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A Directional and Sequential Viewshed Framework for Analysing Terrain-Controlled Visibility along an Escarpment Road

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Abstract: Visibility is a fundamental component of road landscape experience in escarpment environments, where complex terrain produces substantial variation in visual exposure along transportation corridors. Conventional viewshed analyses typically represent visibility as a static and direction-neutral property, providing limited insight into how visibility changes with travel direction. This study develops a GIS-based framework for analysing terrain-controlled visibility dynamics along a 1.5 km section of the Mai Mahiu–Nairobi corridor in Kenya’s Great Rift Valley. Sixteen observation points were used to quantify visibility magnitude, directional asymmetry and sequential change. Visibility was partitioned into uphill and downhill components using a Visibility Asymmetry Index (VAI), while sequential variation was evaluated using a transition metric (ΔV). Spearman’s rank correlation was used to examine associations between visibility and slope, elevation, profile curvature and plan curvature. Visibility ranged from 9.5% to 82.4% (mean = 39.9%), demonstrating substantial spatial variation. Mean uphill visibility (44.4%) exceeded downhill visibility (34.9%), while VAI values (0.034–0.740; mean = 0.428) revealed pronounced directional asymmetry. Slope showed the strongest association with visibility ($\rho = 0.518$, $\rho = 0.040$), followed by profile curvature ($\rho = 0.482$, $\rho = 0.058$), whereas elevation and plan curvature showed weaker associations. Sequential analysis identified alternating states of visual exposure and enclosure, including abrupt transitions between restricted and expansive views. By integrating visibility magnitude, directional asymmetry, terrain association and sequential change, the framework extends conventional viewshed analysis toward a dynamic representation of road landscape visibility and provides a quantitative basis for identifying visually distinctive sections of terrain-constrained corridors.

Keywords: viewshed analysis; escarpment roads; directional viewshed; GIS; Great Rift Valley.

1. Introduction

Visibility is fundamental to how landscapes are perceived and experienced, yet its spatial representation remains dominated by a relatively simple question: what can be seen from a given location? Conventional viewshed analysis answers this through Digital Elevation Models (DEMs) and line-of-sight algorithms that classify terrain as visible or non-visible from defined observation points (Chhetri & Arrowsmith, 2008; Gillings & Wheatley, 2020). More recent GIS-based approaches have extended this binary representation by quantifying the extent and spatial configuration of visual exposure (Li et al., 2021) while three-dimensional modelling has demonstrated that visibility can vary substantially between observer locations (Bolte et al., 2025). Geovisualization has further connected observable landscape conditions with their broader spatial and environmental context (Jenkins et al., 2019). Together, these developments have transformed visibility from a simple line-of-sight property into a measurable dimension of landscape structure and experience.

A remaining challenge is that landscapes are rarely experienced from stationary viewpoints. Movement continuously changes the relationship between observer and environment as terrain is progressively revealed, obscured and reorganised. Consequently, visibility along a route has at least three distinct spatial dimensions: magnitude, representing how much of the surrounding landscape is visible at a location; directionality, representing how visual exposure differs according to viewing or travel orientation; and sequential variation, representing how visibility changes between successive locations. Existing route-based and experiential approaches increasingly recognise this dynamic character of landscape visibility (Chamberlain & Meitner, 2013; Inglis et al., 2022; Openshaw & Chamberlain, 2022), supported by advances in LiDAR, network analysis and machine learning that enable increasingly detailed representations of visual environments (Lehto et al., 2024; Liu et al., 2026). Nevertheless, these dimensions are rarely considered together, and sequential changes in visual exposure remain difficult to represent through conventional viewshed measures.

Road corridors provide a particularly relevant setting for addressing this limitation because they organise observation along constrained linear trajectories. Unlike visibility from a stationary viewpoint, road landscape visibility develops continuously as the observer moves through space. The visual field encountered by road users depends on observer position, travel direction, road alignment and surrounding

55 terrain, making visibility both spatially and directionally contingent (Naskar & Saha, 2026). Horizontal
56 and vertical roadway geometry can further modify available sightlines within the three-dimensional road
57 environment (Papadimitriou et al., 2018). These visual conditions have implications for transportation
58 operation and safety through their influence on driver perception and environmental interpretation (Lioi
59 et al., 2022; Liu et al., 2023; Qu et al., 2023), but they also constitute an important component of road
60 landscape experience. A road corridor can therefore be understood not as a series of independent
61 viewpoints, but as a continuous sequence of changing visual fields.

62 Terrain morphology is a principal mechanism structuring these visual fields. Visibility is rarely
63 distributed uniformly around an observer because landform geometry channels and restricts visual
64 exposure into particular orientations and viewing corridors, producing directional visibility and visual
65 anisotropy (Forczek-Brataniec, 2016). Valley configuration, surrounding relief and other spatial
66 characteristics can substantially alter the extent and distribution of visible landscape (Dallatorre et al.,
67 2025). Such effects are amplified in mountainous and escarpment environments, where slope, elevation
68 gradients and terrain shielding can produce substantial changes in line-of-sight continuity over short
69 distances. Viewscape research has consequently moved towards representations that integrate spatial
70 configuration, observer experience, movement and environmental context rather than treating visibility
71 solely as a binary property of terrain (Inglis et al., 2022; Wu et al., 2023).

72 Escarpment roads intensify these terrain–visibility interactions. Steep gradients, pronounced relief
73 and terrain discontinuities constrain road alignment and contribute to curves, crest transitions and rapid
74 changes in elevation (Misthos et al., 2019; Schlögl et al., 2019). As a road traverses these landforms,
75 convex terrain and escarpment-edge positions can abruptly release extensive views across the
76 surrounding landscape, whereas concave terrain, cut slopes and terrain shielding can compress the visible
77 field. The resulting roadscape may alternate repeatedly between visual exposure and enclosure, creating
78 a spatial rhythm that is not captured by average visibility alone. These conditions are also potentially
79 asymmetric: uphill and downhill movement encounter the same terrain in opposing sequences and may
80 therefore produce markedly different visual fields. Visibility along an escarpment road is consequently
81 not only spatially variable but directional and sequential.

82 Advances in GIS, remote sensing, LiDAR and three-dimensional spatial modelling provide the
83 analytical capacity to quantify these relationships. LiDAR-based approaches improve representations of
84 terrain, vegetation and built structures within visibility models (Chmielewski & Lee, 2015; Jung et al.,
85 2018; Naghdi et al., 2024), while observer-oriented and directional approaches provide increasingly
86 realistic representations of visual exposure (Bornaetxea & Marchesini, 2022; Brinkmann et al., 2022).
87 DEM-based GIS frameworks additionally allow terrain characteristics such as elevation, slope and
88 surface morphology to be integrated with spatial analysis (Rahman et al., 2023). These developments
89 have expanded visibility analysis across scenic assessment, tourism planning, landscape protection,
90 environmental governance and sustainability applications (Cilliers et al., 2023; La Rosa & Izakovičová,
91 2022; Li et al., 2018; Mazzeo et al., 2022; Miller et al., 2024; Šoltésová et al., 2025; Xie et al., 2024;
92 Yang et al., 2024), demonstrating the growing role of geovisual analysis in understanding relationships
93 between observers, terrain and landscape structure.

94 Despite these advances, three limitations remain particularly important for terrain-constrained road
95 corridors. Visibility is commonly represented through individual viewpoints or aggregated viewshed
96 measures, obscuring variation between successive locations. Opposing directions of movement are rarely
97 compared explicitly, despite the directional structure of terrain visibility. Abrupt transitions between
98 visual exposure and enclosure are poorly represented by measures of visibility magnitude alone.
99 Consequently, a corridor may have a moderate average level of visibility while containing highly
100 asymmetric or rapidly changing visual conditions. The relationships between these patterns and terrain
101 parameters such as slope, elevation and curvature also remain insufficiently understood. The
102 methodological challenge is therefore not simply to determine how much is visible, but to establish how
103 visibility differs by direction, how it changes through movement, and how these patterns relate to terrain
104 morphology.

105 These questions are especially relevant to African transportation landscapes, where geospatial
106 methods are increasingly applied to infrastructure assessment across complex terrain and data-
107 constrained environments (Pantha et al., 2010; Wang et al., 2026), but comparatively little attention has
108 been given to the spatial organisation of road landscape visibility. The Mai Mahiu–Nairobi corridor along
109 Kenya’s Great Rift Valley provides a distinctive setting for such analysis. The road traverses a fault-
110 controlled escarpment characterised by steep slopes, pronounced relief, deeply incised valleys and
111 terrain-constrained alignment, producing substantial contrasts between expansive Rift Valley views and
112 locally enclosed sections. The wider corridor is also subject to slope instability, erosion, flooding and
113 rainfall-related disruption (Mukaria, 2025; Njeru et al., 2026). Despite this distinctive geomorphological

setting, the spatial structure of visibility along the corridor, particularly its directional and sequential organisation, remains poorly understood.

Using a 1.5 km escarpment section of the Mai Mahiu–Nairobi corridor, this study develops a GIS-based framework that conceptualises road landscape visibility as a spatial sequence characterised by visibility magnitude, directional asymmetry and transition intensity. Visibility magnitude quantifies the extent of visual exposure at individual observation points; directional asymmetry evaluates differences between uphill and downhill visibility; and transition intensity measures changes in visibility between successive locations. Associations between visibility and slope, elevation, profile curvature and plan curvature are further examined to determine how local terrain morphology relates to visual exposure. Rather than treating corridor visibility as a collection of independent viewsheds, the framework integrates these dimensions to represent how visibility is structured and transformed through movement. In doing so, the study extends conventional viewshed analysis towards a dynamic and terrain-sensitive geovisual representation of road landscapes and provides a transferable framework for analysing visibility along terrain-constrained movement corridors.

