average *TRI*.

3.3.3. Integrated diagnostic and validation

The workflow's final stage involves synthesising the independent fractal and topographic results for a coherent diagnosis. This process relies on an interpretative correlation rather than a single statistical test. First, the calculated fractal dimensions (*D*) for Nuoro and Baunei were directly compared, with a substantial difference hypothesised (Baunei expected to have a lower *D* value). Second, the average slope and *TRI* values for both municipalities were also compared. The central inquiry was determining which topographic metric provided the most compelling explanation for the observed disparity in fractal dimensions. The core of the integration lies in interpreting this correlation: for instance, if Baunei showed both a low *D* and a high average slope, it provided quantitative, empirical evidence that slope steepness is a primary driver of its network fragmentation. This moves the analysis from simple observation ("the network is fragmented") to definitive diagnosis ("the network is fragmented because of these specific topographic constraints"). The final validation of the method rests on the strong, scale-invariant fractal scaling (high r^2 from Fractalyse) and the accurate, cell-by-cell calculation of topographic metrics from a high-resolution DEM. The convergence of findings from two independent analytical streams (network morphology and terrain morphology) provides a robust, multi-evidence basis for the conclusions and recommendations.

To complement the graphical interpretation, the relationship between terrain slope and fractal properties was examined using normalised indicators. Fractal dimension and average slope were independently normalised to a 0–1 range, enabling direct comparison of their relative variation between municipalities. This approach allows the magnitude and direction of the slope–connectivity relationship to be quantified without implying statistical inference beyond the scope of the dataset. It is important to note that the proposed framework is exploratory in nature and calibrated within the specific morphological conditions of the study area. Accordingly, the resulting relationships should be interpreted as context-dependent diagnostics rather than universally generalisable models.

3.4. Derivation of the terrain connectivity constraint index (T_i)

The final methodological stage involves the derivation of the Terrain Connectivity Constraint Index (T_i). This index was developed to synthesise the independent fractal and topographic analyses into a single, comprehensive diagnostic metric. The T_i is specifically designed to quantify the theoretical limitation that average slope imposes on the potential for developing a well-connected road network, thus providing a rapid assessment tool for urban and transport planners. The index is mathematically based on a negative exponential function, which accurately captures the non-linear, constraining relationship observed in the study: network connectivity potential decreases rapidly as the slope of the landscape increases. The T_i is calculated using the following general form:

$$T_i = 1 - e^{-k.S} \quad (7)$$

where *S* is the average slope of a municipality in degrees, *k* is a scaling constant that determines the rate of decay, and *e* is the base of the natural logarithm.

The crucial step of calibrating the scaling constant (*k*) was performed using the study's empirical data. Baunei, which represents the highest-constraint scenario in the study area, was used as the anchor point for this calibration. The resulting index value ranges from 0 to 1, where a value approaching 1 indicates a terrain that imposes a severe constraint on network development, and a value approaching 0 indicates minimal constraint. This range allows for the direct classification of landscapes based on their inherent limitations for sustainable transport planning. Following this calibration, the final formula for the T_i is established as:

$$T_i = 1 - e^{-0.078.S} \quad (8)$$

3.5. Sensitivity and diagnostic behaviour of the terrain connectivity constraint index (T_i)

The stability of the Terrain Connectivity Constraint Index (T_i) was examined by a focused sensitivity analysis. It evaluates how variations in slope representation influence the resulting T_i values and their diagnostic interpretation. Given that slope constitutes the primary explanatory variable in the index formulation, its robustness under alternative but methodologically consistent definitions is critical for ensuring interpretability. The T_i was recalculated for each municipality using three slope measures derived from the same Digital Elevation Model: (i) mean slope, (ii) median slope, and (iii) mean slope calculated after excluding extreme values above 30° The latter representation reduces the influence of highly localised terrain conditions that are unlikely to govern network-scale structural development. The resulting T_i values were compared across slope representations to assess consistency in relative magnitude and constraint classification. The analysis focuses on diagnostic stability rather than index optimisation, examining whether alternative slope inputs alter the identification of terrain-induced transport constraints. This approach provides an internal assessment of T_i's robustness as a spatial diagnostic indicator for transport planning in topographically constrained tourism landscapes.

4. Results and analysis

4.1. Fractal dimension as a metric of network connectivity

The structural connectivity and complexity of the road networks in Nuoro and Baunei were quantitatively assessed using the fractal dimension (*D*). The results, derived from the box-counting method, reveal a fundamental disparity in the spatial organisation of the two municipalities' transport infrastructure. As summarised in Table 1, the road network of the urban hub, Nuoro, possesses a fractal dimension of *D* = 1.52. This value, approaching the theoretical maximum of 2.0 for a plane-filling network, indicates a complex, well-connected, and highly integrated system. Such a structure offers substantial route redundancy and multiple path choices at different scales, which is characteristic of developed urban cores and ideal for supporting conventional public transport. The spatial distribution of this connectivity is visually confirmed by the dense, self-similar patterning evident in Fig. 3(a).

