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# Archaeological Site Distribution in the Lalmai-Mainamati Region: A Least Cost Path Analysis

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**Abstract**

This study investigates the spatial distribution of archaeological sites in the Lalmai–Mainamati region of Bangladesh, which is on the UNESCO World Heritage Tentative List, using Least-Cost Path Analysis (LCP) within a GIS framework. Lalmai–Mainamati—identified with the ancient city of Devaparvata—flourished as a Buddhist cultural and economic centre under the Deva, Khadga, and Chandra kingdoms. Despite its extensive heritage, no previous research has systematically examined site distribution in the area. We implement LCP using slope, palaeochannels, water bodies, and Tobler's hiking function to model ancient mobility. The results indicate that many sites and structures lie within approximately 15 minutes' walking time of one another along least-cost routes, while others are more dispersed; we also assess the potential roles of riverine corridors and terrestrial paths. Overall, the study offers a replicable framework for spatial analysis in South Asian archaeology, particularly in Bangladesh.

**Keywords**

Lalmai-Mainamati or Devaparvata, GIS-based Least Cost Path Analysis (LCPA), Spatial Distribution, Computational Archaeology.

## 1. *Introduction*

Lalmai-Mainamati, the ancient city of Devaparvata, is a tentatively listed UNESCO World Heritage Site and served as a prominent cultural hub of early Samatata (Akmam, 2011, pp. 128–132; Alam, Keysar, & Amiruzzaman, 2021, pp. 93–103; "Archaeological Sites of Lalmai-Mainamati," n.d.; Huda, Khan & Sadequzzaman, 2021, pp. 683–689; Rashid, 2008). An inscription of Srichandra (929–975 CE) designates the region as the Lalambi forest, recognised for its medicinal herbs (Morrison, 1974, p. 135; *Pakistan Archaeology*, 1966, p. 31). Moreover, archaeological findings suggest a prehistoric habitation in the area (Chakrabarti, 2007, p. 3; Roy & Ahsan, 2004; Roy, 2009; Hazarika, 2013, p. 19, 2017; Badal, Sadequzzaman, & Khatun, 2024). The region thrived significantly under the Deva dynasty, while simultaneously being ruled by other dynasties (Islam, 2014, pp. 75–83; Rashid, 2021). Lalmai-Mainamati has developed as a prominent Buddhist cultural landscape, with more than 55 archaeological sites found till now (Ridoy, 2025, p. 34; Rashid & Husain, 2007, p. 32; Chakrabarti, 1992, pp. 122–123). Historical records underscore the significant influence of river systems on the region's settlement patterns and cultural development (Sircar, 1973, pp. 19–40). Husain (1997) asserts that the wealth of the region was maintained through agriculture and both domestic and international trade, establishing Samatata and Devaparvata as flourishing economic and cultural centres.

The abundant archaeological sites in this region suggest contemplation of the ancient lifestyle, religious customs, and social structures of its inhabitants. This region, abundant in archaeological heritage, has been the focus of numerous study initiatives such as the study of Abdullah et al. (2021); Alam (1982); Begum (2010); Chowdhury (1972); Husain, Rashid, Chowdhury, & Imamuddin (1997); Imam (2000); Khan (1963); Zakariah (2011, pp. 705–769) and others. Nonetheless, no existing study has concentrated on the computational distribution patterns of these places. The main aim of this research is to investigate the nature of these concealed patterns of the archaeological sites of the pre-medieval period (from the 7th century CE to before the 12th century CE). This inquiry is anticipated to yield additional and substantial insights into the settlement distribution of the area. To understand the distribution of archaeological sites, GIS-based Least Cost Path (LCP) analysis, a computational archaeological method, has been applied. Because GIS is frequently employed to analyse spatial relationships (Frachetti, 2006, p. 113).

As a sub-branch of Digital Archaeology, Computational Archaeology provides more sophisticated quantitative output. Ullah (2018) posits that the essence of Computational Archaeology should be comprehended in connection with the concept of computation rather than the use of computers. Lock (2003) demonstrates diverse uses of computers in archaeology in his writings. Roe (2019) asserts that Computational Archaeology (CA) use computers to derive insights into human history. This is an expanding area, with numerous notable studies addressing its potential, uncertainty, and sensitivity, such as the works of Barceló (2009); Bevan and Lake (2013); Burg et al. (2016), and others. Ullah (2018) categorises this into two primary forms of computation: Initially, there exist Analytical Computations and Generative Computations.