1. Study Area

1.1. Escarpment Terrain and Road Design Characteristics in Kenya

The Great Rift Valley is one of Kenya's most significant geological and geomorphological features, forming part of the eastern branch of the East African Rift System. The rift is characterised by fault-controlled escarpments, volcanic landforms and elevated plateaus that create pronounced topographic contrasts over short distances. These escarpments form natural barriers between the Rift Valley floor and the surrounding highlands, limiting transportation corridors and creating substantial challenges for road design and operation. Recognising these challenges, the Kenya Road Design Manual classifies escarpments as a distinct terrain category defined by transverse slopes exceeding 50%, compared with flat (<3%), rolling (4–25%) and mountainous (26–50%) terrain. Such conditions impose severe constraints on road alignment, drainage, slope stabilisation and traffic operations, requiring specialised geometric design standards. Escarpment roads typically have reduced design speeds of 30–50 km/h, steep gradients, sharp horizontal curvature, hairpin bends, extensive earthworks, retaining structures and engineered drainage systems. Road geometry within escarpment environments is largely controlled by terrain constraints. Hairpin curves with radii of 15–20 m are often required to overcome significant elevation differences, while gradients may reach 7–10% depending on road class, although steeper sections require additional operational controls. These conditions reduce roadway capacity, increase heavy-vehicle effects and create complex driving environments characterised by restricted sight distances and rapidly changing visual conditions (Ministry of Roads and Transport, 2023). The combination of steep terrain, constrained alignment, abrupt elevation change and extensive engineering interventions distinguishes escarpment roads from other highway environments. These characteristics make escarpment corridors particularly suitable for investigating terrain-controlled visibility, sequential visual exposure and the relationship between road geometry and driver experience.

1.2. Selection of the Mai Mahiu–Nairobi Corridor as a Case Study

Several roads traverse escarpment terrain within Kenya, including corridors associated with the Mau, Elgeyo, Subukia and eastern Rift Valley escarpment systems as seen in figure 1. Although these routes all experience significant terrain-related design constraints, they differ substantially in their strategic importance, traffic characteristics, geomorphological complexity and suitability for visibility-based road landscape analysis. A comparison of representative escarpment corridors is presented in Table 1. Among these alternatives, the Mai Mahiu–Nairobi corridor was selected because it uniquely combines national transportation significance, complex escarpment geomorphology, high traffic demand and highly dynamic visual conditions.

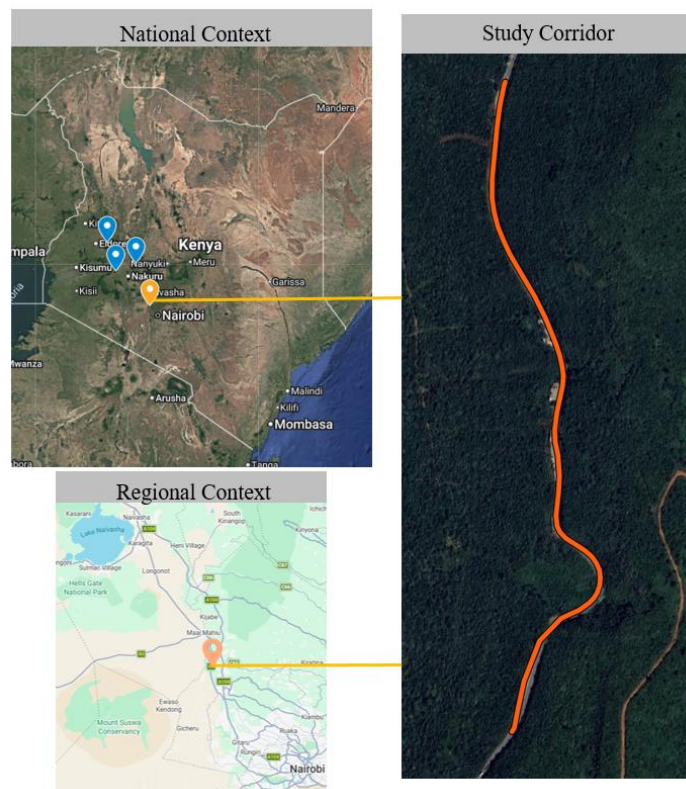


Figure 1: Representative escarpment road corridors in Kenya and the selected Mai Mahiu–Nairobi study corridor(*The yellow marker indicates the selected Mai Mahiu–Nairobi corridor, while blue markers represent other major escarpment corridors considered during case study selection).

Table 1: Comparison of representative escarpment road corridors in Kenya and their terrain, operational and tourism characteristics

Corridor	Escarpment System	Terrain Characteristics	Key Hazards & Driving Risks	Tourism and Economic Significance
Mai Mahiu–Nairobi	Eastern Rift Valley Escarpment	Steep grades, sharp curves, heavy freight traffic	Dense fog, heavy truck roll-overs, brake failures	Primary cargo route to Nairobi; entry point for Great Rift Valley views.
Nakuru–Mau Summit	Mau Escarpment	Long escarpment sections, major freight route	Massive gridlock, active construction zones, truck breakdowns	East Africa Northern Corridor trade artery; tea/agricultural transit.
Iten–Kerio Valley Road	Elgeyo Escarpment	Extremely steep descent, dramatic elevation change	99 switchbacks, narrow lanes, seasonal landslides	Elite athletic training corridor; international paragliding hub.
Nakuru–Nyahururu Road	Subukia Escarpment	Sweeping mountain pass, sharp hillside drops	Brake fade on long declines, unexpected fog, livestock crossings	Famous hillside Equator crossing point; dairy and fresh produce transit vein.

The study focuses on the Mai Mahiu escarpment section of the A8 South corridor along the eastern margin of Kenya’s Great Rift Valley. As part of the Nairobi–Nakuru–Mau Summit highway and Northern Corridor network, the route is a major passenger and freight corridor connecting Nairobi with western Kenya and neighbouring East African countries.

Geomorphologically, the road traverses a fault-controlled escarpment characterised by steep slopes, pronounced relief, incised valleys and abrupt elevation transitions. Its terrain-constrained alignment includes steep gradients, sharp curves and crest transitions that produce substantial spatial and directional variation in visibility, ranging from expansive Rift Valley views to strongly enclosed sections shaped by terrain morphology, roadway curvature and cut slopes. Combined with heavy traffic and exposure to slope instability, flooding and landslides, these characteristics make the Mai Mahiu corridor a suitable case for investigating terrain-controlled visibility dynamics along escarpment roads (Mukaria, 2025; Njeru et al., 2026).

1.3. Corridor Segment Analysed

The analysis focused on an approximately 1.5 km escarpment segment of the Mai Mahiu–Nairobi corridor. The selected section lies within one of the most topographically constrained portions of the escarpment descent and exhibits substantial variation in slope, curvature and visual exposure over short travel distances. The roadway consists of a two-lane undivided highway with narrow or intermittent shoulders and no physical median separation. Owing to the surrounding escarpment terrain, the alignment follows a terrain-adaptive configuration characterised by steep gradients, frequent horizontal curves and compressed vertical transitions.

Terrain morphology exerts a strong influence on line-of-sight continuity throughout the corridor. Convex escarpment-edge sections provide extensive outward visibility across the Rift Valley, whereas concave slopes, crest transitions, cut slopes and roadway curvature create localised visual enclosure and restricted sightlines. The resulting alternation between exposed and constrained conditions produces pronounced spatial variability in visibility and a highly dynamic sequential viewing environment.

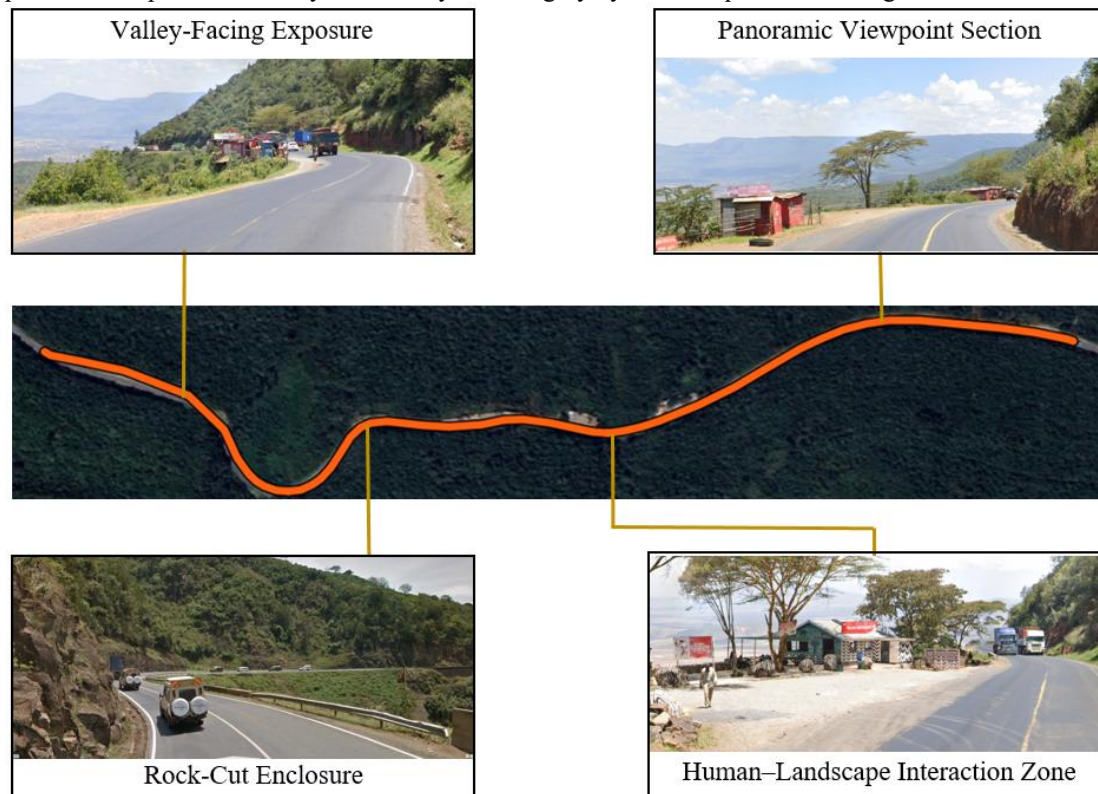


Figure 2: Study corridor characteristics and representative escarpment road conditions along the Mai Mahiu corridor, Kenya

The study segment was selected because it represents one of the most operationally and visually complex sections of the Mai Mahiu escarpment corridor as seen in Figure 2. The area contains established viewpoints overlooking the Rift Valley and attracts frequent tourist activity, while simultaneously serving as a major freight route carrying substantial volumes of heavy commercial traffic. Roadside commercial developments, including curio shops and restaurants, further increase vehicle stopping and pedestrian activity. Combined with a prominent escarpment-edge alignment, steep downslope terrain, limited roadside recovery space and pronounced horizontal curvature, these conditions create a unique convergence of scenic exposure, operational complexity and terrain-constrained visibility. The segment

provides an information-rich setting for investigating directional visibility asymmetry and sequential visibility transitions in an escarpment road environment.