However, the road network of Baunei exhibits a significantly lower

Table 1
Summary of fractal and topographic metrics for Nuoro and Baunei.

Location	*D*	r^2	Avg. Slope (°)	*TRI*	T_i
Nuoro	1.52	> 0.98	11.67	531.13	0.60
Baunei	1.28	> 0.99	20.62	513.59	0.80

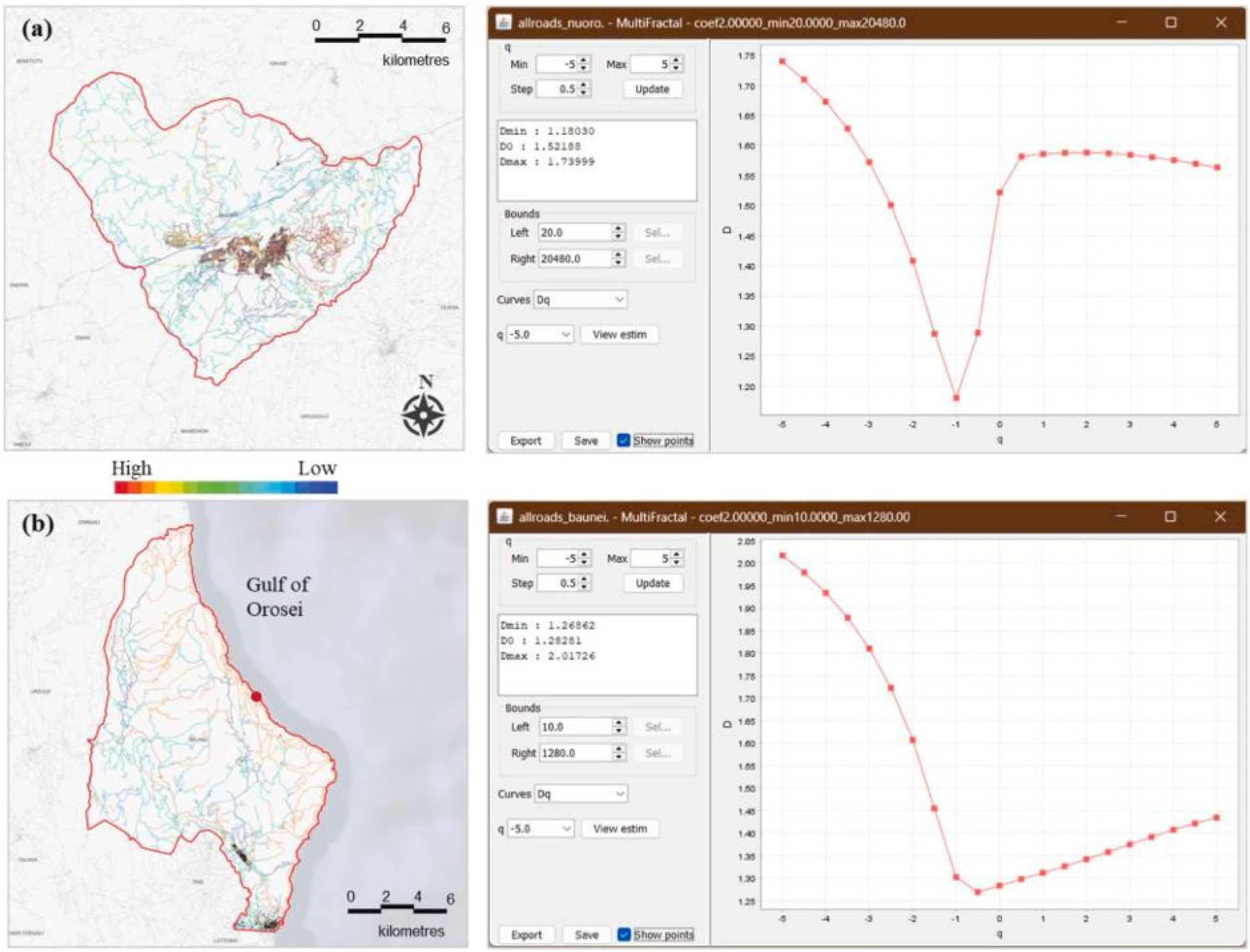

Fig. 3. Road network morphology of (a) Nuoro and (b) Baunei through (multi) fractal analysis.

fractal dimension of $D = 1.28$. This value is closer to 1.0, which represents a simple line, and is indicative of a sparse, tree-like, and fragmented network. This morphology is typical of rural or topographically constrained areas where connectivity is limited. The low D value quantifies the visual impression of Baunei's network: roads are forced into linear corridors with few cross-connections, resulting in a system that is inherently less resilient and inefficient for multi-directional travel. Fig. 3(b) conspicuously displays this fragmented structure, reinforcing the geometric constraint.