The utilisation of LCPA with GIS in archaeological studies in Bangladesh is still inadequately investigated. Nevertheless, analogous approaches have been effectively employed in South Asia and elsewhere, providing significant insights for forthcoming research in areas such as Lalmai-Mainamati. Rees (2021) utilised GIS-based LCP to analyse the location of Buddhist rock-cut monasteries in the Western Ghats, India, demonstrating their strategic proximity to trade routes and communities. This multidisciplinary study integrated archaeological surveys, epigraphy, and cost-surface analysis, demonstrating that although trade was a significant element, monastic expansion also depended on local socio-economic involvement. Bilotti et al. (2024) examined prehistoric mobility in the Western Mediterranean through the application of LCP and network modelling techniques. They created a friction surface that incorporates height, slope, and hydrological characteristics, merging terrestrial and maritime pathways. Their FETE (From Everywhere to Everywhere) model highlighted Sardinia and Gibraltar as crucial nodes. This approach could be tailored to the local Bangladeshi terrain by modifying friction parameters and datasets.

Waiyasusri et al. (2024) rebuilt Queen Cāmadevi's 6th–8th century aquatic expeditions in Thailand utilising Digital Elevation Models (DEMs), Normalised Difference Vegetation Index (NDVI), Normalised Difference Built-up Index (NDBI), and LCP, emphasising riverine connection, pertinent for examining waterway-induced spatial dynamics in Lalmai-Mainamati. Furthermore, Seifried & Gardner (2019) utilised eight LCP approaches to reconstruct historical pathways, determining that modified Tobler functions most accurately aligned with actual paths. Their research highlights the necessity of accounting for social and visible variables, especially in instances where historical paths lack documentation. Branting (2012) and Herzog (2014a) conducted a critical examination of methodological challenges in LCPA, highlighting the necessity of integrating cognitive behaviour, hybrid modelling, algorithm selection, and validation. The methodologies for Lalmai-Mainamati advocate the utilisation of diverse software (ArcGIS, Grass GIS, QGIS) and algorithms (Dijkstra, Tobler, Naismith, Knight Move), in conjunction with modifications.

Collectively, these investigations establish a methodological basis for the application of LCP analysis within Bangladesh archaeological contexts.

## 2. *LCPA Calculating Method*

LCPA is a recognised and efficient technique for determining cost-effective routes between two points (Amini, Mirbagheri, Matkan, & Alimohammadi, 2024). Due to its computational nature, it is essential to perform calculations utilising various parameters. The efficacy of the parameter directly impacts the precision of the findings achieved. In archaeology, LCP is a method utilised to model and rebuild possible historical transit routes by determining the most effective pathways over a landscape (Amini et al., 2024; Bilotti et al., 2024; Herzog, 2014a). This strategy relies on the premise that individuals will opt for the most convenient or least cost travel route, considering variables such as topography, altitude, vegetation, and water availability. It assists archaeologists in understanding human movement across a region by determining the most probable routes between established archaeological sites. This quantitative strategy, centred on geospatial analysis, aids archaeologists in acquiring a more thorough comprehension of prospective mobility patterns of persons throughout a landscape (White, 2015).

The core premise posits that individuals make mobility decisions as entirely rational agents possessing comprehensive information of their environment, aiming to minimise the costs associated with their trip from one area to another. The execution of LCPA is comparatively easier using desktop GIS software, whether commercial or open-source.

Nonetheless, this does not ensure that the output is entirely accurate. The quantity of LCP research in archaeology has surged significantly in recent years (Herzog, 2014b); however, not all methodologies utilised are based on a suitable model and execution. Many archaeologists employ standard GIS software with default settings (Herzog, 2014b). To achieve a more accurate computational result, it is essential to provide additional data, such as the water body and the walking timeline, with the slope derived from the DEM. Certain academics are additionally focused on employing Land Use and Land Cover as a variable. Several prominent software tools utilised for LCPA include Esri's ArcGIS (Rogers, Collet, & Lugon, 2015); QGIS, Grass GIS (Herzog, 2014b, p. 122); and R, among others. Isotropic and anisotropic LCPA represent the two primary kinds of LCPA commonly employed to comprehend historical cultures.