3. Methodology

3.1. Viewshed and Directional Analysis

Conventional viewshed analyses typically represent terrain-based visibility as a static property of a landscape, providing a single estimate of visible terrain from a fixed observation location. However, visual exposure along escarpment roads is inherently dynamic. As drivers move through the corridor, roadway geometry, slope morphology, and terrain obstruction continuously alter the extent and configuration of visible space over short travel distances. Consequently, a single corridor-wide viewshed may mask localised variations in terrain-based visibility and fail to capture the sequential nature of visual exposure experienced along the route. To address this limitation, this study adopted a point-based and direction-sensitive viewshed framework to evaluate spatial and temporal variations in terrain-based visibility along the Mai Mahiu escarpment corridor.

The analysis focused on a 1.5 km study segment represented by 16 observation points established at 100 m intervals along the road centreline (Figure 3). Each observation point was treated as an independent viewpoint from which local terrain-based visibility was quantified. This sampling strategy enabled sequential assessment of viewshed conditions along the corridor and provided a basis for examining spatial variability, directional asymmetry, and visibility transitions between successive locations. The interval spacing was selected to capture short-distance changes in terrain-controlled visibility associated with escarpment morphology, roadway curvature, and vertical alignment.

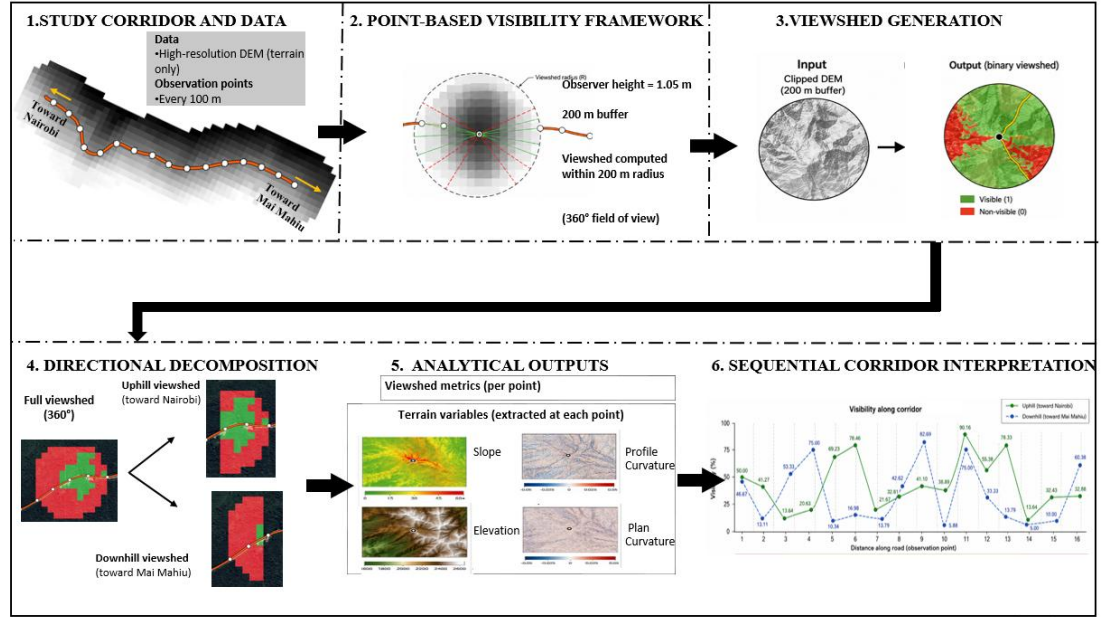


Figure 3: Integrated methodological framework for directional viewshed analysis along the Mai Mahiu escarpment corridor, Kenya.

Terrain conditions were represented using a high-resolution Digital Elevation Model (DEM), which formed the basis for all line-of-sight calculations. The analysis was restricted to terrain-controlled visibility and therefore excluded vegetation, buildings, roadside infrastructure, traffic, lighting conditions, and atmospheric influences. A circular analysis zone with a 200 m radius was established around each observation point to represent the immediate road landscape. The selected radius was intended to capture local terrain features most likely to influence near-road visual exposure while minimizing the influence of distant landforms unrelated to the immediate driving environment. An observer height of 1.05 m was assigned to approximate driver eye level. Elevation, slope, profile curvature, and plan curvature were extracted for each observation point and subsequently analysed in relation to terrain-based visibility metrics.

Viewshed modelling was conducted in QGIS using the GRASS GIS `r.viewshed` algorithm. For each observation point, the DEM was clipped to the corresponding 200 m analysis radius, and terrain-based visibility was calculated using a 360° field of view. Viewshed outputs were generated as raster surfaces and subsequently reclassified into binary visible (1) and non-visible (0) cells to facilitate quantitative

analysis. Standardised observer parameters and processing settings were applied across all observation points to ensure methodological consistency and comparability. As noted by (Fisher, 1993), viewshed results are sensitive to DEM quality, observer representation and algorithmic implementation, highlighting the importance of transparent parameter specification.

To investigate directional differences in terrain-based visibility, each viewshed was subdivided according to local road orientation into uphill (toward Nairobi) and downhill (toward Mai Mahiu) visibility domains. This enabled separate quantification of viewshed coverage experienced in opposing travel directions and facilitated assessment of directional visibility asymmetry along the corridor. Terrain aspect derived from the DEM was further integrated to characterise the directional composition of visible terrain. Only cells classified as visible within each viewshed were extracted and grouped according to aspect orientation, enabling evaluation of dominant viewing directions and the spatial distribution of visible landforms.

The resulting dataset comprised 16 independent viewsheds and their associated directional visibility metrics. Comparison of viewshed characteristics between successive observation points enabled assessment of spatial variability, directional asymmetry, and changes in terrain-based visibility along the corridor. By representing visibility as a sequence of interconnected viewpoints rather than a single static observation, the framework provides a basis for analysing localised variations in visual exposure and viewshed transitions within a complex escarpment road environment.

3.2. Viewshed Metrics and Analytical Methods

Viewshed conditions along the escarpment road were conceptualised as a sequential and direction-dependent spatial phenomenon that changes as road users move through the corridor. The methodological framework therefore evaluates viewshed characteristics in terms of directional asymmetry and sequential transition intensity to examine how terrain geometry influences the extent and distribution of visible terrain along the roadway.

Viewshed magnitude at each observation point and travel direction was quantified using raster-based statistics derived from binary viewshed outputs and expressed as the percentage of visible cells relative to the total number of valid cells within each 200 m analysis buffer.

$$\text{Visibility (\%)} = \frac{N_{\text{visible}}}{N_{\text{total}}} \times 100$$

Here, N_{visible} represents the number of raster cells classified as visible (value = 1) and N_{total} denotes the total number of valid cells within the analysis extent. This normalised metric enables direct comparison across observation points and between directional components, ensuring consistency in the evaluation of near-road visibility (Ogburn, 2006; Llobera, 2003). Pixel counts were extracted directly from raster attribute tables following reclassification and since each raster cell corresponds to a fixed ground area defined by DEM resolution, the resulting percentages inherently capture both spatial extent and terrain configuration.

Directional visibility metrics were computed separately for downhill and uphill directions, with an additional combined metric calculated as the mean of the two to provide an overall representation while avoiding directional masking. To support interpretation, visible and non-visible areas were symbolised using a binary colour scheme, allowing rapid identification of occluded zones and exposed segments along the corridor.

To quantify directional anisotropy in viewshed visibility conditions, uphill and downhill visibility were calculated independently for each observation point. Directional visibility asymmetry was subsequently quantified using a Visibility Asymmetry Index:

$$A_v = \frac{|V_u - V_d|}{V_u + V_d}$$

where A_v represents directional visibility asymmetry, V_u represents uphill visibility and V_d represents downhill visibility. Higher values indicate stronger directional imbalance in line-of-sight conditions and therefore greater terrain-induced visual anisotropy. Higher asymmetry values indicate stronger directional imbalance in line-of-sight conditions and therefore greater terrain-induced visual anisotropy. Low asymmetry values represent relatively balanced visibility conditions between travel directions, whereas high asymmetry values indicate substantially different perceptual and anticipatory conditions for opposing traffic movements. For interpretive purposes, asymmetry values were classified into low (<0.20), moderate (0.20–0.40) and strong (>0.40) directional asymmetry environments.

Sequential visibility transitions between adjacent observation points were quantified using a transition intensity metric:

$$\Delta V = |V_{i+1} - V_i|$$

where V_i and V_{i+1} represent visibility percentages at consecutive observation points. Larger ΔV values indicate abrupt changes in visual exposure and stronger visibility discontinuities along the roadway corridor. Changes in visibility (ΔV) between consecutive observation points were calculated and classified into three categories: stable ($|\Delta V| \leq 10\%$), moderate ($10\% < |\Delta V| \leq 20\%$) and strong transitions ($|\Delta V| > 20\%$), the latter interpreted as visibility breakpoints. This approach enables identification of zones of visual instability, where visibility changes abruptly over short distances, which is particularly relevant for safety-critical segments in steep and geometrically complex terrain.