The steep negative slope of Baunei's $D(q)$ (Fig. 3(b)) curve confirms that sparse linear corridors dominate its structural character, creating inherent vulnerability where single points of failure can sever access to entire regions. This geometric configuration is fundamentally ill-suited for the efficient development of circular or redundant public transport routes, instead necessitating linear, adaptive mobility solutions that respect the network's dichotomous nature. The low D is thus more than a numerical curiosity; it is a quantitative representation of endemic structural inequity.

Across alternative box-size subsets, the estimated fractal dimensions exhibited only marginal variation, and the relative difference between Nuoro and Baunei remained consistent, confirming that scale choice does not influence the comparative interpretation of network connectivity.

4.2. Topographic constraints on network development

The stark contrast in network structures is powerfully explained by the quantitative assessment of the underlying topography. The analysis identified average slope, rather than general ruggedness, as the critical discriminating factor between the two municipalities. As shown in Table 1, Baunei is characterised by a significantly steeper average slope of 20.62° This gradient, prevalent across the municipality as visualised by the darker tones in Fig. 4(b), represents a profoundly challenging landscape for infrastructure development. Slopes of this magnitude impose severe geotechnical and economic constraints on road construction, limiting feasible alignments and physically preventing the creation of the cross-connections necessary for developing a complex, high-dimension network. Roads are forced to follow a limited set of ridges and valleys, resulting in the observed tree-like pattern. In contrast, Nuoro's more moderate average slope of 11.67° has permitted a more flexible and organic development of the road network. The gentler topography, visible through the prevalence of lighter, yellow tones in Fig. 4(a), allowed for the infilling and interconnection of routes, thereby supporting the emergence of a high-dimension network capable of sustaining diverse mobility needs.

A crucial and discrete finding was the behaviour of the *TRI*. Both municipalities exhibited extremely high values (Baunei: 513.59; Nuoro: 531.13), demonstrating that both landscapes are highly rugged with significant local relief. However, the fact that Nuoro's *TRI* is slightly higher is critical. It underscores that the primary limiting factor for network connectivity is not the local variation in elevation (ruggedness), but the pervasive, high average inclination (slope). Baunei's terrain is not just rugged; it is pervasively and steeply inclined, which actively curtails space-filling construction. This distinction is vital for planners, as it substantiates the focus towards mitigating the impacts of pervasive steepness rather than general terrain variation.