To examine terrain–visibility relationships, a rank-based correlation analysis was employed, preserving the continuous nature of the dataset. Spearman’s rank correlation coefficient was used to assess the relationships between visibility and terrain variables including slope, elevation, profile curvature and plan curvature. The method was selected because it does not assume normally distributed variables or a linear relationship between terrain characteristics and visibility.

$$\rho = 1 - \frac{6 \sum_{i=1}^n d_i^2}{n(n^2 - 1)}$$

where ρ represents Spearman’s rank correlation coefficient, d_i represents the difference between the ranked terrain variable and ranked visibility at observation point (i), and (n) represents the number of observation points. Spearman’s rank correlation was used to identify the strength and direction of monotonic terrain–visibility relationships within the escarpment environment, with statistical significance evaluated at ($\rho < 0.05$).

Finally, roadway segments were classified into exposed, transitional and enclosed visibility environments based on overall visibility magnitude, enabling interpretation of the escarpment corridor as a sequential visibility landscape characterised by varying levels of visual openness, enclosure and directional asymmetry.

4. Results

Viewshed-derived visibility was evaluated using three complementary dimensions: visibility magnitude, directional asymmetry and transition intensity. Visibility magnitude quantified the proportion of terrain visible within each 200 m analysis zone, directional asymmetry measured differences between uphill and downhill visibility conditions and transition intensity quantified changes in visibility between successive observation points. These metrics enabled visibility to be analysed as a spatial, directional and sequential characteristic of movement through the escarpment corridor. Visibility conditions varied substantially across the corridor as seen in Table 2. Overall visibility averaged 39.9% (SD = 17.1%), with values ranging from 9.5% to 82.4%. Uphill visibility (mean = 44.4%) was generally greater than downhill visibility (mean = 34.9%), while the Visibility Asymmetry Index averaged 0.43, indicating a moderate-to-high degree of directional imbalance across the corridor.

Table 2: Descriptive statistics of overall visibility, directional visibility and visibility asymmetry derived from the 16 observation points along the Mai Mahiu escarpment corridor.

Metric	Mean (%)	SD (%)	Minimum (%)	Maximum (%)
Overall Visibility	39.87	17.14	9.52	82.40
Uphill Visibility	44.41	24.33	13.64	90.16
Downhill Visibility	34.93	27.56	5.00	82.69
Visibility Asymmetry Index (VAI)	0.428	0.224	0.034	0.740

4.1. Distribution of Terrain Visibility Within 200 m Viewsheds

The viewshed analysis reveals substantial variability in visibility conditions along the road corridor. Terrain visibility values range from a minimum of 9.52% at Point 14 to a maximum of 82.40% at Point 11, indicating strong differences in visual exposure across the study area as shown in Table 3. The mean visibility across all 16 observation points is approximately 42.8%, although the distribution is highly uneven. Most points fall within a moderate visibility range of roughly 30% to 50%, while only a few locations exhibit either very high (>70%) or very low (<20%) visibility. Visible surface area follows the same pattern, ranging from approximately 11,402 m² to 97,871 m², with larger visible areas corresponding directly to higher visibility percentages.

Table 3: Overall visibility distribution within a 200 m viewshed for sampled viewpoints along the road corridor, showing visibility and non-visibility percentages and corresponding surface areas.

Point	Visibility (%)	Non-Visibility (%)	Visible Area (m ²)	Non-Visible Area (m ²)
1	48.41	51.59	57,962.34	61,763.14
2	27.42	72.58	32,306.88	85,518.20
3	32.54	67.46	38,958.29	80,767.19
4	47.15	52.85	55,111.73	61,763.14
5	41.46	58.54	48,460.31	68,414.56
6	50.85	49.15	57,012.13	55,111.73
7	17.8	82.2	19,954.25	92,169.62
8	37.6	62.4	44,659.50	74,115.77
9	58.4	41.6	69,364.76	49,410.52
10	25.2	74.8	29,456.27	87,418.60
11	82.4	17.6	97,870.83	20,904.45
12	44.8	55.2	53,211.32	65,563.95
13	46.61	53.39	52,261.12	59,862.74
14	9.52	90.48	11,402.43	108,323.05
15	23.39	76.61	27,555.86	90,269.21
16	44.44	55.56	53,211.32	66,514.16

Terrain visibility does not follow a consistent increasing or decreasing trend along the corridor. Instead, it fluctuates considerably between adjacent observation points, producing alternating zones of openness and visual restriction as shown in Figure 4. In the initial segment of the corridor (Points 1–6), visibility remains relatively stable, varying between 27.42% and 50.85%. In the middle section (Points 7–10), visibility becomes more variable, decreasing to 17.80% at Point 7, increasing to 58.40% at Point 9 and then declining again to 25.20% at Point 10. These shifts indicate localised changes in visual exposure occurring over relatively short distances.

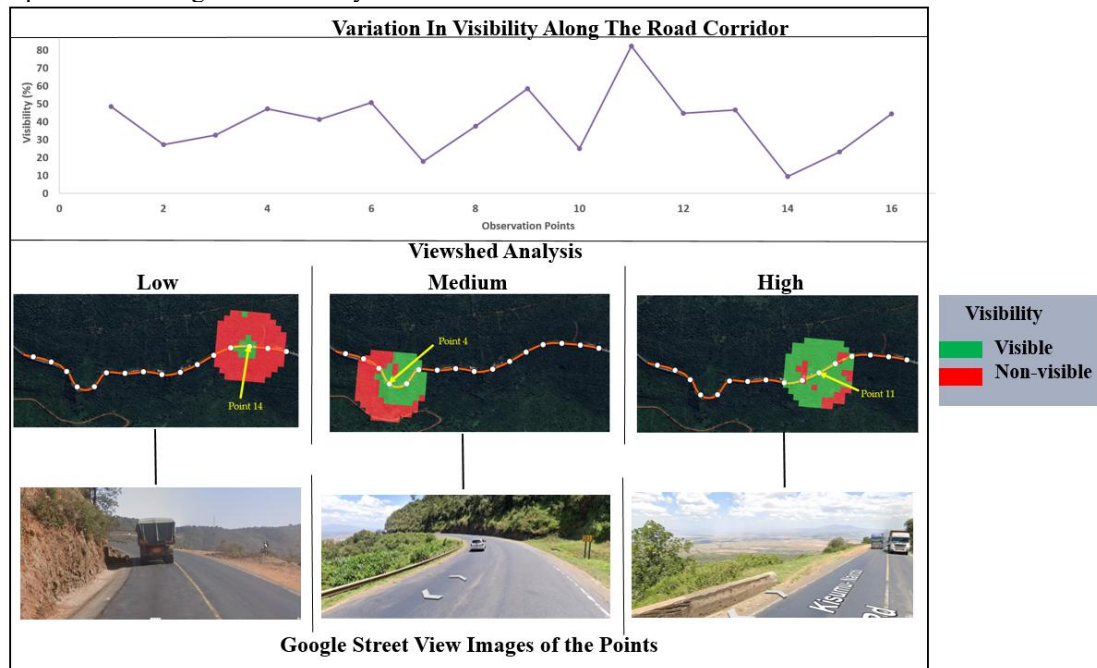


Figure 4: Variation in viewshed-derived visibility along the Mai Mahiu escarpment corridor.

The strongest visibility contrast occurs between Points 10 and 14. Visibility rises sharply from 25.20% at Point 10 to 82.40% at Point 11 before progressively declining to only 9.52% at Point 14, the lowest recorded value along the corridor. This sequence demonstrates that visibility conditions along the escarpment are highly discontinuous and strongly influenced by localised terrain configuration. In the final section of the corridor (Points 14–16), visibility increases again to 44.44%, indicating a partial recovery in visual openness.

Patterns of visible and non-visible surface area further reinforce these findings. At highly exposed locations such as Point 11, visible terrain dominates the surrounding landscape, with approximately

97,871 m² classified as visible compared to 20,904 m² classified as non-visible. In contrast, visually enclosed locations such as Point 14 contain only 11,402 m² of visible area and more than 108,323 m² of non-visible terrain. These contrasts highlight the pronounced spatial variability in visual openness experienced along the escarpment corridor.

The results indicate that visibility along the corridor is spatially fragmented, with highly exposed and highly enclosed conditions occurring in close proximity. This pattern suggests that local terrain configuration exerts a stronger influence on visibility than broad-scale topographic gradients.

4.2. Directional Visibility Asymmetry

Separating visibility into uphill and downhill travel directions reveals that the Mai Mahiu escarpment corridor exhibits a strongly anisotropic visual environment as shown in Figure 5. Drivers travelling in opposite directions frequently encounter substantially different levels of visual exposure, enclosure and sightline continuity along the same roadway segment.

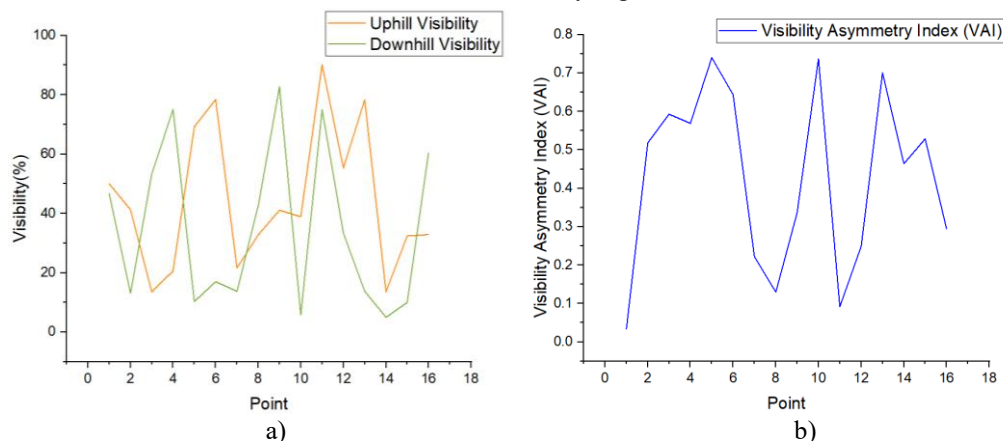


Figure 5: Directional variation in viewshed-derived visibility along the Mai Mahiu escarpment corridor. Panel (a) shows independently calculated uphill and downhill visibility percentages at sequential observation points, while panel (b) presents the corresponding (VAI).