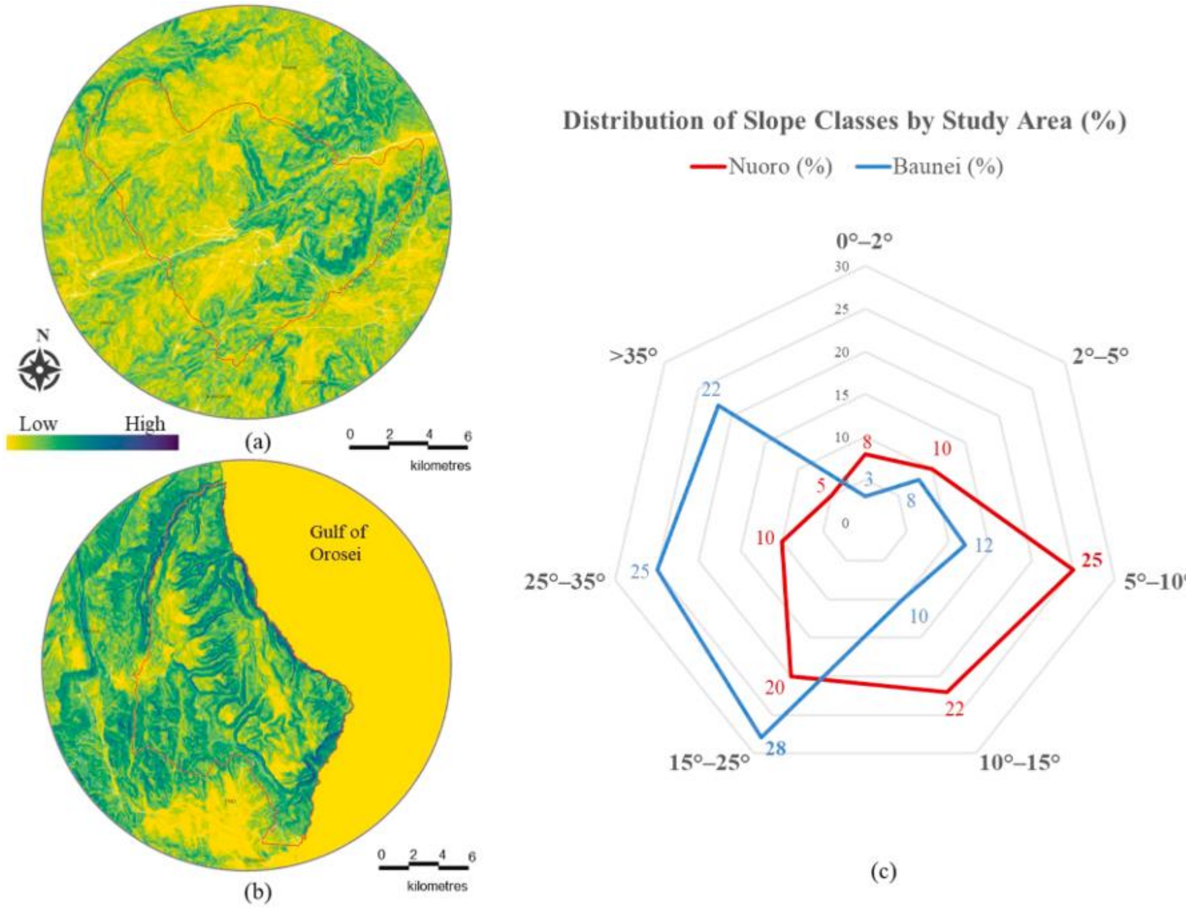

Fig. 4. Slope analysis of (a) Nuoro and (b) Baunei (c) Radar chart comparing the proportion of municipal area per slope class.

4.3. Integrated diagnostic: the terrain connectivity constraint index (T_i)

The Terrain Connectivity Constraint Index (T_i) was applied to synthesise the fractal and topographic findings into a single, diagnostic value. The results, presented in Table 1, provide a clear and interpretable metric of terrain-mediated accessibility limitation. The calculated T_i values show a clear divergence: Baunei registers a T_i of 0.80, while Nuoro scores 0.60. According to the proposed interpretive scale, this places Baunei in the High Constraint band and Nuoro in the Moderate Constraint band. This index successfully substantiates the core relationship identified in this study: the challenging morphology of the land is the fundamental driver of the accessibility deficit. For planners, a high T_i value immediately signals that conventional transport network expansion is not a viable solution and that interventions must be radically adaptive to the terrain's structural limitations. The power of the T_i lies in its diagnostic capability. It moves beyond observing a correlation between high slope and low fractal dimension to providing a calibrated index that proactively predicts the degree of network constraint from topographic data alone. This offers a powerful, antecedent tool for preliminary regional assessments, enabling robust, evidence-based decisions before committing to detailed and costly planning processes.

4.4. Quantifying and validating the disparity in connectivity potential

To contextualise the practical impact of this constraint in terms of sustainable mobility, the utilised geometric potential of each network was calculated. This metric expresses the observed fractal dimension as a percentage of the theoretical maximum complexity for a two-dimensional network, providing an intuitive measure of realised connectivity.

- Nuoro's Utilised Potential: 1.52 - 1 = 0.52 or 52%
- Baunei's Utilised Potential: 1.28 - 1 = 0.28 or 28%

The reduction in potential between the high-constraint area (Baunei) and the low-constraint area (Nuoro) was then calculated as follows:

$$\text{Reduction} = 1 - (0.28 / 0.52) \approx 0.46$$

This calculation quantifies that the terrain in high-constraint coastal areas like Baunei reduces the geometric potential for creating well-connected transport pathways by approximately 46% compared to the potential achievable in a less constrained area like Nuoro. This outcome translates the abstract geometric constraints into a compelling, tangible planning barrier: the possibility of developing an efficient, multi-directional public transport network is diminished by nearly half in Baunei due to its topography.

To confirm the robustness of this finding, the direct relationship between average slope (S) and fractal dimension (D) was examined (Fig. 5). The comparison reveals a clear inverse trend—Nuoro, with an average slope of 11.67° and D = 1.52, contrasts sharply with Baunei, with steeper 20.62° terrain corresponds to D = 1.28. This gradient visually substantiates the analytical logic of the Terrain Connectivity Constraint Index (T_i): as slope increases, the geometric complexity of the network declines. Annotated T_i values (0.60 for Nuoro and 0.80 for Baunei) confirm that higher constraint levels align with lower spatial connectivity. Beyond visual inspection, the normalised comparison reveals a clear inverse correspondence between average slope and fractal dimension. Baunei exhibits a substantially higher normalised slope value alongside a lower normalised fractal dimension, while Nuoro displays the opposite configuration. This monotonic contrast quantitatively supports the interpretation that increased terrain steepness is

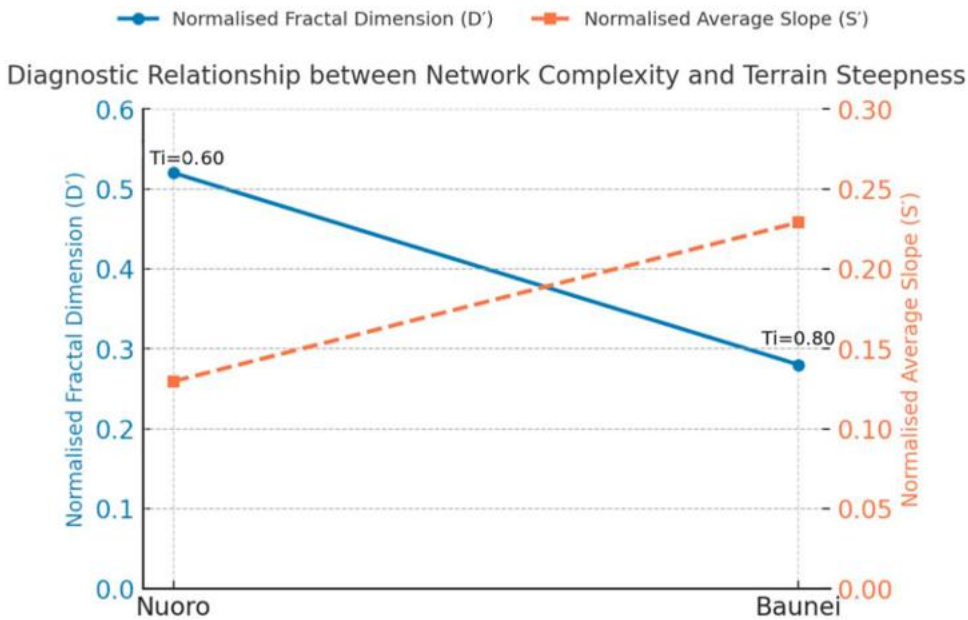

Fig. 5. Diagnostic relationship between normalised road network complexity (D') and terrain steepness (S') for Nuoro and Baunei. Normalised values are scaled to a 0–1 range to enable direct comparison. Annotated T_i values represent the resulting Terrain Connectivity Constraint Index derived from the combined behaviour of D' and S'.

associated with reduced geometric network complexity within the study area.

Taken together, the quantitative reduction in geometric potential and the inverse slope–fractal pattern provides a dual validation of the T_i framework. The results demonstrate that terrain steepness not only constrains the overall magnitude of connectivity but also systematically suppresses the fractal efficiency of road-network structures. This evidence establishes T_i as a reliable diagnostic measure for capturing the slope-connectivity trade-off that governs transport accessibility in topographically complex landscapes.

The inverse gradient illustrates that as terrain steepness increases, geometric network complexity decreases. Annotated T_i values (0.60 for Nuoro, 0.80 for Baunei) confirm that higher topographic constraint corresponds to reduced spatial connectivity, validating the Terrain Connectivity Constraint Index.

This profound disparity underscores that solutions cannot rely on replicating the complex network models of flatter urban areas. Instead, mobility planning must be radically adapted to the structural limitations of the landscape. The findings mandate a shift towards low-impact, linear transport solutions, such as scheduled shuttle services operating along the existing constrained corridors, which work in harmony with the natural geometry of the land rather than fighting against it. This quantitative diagnostic provides strong evidence base for prioritising context-sensitive and sustainable transport policies, ensuring spatial justice in ecologically fragile tourism destinations worldwide. Given the limited number of observations, this relationship is interpreted as a comparative diagnostic pattern rather than a statistically generalisable correlation.

Table 2
Sensitivity of T_i values under alternative slope representations.

Municipality	T_i (Mean Slope)	T_i (Median Slope)	T_i (Slope < 30°)	Constraint Class
Nuoro	0.60	0.58	0.59	Moderate
Baunei	0.80	0.78	0.79	High

4.5. Sensitivity analysis of the terrain connectivity constraint index (T_i)

The sensitivity analysis confirms that the T_i exhibits stable diagnostic behaviour under alternative slope representations (Table 2). While absolute T_i values vary slightly depending on whether mean, median, or truncated mean slope is used, the relative ordering between municipalities remains unchanged. In all tested scenarios, Baunei consistently exhibits a higher T_i value than Nuoro, and both municipalities retain their original constraint classifications. Specifically, Nuoro remains within the moderate-constraint range across all slope inputs, while Baunei consistently falls within the high-constraint category. This stability demonstrates that T_i is not overly sensitive to minor variations in slope estimation and reliably captures the structural limitation imposed by terrain steepness on transport network connectivity. These findings support the use of T_i as a robust diagnostic indicator capable of distinguishing between landscapes with differing levels of terrain-induced transport constraint, even when slope is represented using alternative but methodologically reasonable approaches.

5. Discussion

This study moves beyond simply identifying an accessibility problem to diagnosing its root cause with quantitative precision. Crucially, our analysis demonstrates that the primary constraint is not general terrain ruggedness (*TRI*), but specifically the pervasiveness of steep slopes, a distinction critical for targeted intervention. This framework, detailed in Table 3, allows for the categorisation of landscapes and links these categories to appropriate transport strategies. Baunei confirms that conventional, network-based public transport models—which rely on the high fractal dimension and route redundancy seen in Nuoro—are geometrically and economically unviable here. This aligns with global observations in other sensitive landscapes, where inflated costs and environmental impacts often lead to transport poverty (Sheller, 2020; Sovacool et al., 2023; Verlinghieri & Schwanen, 2020). While traditional planning often relies on simplistic metrics like road density, the use of fractal dimension provides a superior metric, quantifying the intrinsic structural capacity for sustainable mobility (Pavón-Domínguez et al., 2017; Yamu & van Nes, 2019). However, given the limited empirical base of two case-study municipalities, the findings should be interpreted

Table 3
Diagnostic framework for sustainable transport planning based on the T_i.