Uphill visibility, representing travel toward Nairobi, ranges from 13.64% to 90.16%, with a mean of approximately 44.6%. Several locations provide relatively open uphill visibility conditions, particularly Points 5, 6, 11 and 13, where visibility exceeds 69%. In contrast, Points 3, 7 and 14 exhibit strongly restricted uphill visibility below 22%, indicating localised enclosure despite the ascending travel direction. Downhill visibility, representing travel toward Mai Mahiu, shows even greater variability, ranging from 5.00% at Point 14 to 82.69% at Point 9, with a lower mean value of approximately 34.8%. Highly exposed downhill conditions occur at Points 4, 9, 11 and 16, whereas severe restriction is observed at Points 5, 10, 14 and 15, where visibility falls below 11% as seen in Table 4.

Several observation points demonstrate pronounced directional asymmetry. Point 5 exhibits high uphill visibility (69.23%) but severe downhill restriction (10.34%), while Point 9 displays the opposite pattern, with moderate uphill visibility (41.10%) and highly exposed downhill conditions (82.69%). Similarly, Point 4 records only 20.63% uphill visibility compared to 75.00% downhill visibility. These contrasting conditions indicate that local terrain morphology reorganises visual exposure differently according to direction of travel.

The Visibility Asymmetry Index further quantifies the magnitude of this imbalance. Points 5, 10 and 13 exhibit the highest asymmetry values along the corridor, all exceeding 0.70, indicating extremely uneven visibility between opposing travel directions. In contrast, Point 1 (0.034) and Point 11 (0.092) display relatively balanced conditions. In addition to directional imbalance, several locations exhibit restricted visibility in both directions, forming localised zones of visual confinement. Point 14 (13.64% uphill; 5.00% downhill) and Point 7 (21.67% uphill; 13.79% downhill) are particularly notable, with combined visibility below 20%. These sections represent terrain-controlled bottlenecks where obstruction limits visual exposure regardless of travel direction.

Figures 6 and 7 illustrate the cumulative and directional visibility characteristics of the escarpment corridor. The cumulative viewshed analysis highlights substantial spatial variation in visibility exposure, while the directional viewsheds show clear differences between uphill and downhill viewing conditions. Drivers travelling in opposite directions often experience markedly different levels of visual exposure and sightline continuity despite occupying the same roadway alignment. These patterns reflect the influence of terrain configuration, slope transitions, roadway curvature and localised topographic

obstruction on the distribution of visibility along the corridor. As a result, a single aggregated visibility measure may not adequately capture the visual conditions experienced by opposing traffic movements.

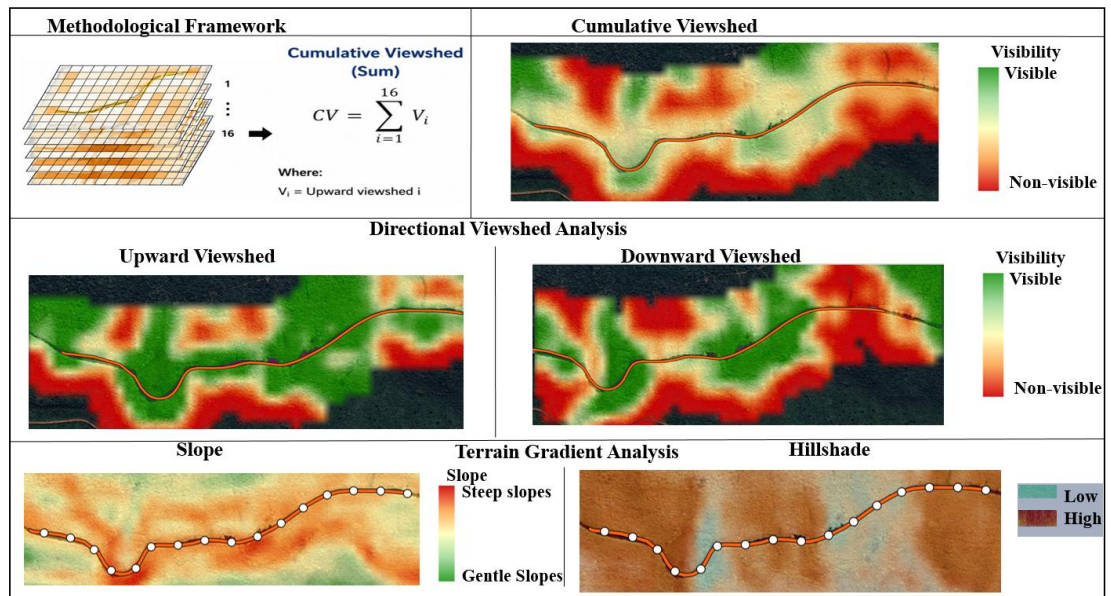


Figure 6: Analytical framework for evaluating visibility along the Mai Mahiu escarpment corridor.

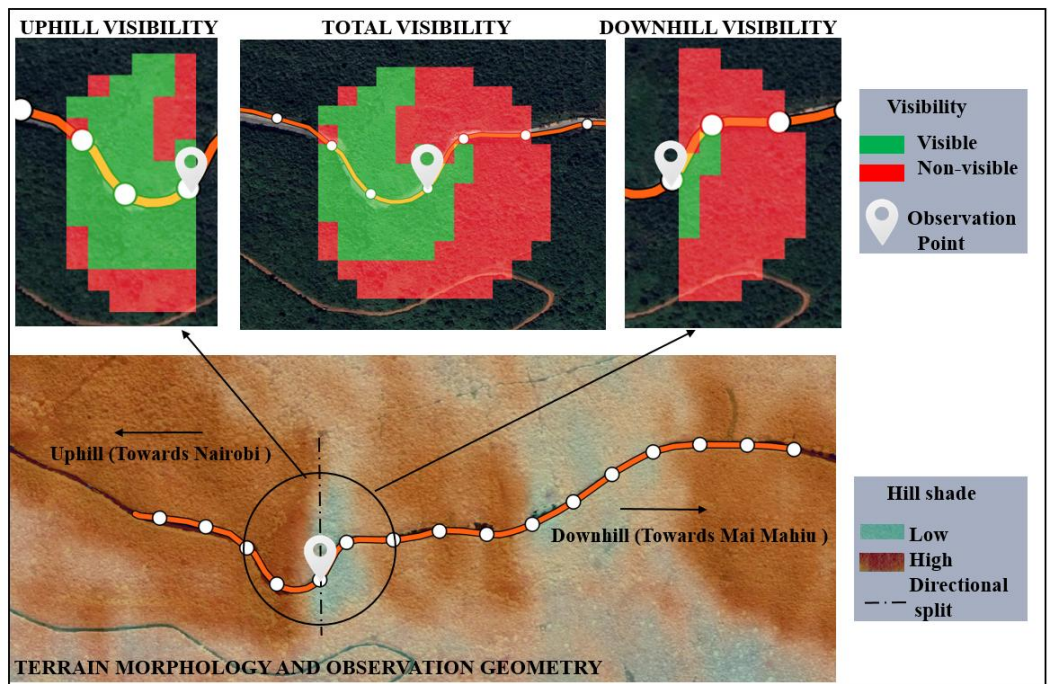


Figure 7: Directional visibility asymmetry at Observation Point 5 along the Mai Mahiu escarpment corridor

4.3. Sequential Visibility Transitions and Breakpoints

Sequential transition analysis reveals that visibility along the Mai Mahiu escarpment corridor changes abruptly. Visibility conditions frequently reorganise over short travel distances, producing alternating sequences of visual expansion and enclosure. Several adjacent-point transitions exceed the 20% threshold used to classify strong visibility discontinuities, indicating the presence of localised visibility breakpoints where line-of-sight continuity changes rapidly between consecutive road segments.

The results demonstrate a strong directional asymmetry in transition behaviour as shown in Table 4. In many cases, visibility changes substantially in one travel direction while remaining relatively stable in the opposite direction. The clearest example occurs between Points 9 and 10, where downhill visibility decreases by 76.81%, representing the strongest downhill transition observed along the corridor. Over

the same segment, uphill visibility changes by only 2.21%, indicating comparatively stable uphill visual conditions. This contrast suggests that descending drivers experience a sudden collapse in visual openness, while uphill drivers encounter little perceptual restructuring along the same roadway section.

The strongest uphill transition occurs between Points 13 and 14, where uphill visibility decreases by 64.69%, indicating a major reduction in uphill visual continuity. Additional strong transitions are observed between Points 4 and 5, Points 6 and 7 and Points 10 and 11, all of which display abrupt shifts between visually exposed and visually enclosed conditions. These discontinuities likely correspond to localised terrain controls such as crest curves, escarpment-edge exposure, cut-slope obstruction and rapid changes in road alignment that alter visibility over relatively short distances. In contrast, some sections exhibit comparatively stable visibility conditions in both travel directions. Segments such as Points 5–6 and Points 14–15 show relatively low transition intensity, suggesting more uniform terrain configuration and more consistent line-of-sight continuity between adjacent observation points.

Table 4: Sequential visibility transition intensity showing localised visibility breakpoints and abrupt changes in visual continuity.

Transition	Uphill ΔV (%)	Class	Downhill ΔV (%)	Class
P1 → P2	8.73	Low	33.56	High
P2 → P3	27.63	High	40.22	High
P3 → P4	6.99	Low	21.67	High
P4 → P5	48.60	High	64.66	High
P5 → P6	9.23	Low	6.64	Low
P6 → P7	56.79	High	3.19	Low
P7 → P8	11.14	Moderate	28.83	High
P8 → P9	8.29	Low	40.07	High
P9 → P10	2.21	Low	76.81	High
P10 → P11	51.27	High	69.12	High
P11 → P12	34.78	High	41.67	High
P12 → P13	22.95	High	19.54	Moderate
P13 → P14	64.69	High	8.79	Low
P14 → P15	18.79	Moderate	5.00	Low
P15 → P16	0.45	Low	50.38	High

*P1, P2, P3 ... P16 represent sequential observation points established along the Mai Mahiu escarpment corridor. Each transition (e.g., P1 → P2) therefore represents the change in visibility conditions between two consecutive observation points along the road.