T_i Range	Constraint Level	Expected Network Morphology	Recommended Transport Strategy
0.00 - 0.50	Low	Complex, web-like (High D)	Conventional public transport (grid-based bus networks, trams)
0.51 - 0.70	Moderate	Moderately connected (Medium D)	Enhanced bus services on key corridors; feeder routes
0.71 - 0.85	High	Sparse, tree-like (Low D)	Adaptive, linear shuttles (e.g., Electric minibuses on fixed corridors)
0.86 - 1.00	Severe	Isolated, linear (Very Low D)	Non-standard solutions (e.g., boat access, cable cars, focused pedestrian/e-bike pathways)

as indicative of context-specific morphological dynamics rather than as statistically generalisable relationships.

The (multi)fractal analysis further refined this diagnosis, revealing that Baunei's constraint manifests not as uniform fragmentation but as structural bifurcation and locally complex. This bifractal geometry explains why conventional transport fails: it requires the homogeneous connectivity of Nuoro's narrow spectrum but encounters Baunei's dichotomous structure where sparse connectors dominate the network's global character.

While terrain has been incorporated into transport planning through classical approaches, these methods primarily optimise routes based on travel impedance rather than diagnose the structural limitations imposed by the landscape itself (Dean et al., 2015). Such approaches yield context-specific alignments, but they lack a generalisable metric that can characterise and compare terrain constraints across different spatial systems. The proposed T_i advances beyond these frameworks by offering a scale-independent diagnostic measure that quantifies how slope non-linearly restricts the geometric potential for network connectivity. As Rydin et al. (2025) note, traditional routing models typically predict a single optimal path. However, T_i captures the underlying capacity of the terrain to sustain a connected network, thereby complementing traditional least-cost and accessibility analyses with a higher-order diagnostic perspective.

The integrated fractal-topographic methodology and the T_i provide a transferable, evidence-based model for planning in tourism-dependent, geographically challenged regions worldwide. From the coastal cliffs of Greece to the volcanic islands of Southeast Asia, the challenge of reconciling conservation with access is a global sustainability imperative. The T_i offers a rapid, preliminary assessment tool; planners can calculate it from widely available DEMs to diagnose terrain-mediated constraints before committing to costly detailed studies, enabling more efficient and ecologically attuned resource allocation from the outset (Mexa & Coccossis, 2017; Zamparini et al., 2022; Zhang et al., 2025).

In practice, T_i can be employed as a preliminary screening metric to guide strategic decision-making before detailed accessibility modelling or infrastructure design is undertaken. High T_i values signal contexts where conventional public transport network expansion is structurally constrained and where adaptive, terrain-sensitive mobility solutions are more appropriate. This diagnostic positioning enhances T_i's practical relevance for sustainable transport planning in sensitive tourism landscapes, where environmental limits and infrastructural feasibility must be assessed concurrently. Therefore, this research demonstrates that the path to sustainable tourism in fragile landscapes is not through conquering geography with infrastructure, but through understanding it with sophisticated spatial diagnostics. By interpreting the relationship between slope and network structure, the study provides an evidence base to advocate for smarter, more respectful mobility systems.

5.1. Policy and planning implications: A necessary paradigm shift

The diagnostic clarity provided by the T_i framework necessitates a fundamental shift in planning philosophy. It demands a move away from the conventional and often ineffective model of attempting to overcome geography through extensive and environmentally destructive road construction (Giunta, 2020). This outdated approach, which seeks to force a high-fractal-dimension network into a constrained landscape, is geometrically unviable and ecologically damaging in high-constraint municipalities like Baunei. Instead, a new paradigm is imperative: a diagnostic, service-centric approach that optimises mobility within the inherent structural limits of the terrain. Such integrated strategic-performative planning is crucial for the sustainable regeneration of fragile territories, ensuring that interventions are both effective and respectful of environmental limits (Stanganelli et al., 2020). The model illustrates a structured workflow that begins with quantitative terrain assessment via the T_i index. This diagnosis directly informs the expected network morphology and, crucially, prescribes a corresponding, adaptive transport strategy (Fig. 6).

For a high-constraint landscape like Baunei, the model logically leads away from conventional public transport and towards tailored solutions, thereby creating a direct, evidence-based link between spatial diagnosis and planning intervention. For Baunei, this diagnostic model translates into specific, actionable policy recommendations:

- **Implementation of Adaptive Linear Shuttles:** Introduce high-frequency, low-impact electric shuttle services operating exclusively on the main existing corridors, strategically designed to connect the isolated complex nodes revealed by multifractal analysis while respecting the linear geometry of connecting routes. This strategy accepts the structural divergence of the network, prioritising service reliability over unattainable network expansion.
- **Establishment of Integrated Mobility Hubs:** Develop strategic park-and-ride facilities at the urban-rural interface (e.g., in Baunei town) to connect with regional bus services from Nuoro, creating a sustainable inter-modal chain that reduces private vehicle intrusion into fragile coastal zones, thereby mitigating ecosystem degradation.
- **Prioritisation of Regulatory Sandboxes:** Create flexible regulatory frameworks that encourage and expedite the deployment of innovative, small-scale transport solutions suited to difficult terrain. This agility is essential given the dynamic and unique constraints presented by topographically diverse regions.
- **Formulation of Terrain-Sensitive Zoning:** Integrating T_i mapping into regional land-use plans is a form of strategic-performative planning, crucial for directing growth and enhancing the resilience of fragile territories. Such a data-driven approach is central to modern comprehensive planning frameworks. This ensures that future development aligns with the land's intrinsic capacity to sustain infrastructure, preventing the recurrence of accessibility deficits.

The quantitative reduction in geometric potential, together with the inverse slope–fractal relationship (Fig. 5), provides strong empirical reinforcement for the T_i framework. This cross-validation confirms that the index not only captures the mathematical link between terrain steepness and network complexity but also aligns with observed spatial behaviour. By demonstrating that higher slopes systematically correspond to lower fractal dimensions, the analysis transforms T_i from a theoretical construct into a diagnostic tool grounded in measurable evidence. In the broader context of sustainable mobility, this reinforces the argument that accessibility in steep or insular regions cannot be addressed through conventional network expansion, but through terrain-adaptive design strategies. The slope–complexity validation thus extends T_i's relevance beyond the Sardinian case, offering a transferable analytical approach for evaluating transport potential in other topographically constrained landscapes worldwide. By adopting this

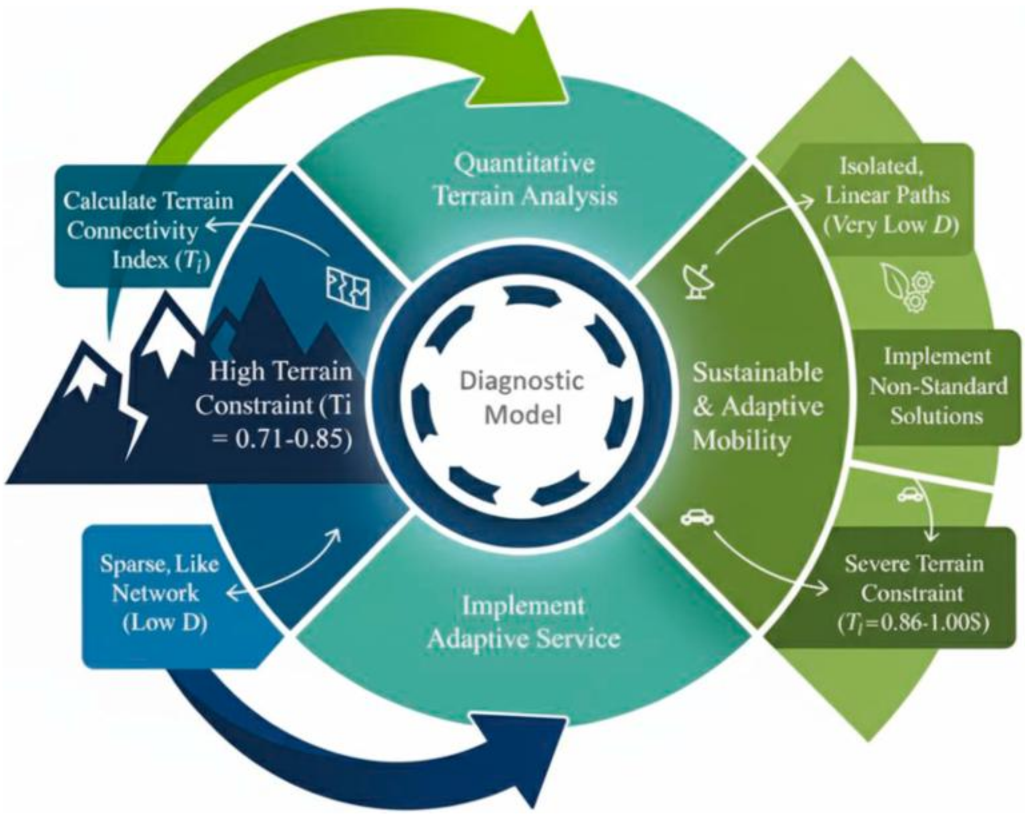

Fig. 6. A diagnostic model for adaptive transport planning in topographically constrained landscapes.

diagnostic approach, planners can replace a one-size-fits-all mentality with targeted, sustainable, and cost-effective mobility solutions. Ultimately, the T_i framework shifts the goal of planning from forcing connectivity into a landscape to sustainably optimizing the connectivity the landscape can naturally support.