The findings demonstrate that visibility along the escarpment corridor is governed by overall visibility magnitude and also by the rate and intensity of sequential visibility change. The prevalence of strong transition zones indicates that visibility is organised as a sequence of discrete exposure–enclosure states. The corridor functions as a fragmented visual environment characterised by repeated visibility breakpoints where openness abruptly expands or contracts over short travel distances. These rapid transitions restructure visual conditions during movement and may increase perceptual workload, visual adaptation demands and the complexity of hazard anticipation, particularly where visibility changes differ substantially between travel directions.

4.4. Relationships between Visibility and Terrain Variables

To investigate the influence of terrain morphology on visibility conditions along the Mai Mahiu escarpment corridor, Spearman's rank correlation was applied between visibility and the principal terrain variables: slope, elevation, profile curvature and plan curvature (Figure 8; Table 5). The results indicate that terrain variables differ substantially in their association with visibility, with slope and profile curvature showing stronger relationships than elevation and plan curvature.

Slope showed the strongest statistically significant association with visibility ($\rho = 0.518$, $p = 0.040$), indicating a moderate tendency for visibility to increase with increasing slope. This pattern is evident at several observation points. Point 14 combines the lowest slope value (24.24°) with the minimum recorded visibility (9.52%), whereas relatively steep locations include Point 9 (36.18° , 58.40%) and Point 11 (33.65° , 82.40%). However, substantial variation remains among locations with similar slope

gradients, indicating that slope does not independently determine visibility and that its influence is conditioned by local terrain configuration.

Elevation showed a weak positive and statistically non-significant association with visibility ($\rho = 0.242, p = 0.367$). Visibility varied considerably across the elevation range of 2115–2175 m, with high and low visibility conditions occurring at comparable elevations. Point 3, for example, occurs at one of the highest elevations (2175 m) but records only moderate visibility (32.54%), whereas Point 11 records the highest visibility (82.40%) at 2135 m. Absolute elevation therefore appears to provide limited explanatory power for visibility variation along the escarpment.

Profile curvature showed a moderate positive association with visibility ($\rho = 0.482, p = 0.058$), although the relationship did not reach statistical significance at the 0.05 level. The magnitude of the coefficient nevertheless suggests that vertical terrain form may contribute to visibility organisation. Positive profile curvature occurs at several highly exposed locations, including Points 4 and 11, while visually restricted conditions occur at several locations with negative profile curvature, including Points 7, 10 and 14. The result should therefore be interpreted as evidence of a moderate terrain–visibility association rather than a statistically confirmed independent effect.

Plan curvature showed a weak positive and statistically non-significant association with visibility ($\rho = 0.259, p = 0.333$). The broad dispersion of visibility values across positive and negative plan-curvature conditions indicates that lateral terrain form alone provides limited explanation of visibility variation. Its influence may instead operate locally through interaction with slope orientation, roadway alignment and surrounding terrain geometry.

The correlation analysis indicates that visibility along the Mai Mahiu escarpment corridor cannot be explained by a single terrain parameter. Slope exhibited the strongest and only statistically significant association with visibility, while profile curvature showed a moderate but non-significant relationship. Elevation and plan curvature were comparatively weakly associated with visibility. These findings suggest that local terrain morphology, rather than absolute elevation alone, is more closely associated with spatial variations in visual exposure along the escarpment corridor.

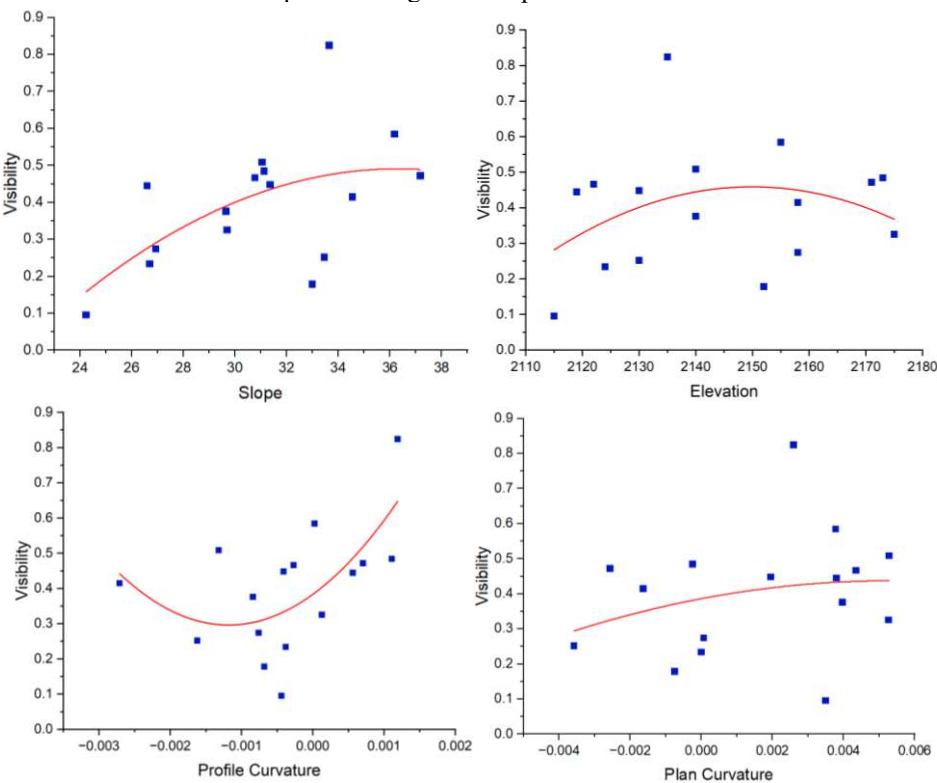
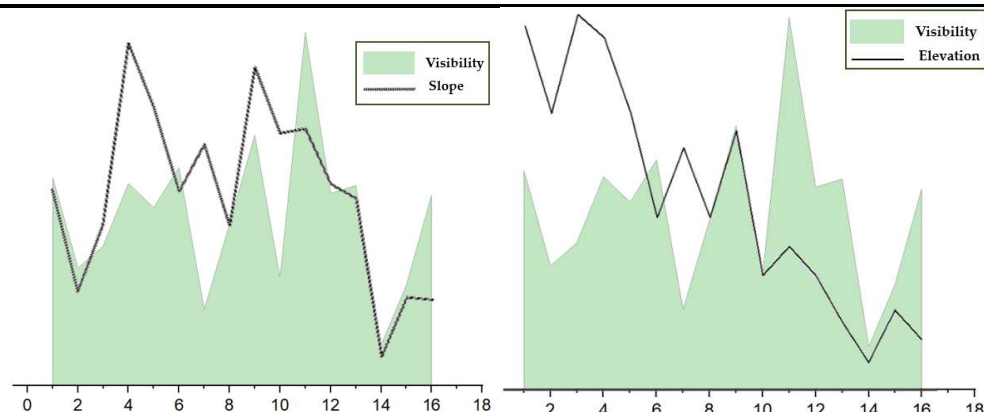


Figure 8: Scatterplots showing relationships between visibility and terrain variables (slope, elevation, profile curvature and plan curvature)

Table 5: Terrain parameters (elevation, profile curvature and plan curvature) and corresponding visibility (%) extracted from QGIS at sampled observation points across the escarpment for terrain–visibility analysis.

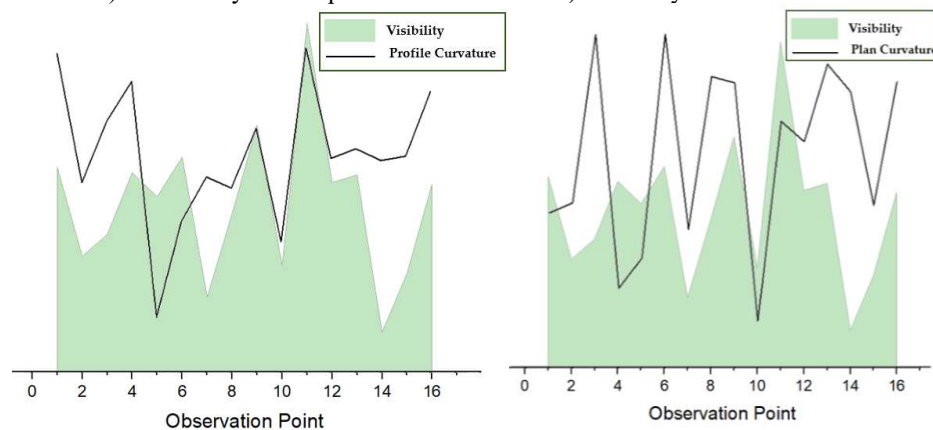
Slope	Elevation	Profile Curvature	Plan Curvature	Visibility %
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1	31.12955	2173	0.001109	-0.00024	48.41%
2	26.9331	2158	-0.00076	7.14E-05	27.42%
3	29.69978	2175	0.000128	0.00527	32.54%
4	37.17583	2171	0.000704	-0.00256	47.15%
5	34.55081	2158	-0.00271	-0.00163	41.46%
6	31.05941	2140	-0.00132	0.00528	50.85%
7	32.99865	2152	-0.00068	-0.00075	17.80%
8	29.64783	2140	-0.00084	0.003972	37.60%
9	36.18198	2155	2.47E-05	0.003779	58.40%
10	33.46206	2130	-0.00162	-0.00358	25.20%
11	33.64664	2135	0.001191	0.002593	82.40%
12	31.36329	2130	-0.00041	0.001959	44.80%
13	30.77579	2122	-0.00027	0.004353	46.61%
14	24.24199	2115	-0.00044	0.003503	9.52%
15	26.69867	2124	-0.00038	0	23.39%
16	26.60106	2119	0.000561	0.003808	44.44%



a) Visibility and slope variation

b) Visibility and elevation variation



c) Visibility and profile curvature variation

d) Visibility and plan curvature variation

Figure 9: Relationships between terrain parameters (slope, elevation, profile curvature and plan curvature) and visibility across the study area.

Figure 9 illustrates the relationships between terrain parameters and visibility, with slope and profile curvature showing comparatively stronger associations than elevation and plan curvature.