5.2. Limitations and future research

While this study provides a robust diagnostic framework, certain limitations should be acknowledged. The analysis is fundamentally static, capturing the spatial structure of the road network and terrain at a specific point in time. It does not incorporate dynamic factors such as seasonal traffic flows, travel demand patterns, or the real-world travel behaviour of tourists and residents. Furthermore, the fractal dimension, while excellent for quantifying network form, does not directly measure travel time or cost, which are critical for user experience. The social dimension of accessibility, including the affordability and perceived safety of transport options, as emphasised in previous studies (Giuffrida et al., 2023; Kapatsila et al., 2024; Wan & Titheridge, 2024), also falls outside the scope of this spatial diagnostic. These limitations present clear pathways for future research. A logical next step would be to integrate the fractal-topographic framework with transport network analysis to model actual travel times and identify specific bottlenecks under different demand scenarios. Subsequently, incorporating other configurational analytical frameworks or survey data on user preferences and willingness-to-pay would enrich the model, ensuring that proposed transport solutions are not only spatially efficient but also socially equitable and economically viable. Finally, applying this integrated methodology to other topographically complex tourism regions, such as mountainous or archipelagic settings, would test its transferability and refine the interpretive scales of the T_i, contributing to a more generalised theory of sustainable mobility in fragile landscapes. Furthermore, future work could employ multifractal analysis to investigate the internal heterogeneity and scaling irregularities within these networks, providing even deeper diagnostic precision.

6. Conclusion

The inherent challenge for tourism-driven regions lies in providing sustainable transport access to pristine natural heritage sites without precipitating ecological degradation. This study directly confronted this defining challenge by developing and demonstrating a novel diagnostic framework that integrates fractal analysis of road networks with quantitative topographic assessment. Applying this methodology to the striking urban-rural gradient of Nuoro and Baunei in Sardinia has yielded critical insights with direct implications for sustainable spatial planning.

The core finding of this research is a quantitative diagnosis of the accessibility problem. The road network in Baunei was revealed to exhibit a significantly lower fractal dimension ($D = 1.28$) compared to Nuoro ($D = 1.52$), quantifying its state as a sparse, fragmented, and tree-like system. Crucially, this disparity was driven not by general terrain ruggedness, but specifically by Baunei's steeper average slopes. This relationship was successfully synthesised into a new Terrain Connectivity Constraint Index (T_i), which provides planners with a practical tool to predict the limiting effect of slope on network development from topographic data alone. The power of this diagnostic approach is crystallised in a single, compelling figure: the terrain in high-constraint coastal areas like Baunei reduces the geometric potential for creating well-connected transport pathways by approximately 46% compared to an urban hub.

This evidence necessitates a paradigm shift in transport planning for sensitive landscapes. The drastically reduced connectivity potential means that conventional public transport models, which rely on dense, web-like networks, are geometrically unviable. Instead, policy must pivot towards adaptive, terrain-sensitive solutions. For high-constraint areas like Baunei, this means prioritising low-impact, linear mobility systems, such as scheduled electric shuttle services on fixed corridors and integrated park-and-ride hubs that operate in harmony with the natural geometry of the land. However, the proposed T_i index and the broader diagnostic framework offer a transferable methodology for planners in similar fragile contexts worldwide, from coastal cliffs to mountainous regions. By enabling an evidence-based assessment of terrain constraints, this approach helps target interventions that can improve equitable access while safeguarding ecological integrity. Future research should build upon this spatial diagnostic foundation by integrating dynamic data on tourist flows and travel behaviour, and by validating the T_i index across diverse geographical settings. Ultimately, this study demonstrates that the path to sustainable urban-rural connectivity in fragile landscapes lies not in conquering geography, but in understanding its inherent constraints and designing smarter, more respectful mobility systems that work within them.

CRediT authorship contribution statement

Tazyeen Alam: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mana Dastoum:** Writing – original draft, Conceptualization. **Reza Askarizad:** Writing – review & editing, Writing – original draft, Conceptualization. **Chiara Garau:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by the project "From Ports to People: Reconfiguring Urban Access for Smart Cities in Porto and Cagliari (PORT2PEOPLE)", founded by the program "Bando 2025 Mobilità Giovani Ricercatori (MGR)," financed by the Autonomous Region of Sardinia (under the Regional Law of 7 August 2007, n. 7 "Promotion of Scientific Research and Technological Innovation in Sardinia"). This study was also supported by the MUR through the project "SMART3R-FLITS: SMART Transport for Travellers and Freight Logistics Integration Towards Sustainability" (Project protocol: 2022J38SR9; CUP Code: F53D23005630006), financed with the PRIN 2022 (Research Projects of National Relevance) program. We authorise the MUR to reproduce and distribute reprints for Governmental purposes, notwithstanding any copyright notations thereon. Any opinions, findings, and conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the MUR.

Data availability

The data that has been used is confidential.

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