5. Discussion

The visibility patterns observed along the corridor have several implications for both road users and corridor management. Sections with restricted visibility offer fewer visual cues about upcoming roadway conditions and surrounding terrain, potentially increasing demands on driver perception and decision-

making. In contrast, highly visible sections offer broader visual exposure and stronger connections with the surrounding landscape. This contrast highlights the uneven distribution of visual experience along escarpment roads, where terrain can alternately open and constrain views over relatively short distances. Visibility may therefore be considered an important landscape attribute. Locations with extensive visual exposure may warrant protection from intrusive development, while areas of persistently limited visibility could be prioritised for further investigation where safety, wayfinding, or user experience are concerns. The results also suggest that visibility is closely tied to local terrain configuration, indicating that relatively small changes in landform can produce substantial differences in visual conditions along the corridor.

5.1. Escarpment roads as sequential visual landscapes

5.1.1 Terrain morphology and directional visibility asymmetry

The results demonstrate that visibility along the Mai Mahiu escarpment corridor is fundamentally directional. Although visibility is often treated as a fixed property of a road environment, the findings show that the same roadway segment can generate markedly different visual conditions depending on travel direction. This directional variability arises from the interaction between escarpment topography, roadway alignment and line-of-sight geometry, which selectively reveal and conceal portions of the surrounding landscape according to movement orientation. Visibility within escarpment corridors cannot be adequately represented by a single aggregated viewshed measure.

The magnitude of this directional effect is substantial. Mean uphill visibility (44.4%) exceeded mean downhill visibility (34.9%), while the average Visibility Asymmetry Index ($VAI = 0.43$) indicates a moderate-to-high degree of directional imbalance across the corridor. Several locations exhibited pronounced asymmetry. At Point 5, uphill visibility reached 69.23% while downhill visibility declined to only 10.34%, whereas Point 9 displayed the opposite condition, with downhill visibility exceeding 82% and substantially lower uphill exposure. These contrasts demonstrate that drivers travelling in opposing directions frequently experience fundamentally different levels of visual exposure, enclosure and sightline continuity despite occupying the same physical roadway.

The observed asymmetry is primarily a consequence of terrain morphology and its interaction with roadway geometry. Escarpment-edge alignments, convex slopes and outward-facing valley slopes tend to create extensive outward visibility by extending sightlines across the Rift Valley landscape. In contrast, horizontal curves, crest transitions, cut slopes, embankments and terrain-induced screening interrupt line-of-sight continuity and restrict the visible field. Because these geometric controls interact differently with opposing viewing directions, terrain continuously reorganises the visual environment according to travel orientation. Visibility should therefore be understood as an emergent property of the terrain–roadway system.

The question of whether visibility is generally “better” in the uphill or downhill direction cannot be resolved in absolute terms because visibility conditions remain spatially heterogeneous throughout the corridor. Nevertheless, clear directional patterns emerge. Downhill visibility exhibits greater extremes, ranging from 5.0% to 82.7% and therefore combines some of the most visually exposed and most visually restricted locations within the study area. By comparison, uphill visibility ranges from 13.6% to 90.2% and exhibits fewer extreme low-visibility conditions. This suggests that downhill travel is characterised by a more volatile visual environment in which panoramic exposure may be interrupted abruptly by terrain-induced enclosure, whereas uphill visibility is comparatively more stable and continuous.

These findings indicate that escarpment roads function as anisotropic visual environments in which terrain selectively structures visibility according to movement direction. Drivers travelling uphill and downhill are therefore exposed to different patterns of visual information, landscape exposure and perceptual continuity. This has important methodological implications because conventional non-directional viewshed approaches implicitly assume that visibility conditions are equivalent in opposing travel directions. The results demonstrate that such assumptions may obscure critical differences in how visibility is experienced within complex terrain environments.

The operational implications are equally significant. Visibility directly influences preview distance, spatial legibility and hazard anticipation. Downhill travel toward Mai Mahiu combines greater visibility volatility with higher operating speeds, gravitational acceleration and increased braking demand. Under such conditions, abrupt reductions in sight distance may reduce the time available for hazard detection and driver response. Uphill travel toward Nairobi generally occurs under lower speeds and greater vehicle control, partially moderating the effects of localised visibility restriction. Terrain-induced visibility asymmetry therefore influences landscape experience and also the way drivers perceive, interpret and respond to the escarpment road environment.

5.1.2. Scenic rhythm, exposure and enclosure

The Mai Mahiu escarpment road operates as a sequential landscape structured by alternating states of exposure and enclosure as discussed in Table 6. Visibility is highly fragmented, with expansive visual exposure and severe restriction occurring in close spatial proximity. Highly exposed locations, such as Point 11 (82.4% visibility), provide extensive visual access across the Rift Valley and function as major exposure zones. In contrast, Points 7 (17.8%) and 14 (9.5%) represent strongly enclosed environments where terrain and roadway geometry substantially restrict sightlines. The corridor is therefore characterised by abrupt shifts between openness and enclosure.

Table 6: Directional scenic rhythm and visibility structure of the Mai Mahiu escarpment corridor

Scenic condition	Quantitative evidence	Landscape interpretation
Major exposure zone	Point 11: 82.4% visibility; 90.16% uphill visibility	Extensive visual exposure, panoramic Rift Valley views and high spatial legibility
Downslope exposure zone	Points 4 and 9: downhill visibility >75%	Strong valley-facing exposure and panoramic opening during descent
Major enclosure zone	Point 14: 9.5% visibility; Point 7: 17.8% visibility	Terrain-controlled visual containment and restricted sightline continuity
Directional enclosure zone	Point 5: 10.34% downhill visibility; Point 10: 5.88% downhill visibility	Severe direction-specific visibility restriction and visual compression
Scenic release transition	Point 10 → Point 11: largest positive ΔV	Abrupt expansion of the visible field and transition from enclosure to exposure
Visual compression transition	Point 6 → Point 7; Point 9 → Point 10: largest negative ΔV	Rapid contraction of the visible field and transition from exposure to enclosure
Stable exposure sequence	Mean uphill visibility = 44.4%; fewer extreme low-visibility segments	More continuous visual access and stronger spatial orientation during ascent
Volatile exposure sequence	Mean downhill visibility = 34.9%; range = 5.0–82.7%	Alternation between panoramic exposure and abrupt enclosure during descent

This sequential structure is captured by the visibility transition metric (ΔV), which quantifies changes in visibility between adjacent observation points. Large ΔV values identify visibility breakpoints where terrain morphology abruptly reorganises the visible field. The transition from Point 10 to Point 11 represents the strongest exposure event within the corridor, where visibility increases sharply following a highly restricted segment. Conversely, the transitions from Point 6 to Point 7 and Point 9 to Point 10 represent major visual compression events, where visibility declines rapidly over short distances. These locations correspond to terrain-induced interruptions in line-of-sight continuity produced by roadway curvature, cut slopes, embankments and enclosed landforms. The results demonstrate that the scenic character of the corridor is determined by highly visible viewpoints and by the frequency and intensity of transitions between visibility states.

These transitions create a rhythmic viewing experience characterised by repeated cycles of expansion and constriction. Exposure zones visually connect drivers to the broader escarpment landscape through extended sightlines, distant ridgelines, valley panoramas and visible sky. Enclosed zones, by contrast, compress the visual field and concentrate attention on the immediate roadway environment. Visibility is therefore experienced as a dynamic sequence in which environmental information is continuously gained, lost and reconfigured during movement through the corridor.

The significance of this pattern extends beyond scenic perception. Exposure–enclosure transitions influence how drivers acquire and process spatial information, affecting environmental legibility, preview continuity and anticipation of upcoming roadway conditions. Abrupt visual compression may reduce the amount of information available ahead of the vehicle, while rapid scenic release can suddenly expand the visible field and alter perception of the surrounding environment. The experiential quality of the corridor is governed by the rate at which visual conditions change.

The scenic character of the Mai Mahiu escarpment therefore emerges from the rhythm between exposure and enclosure. A corridor composed entirely of open views would provide extensive visual access but limited experiential variation. In contrast, the repeated alternation between openness and restriction creates contrast, anticipation and visual progression throughout the journey. By quantifying sequential visibility change through ΔV , this study demonstrates that scenic rhythm can be interpreted as a measurable structural property of the terrain–road system.

5.2 Corridor Management Implications

The results demonstrate that visibility-related risk along the Mai Mahiu escarpment corridor cannot be evaluated using visibility magnitude alone. Locations with low visibility, strong directional asymmetry and abrupt visibility transitions represent different operational conditions and therefore require different management responses. Visibility assessment should be approached as a multi-criteria process integrating overall visibility (V), directional asymmetry (VAI) and visibility transition intensity (ΔV).

A practical implication of this approach is the development of a tiered visibility-risk framework for identifying and prioritising terrain-controlled hazard locations. Sections characterised by severe visibility restriction ($V < 20\%$) represent locations where drivers receive limited visual information regarding roadway alignment, roadside conditions and potential hazards. Locations exhibiting strong directional asymmetry ($VAI > 0.40$) indicate segments where visibility conditions differ substantially between uphill and downhill traffic movements. Sections associated with large visibility transitions ($\Delta V > 20\%$) represent visibility breakpoints where visual continuity changes abruptly over short distances. The highest-priority locations are those where multiple conditions occur simultaneously, such as low visibility combined with strong directional asymmetry or abrupt visibility compression.

Importantly, the appropriate intervention depends on the type of visibility deficit identified as shown in Table 7. Low-visibility locations primarily require measures that improve driver awareness and compensate for restricted visual access. Potential treatments include advance warning signage, speed management, no-passing restrictions, enhanced pavement markings, roadside delineation and improved guardrail visibility. In contrast, visibility breakpoints characterised by strong ΔV values are more appropriately addressed through measures that improve alignment legibility and visual guidance, including chevron systems, reflective delineators, transition warning signs and enhanced curve marking. Locations exhibiting strong directional asymmetry may require direction-specific interventions because visibility conditions experienced by uphill and downhill drivers are not equivalent.

Table 7: Visibility-based risk classification and management priorities for escarpment roads

Visibility condition	Quantitative criterion	Operational implication	Recommended intervention
Severe enclosure	$V < 20\%$	Restricted visual access and reduced preview continuity	Speed management, advance warning signs, enhanced delineation, no-passing restrictions
Extreme enclosure	$V < 10\%$	Very limited sight environment and reduced information availability	Highest-priority field assessment, speed control, chevron systems, guardrail enhancement
Strong directional asymmetry	$VAI > 0.40$	Visibility conditions differ substantially between travel directions	Direction-specific assessment and targeted mitigation based on the more restrictive direction
Visibility breakpoint	$\Delta V > 20\%$	Abrupt visibility compression or expansion over short distances	Transition warning signs, reflective delineators, alignment guidance, curve marking
Compound visibility risk	$V < 20\%$ combined with $VAI > 0.40$ and/or $\Delta V > 20\%$	Multiple terrain-controlled visibility constraints occurring simultaneously	Highest intervention priority and detailed engineering assessment

The management implications are particularly relevant within the Mai Mahiu escarpment environment, where terrain-induced visibility constraints are largely controlled by permanent geomorphological conditions. Many of the most restricted locations are associated with cut slopes, escarpment-edge geometry, terrain-enclosed bends and abrupt changes in topography. As a result, complete elimination of visibility restrictions is often impractical. The objective should therefore be to improve road readability and hazard anticipation.

The corridor also accommodates a complex mix of road users, including long-distance freight vehicles, passenger vehicles, public transport operators and tourist traffic drawn to the escarpment viewpoints. Under such conditions, visibility management becomes particularly important because different vehicle types may respond differently to terrain-induced restrictions and visibility transitions. Locations where visibility is severely restricted, or changes abruptly, may therefore warrant enhanced operational controls regardless of whether geometric reconstruction is feasible.

The framework developed in this study provides a proactive approach for corridor-level visibility assessment. Visibility metrics can be used to identify locations where terrain morphology may reduce the availability of visual information, disrupt visual continuity, or impose direction-specific constraints. This allows road agencies to prioritise field inspections, allocate maintenance resources more effectively and target engineering interventions toward locations where visibility-related operational challenges are most likely to occur as shown in Figure 10.

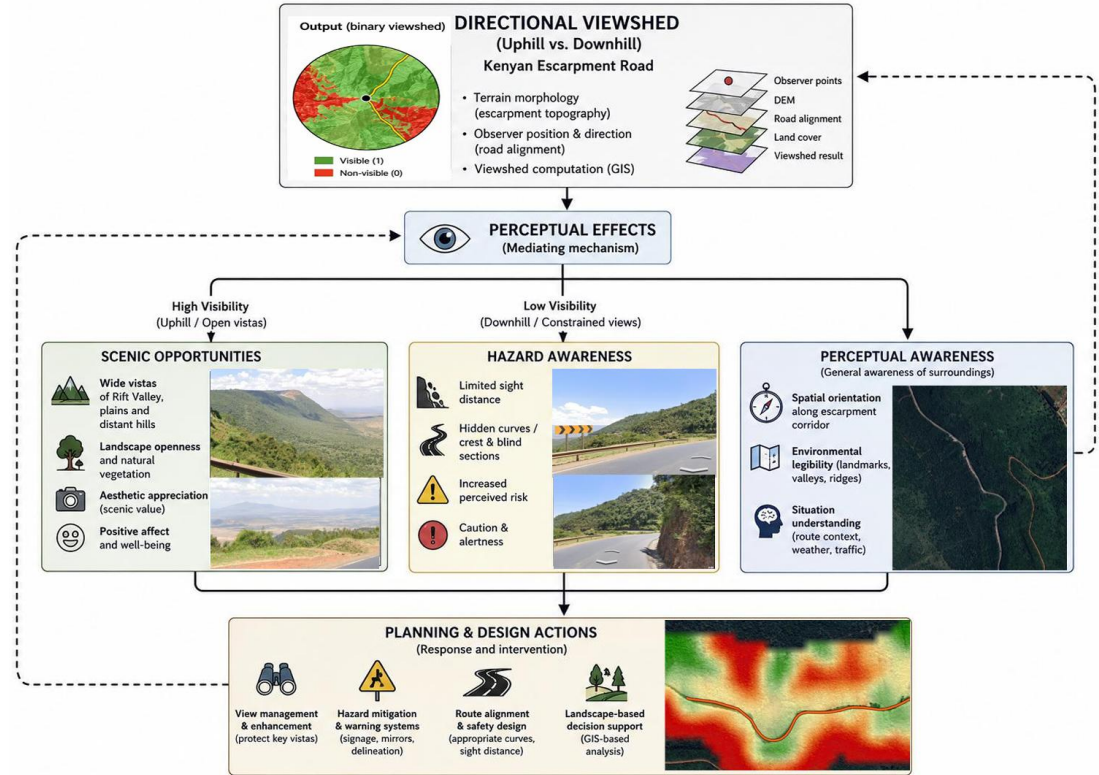


Figure 10: Conceptual framework illustrating the relationships between directional viewshed conditions, perceptual response and planning implications within escarpment transportation corridors.

5.3. Methodological Contribution and Limitations

This study extends conventional viewshed analysis by treating visibility as a directional and sequential property of movement. The framework integrates visibility magnitude, directional asymmetry and sequential visibility change to capture how visibility is experienced along an escarpment road corridor. The results demonstrate that opposing traffic movements can experience substantially different visibility conditions and that abrupt visibility transitions constitute important components of corridor visibility structure that are not captured by conventional viewshed measures alone. A key contribution of the study is the incorporation of directional visibility assessment through the Visibility Asymmetry Index (VAI), which quantifies differences between uphill and downhill visibility conditions. The analysis further introduces the visibility transition metric (ΔV), enabling identification of visibility breakpoints where the visible field expands or contracts rapidly due to terrain–road interactions. These metrics provide a more comprehensive representation of corridor visibility than visibility magnitude alone. The study also adopts a near-field corridor visibility framework based on regularly spaced observation points and a fixed 200 m analysis radius. This approach was intentionally designed to evaluate local visibility conditions relevant to roadway reading, alignment interpretation and immediate hazard anticipation while maintaining a consistent analytical extent throughout the corridor.

Beyond its methodological contribution, the study also addresses a geographical gap in the visibility-analysis literature. Existing viewshed and visibility research has been undertaken predominantly in European, North American and East Asian contexts, while applications within African transportation environments remain comparatively scarce. The Mai Mahiu corridor therefore provides an important case study for extending visibility research to Rift Valley escarpment landscapes, demonstrating the applicability of directional and sequential visibility assessment within a region where

terrain-related transportation challenges are both operationally significant and underrepresented in the literature.

Several limitations should be acknowledged. The analysis represents terrain-controlled visibility and therefore excludes the effects of vegetation, roadside infrastructure, traffic, weather and lighting conditions. The 200 m radius was adopted as a methodological control for comparing local visibility conditions and does not represent the maximum extent of visibility available to drivers. In addition, the study evaluates visibility as a spatial property and does not directly measure driver behaviour, operating speed, vehicle dynamics, workload, or crash occurrence. The safety implications presented here should be interpreted as engineering interpretations of visibility structure.

Despite these limitations, the framework demonstrates that visibility along escarpment roads is shaped by the amount of visible terrain and by travel direction and changes in visibility continuity. By integrating visibility magnitude, directional asymmetry and transition intensity, the study provides a practical approach for analysing terrain-controlled visibility within complex road environments.

6. Conclusions

This study examined terrain-controlled visibility patterns along a 1.5 km escarpment section of the Mai Mahiu–Nairobi corridor within Kenya’s Great Rift Valley. Using a GIS-based viewshed framework, visibility was evaluated at 16 sequential observation points and analysed in relation to terrain morphology, roadway geometry, travel direction and visibility transitions. The approach combined visibility magnitude, directional visibility assessment and sequential visibility analysis to investigate how escarpment terrain structures the visual environment experienced along a major transportation corridor.

The results revealed substantial spatial variability in visibility throughout the corridor, with visibility ranging from 9.52% to 82.40% across the observation points. Terrain morphology emerged as the primary control on visibility structure, with convex escarpment-edge positions and exposed slopes generating extensive visual access, while concave landforms, cut slopes and terrain-enclosed sections produced severe visibility restriction. The corridor, therefore, functions as a terrain-conditioned visibility system characterised by alternating states of exposure and enclosure.

Directional analysis demonstrated that visibility is inherently asymmetric. Mean uphill visibility (44.4%) exceeded mean downhill visibility (34.9%), while the average Visibility Asymmetry Index (0.43) indicated moderate-to-high directional imbalance across the corridor. The findings show that opposing traffic movements frequently experience different visibility conditions despite occupying the same roadway alignment, highlighting the limitations of conventional non-directional visibility assessments. Downhill visibility was found to be particularly variable, combining some of the highest levels of visual exposure with some of the most restricted visibility conditions observed within the study area.

Sequential visibility analysis further showed that visibility along the escarpment is organised as a series of discrete exposure–enclosure states. Major visibility breakpoints were identified where the visible field expanded or contracted rapidly over short distances, demonstrating that visibility continuity is an important characteristic of the corridor environment. These transitions contribute to the scenic rhythm of the route and represent locations where the amount of visual information available to road users changes abruptly.

The study advances visibility assessment by demonstrating that escarpment road environments should be evaluated in terms of visible area and also through travel direction and sequential changes in line-of-sight continuity. By integrating visibility magnitude, directional asymmetry and transition intensity within a single analytical framework, the approach captures critical terrain-controlled characteristics that are overlooked by conventional static viewshed methods. The findings highlight the importance of treating visibility as a dynamic corridor property shaped by the interaction of terrain morphology, roadway geometry and movement, while providing a practical basis for identifying locations where terrain-induced constraints may warrant detailed investigation, monitoring, or targeted engineering intervention. Beyond its methodological contribution, the study also addresses a significant geographic gap in the literature by providing empirical evidence from an African escarpment transportation corridor, a context that remains substantially underrepresented in visibility research

Declaration of interests

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.

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