It requires compatible hardware and software, meticulously organised vector and raster datasets, and defined analytical parameters. Such as including study areas, archaeological sites, digital elevation models for slope computation, computational algorithms, and considerations of social or religious philosophy, etc. Proficiency in digital cartography is also crucial in this case. Subsequent to the creation of a cost surface, the following phase involves employing pathfinding algorithms to identify the least costly route for traversal. Edsger W. Dijkstra developed Dijkstra's algorithm in 1959. It is extensively utilised in GIS systems such as Esri's ArcGIS to determine the shortest path from a source node to all other nodes inside a network ("Edsger W. Dijkstra," n.d.).

The A* algorithm enhances this strategy by employing heuristics to prioritise nodes, hence increasing its efficiency. Naismith's Rule, established in 1892, employs distance and elevation gain to estimate the duration required to traverse a specific terrain. Waldo Tobler developed Tobler's Hiking Function, which calculates an individual's walking speed based on the gradient. The equation is $W = 6e^{-3.5|\frac{dh}{dx}+0.05|}$, $\frac{dh}{dx}$ = S = $\tan\theta$; Where, $W$ = walking velocity/speed [km/h], $dh$ = elevation difference, $dx$ = distance, S = slope, $\theta$ = angle of slope (inclination). It is frequently utilised in LCPA (Tobler, 1993). On the other hand, the Knight Move Algorithm transcends conventional movement models by employing knight movements from chess to navigate challenging terrain (Simon, 2013, pp. 449–459).

Here, Dijkstra and A algorithms offer conventional shortest-path solutions, whereas A* integrates heuristics to enhance efficiency. Naismith's Rule and Tobler's Hiking Function consider slope and elevation to estimate travel time, but the Knight Move Algorithm facilitates movement through complex or constrained terrain. As this study does not do a comprehensive quantitative analysis of algorithm performance, instead, it assesses the functional differences of each strategy to ensure suitable application based on the landscape and mobility features of the Lalmai-Mainamati region.

Preparing all the parameters is the preliminary stage in determining the least cost in the study region. Subsequently, it will utilise Esri's ArcGIS, QGIS and GRASS GIS platforms. Also, the result and the completed analysis will be presented.

### 2.1. Determined Parameters

As LCPA identifies optimal routes across a landscape by reducing travel costs based on specified criteria. Here, five parameters, a. Slope from DEM, b. River (Khiroda's paleochannels) as the communication way, c. Reservoir/pond/water tank as the obstacle, d. Water stream as the obstacle, e. Tobler's Hypothesis (Tobler Hiking Function), has been evaluated for the study region.

#### 2.1.1. Slope From DEM

The slope of land denotes the inclination or gradient of its surface. It is a crucial factor to consider when developing land or planning its use. The computation entails ascertaining the rate of variation in the height of a surface between a central cell and its neighbouring cells. It may be expressed in degrees or as a percentage. LCPA must calculate the slope in degrees to generate the cost surface or friction cost. The value entered for slope calculation is displayed in Table 1.

Subsequently, the slope has been reclassified into nine categories (Table 2, Figure 1.i).

**Table 1:** Slope generating parameter

| Parameter | Value |
|---|---|
| Input raster | Mask_DEM.tif (GeoTIF) |
| Output measurement | DEGREE |
| Z factor | 1 |
| Method | PLANAR |
| Z unit | METER |

**Table 2:** Slope reclassification parameters

| Range Start | Range End | Reclassified Value |
|---|---|---|
| 0 | 1.139226 | 1 |
| 1.139226 | 1.967864 | 2 |
| 1.967864 | 2.736123 | 3 |
| 2.736123 | 3.584252 | 4 |
| 3.584252 | 4.582315 | 5 |
| 4.582315 | 6.063765 | 6 |
| 6.063765 | 8.186160 | 7 |
| 8.186160 | 11.804834 | 8 |
| 11.804834 | 27.092813 | 9 |

### *2.1.1.1. SRTM 30m DEM for Slope Creation*

The Digital Elevation Model (DEM) employed for the analysis of the study region is SRTMIN23E091V3. The study area has experienced significant disturbance owing to human habitation, and the DEM provided by USGS is the sole viable alternative for this region. Herzog (2014b) in a study, identifies the slope employed for LCPA by most researchers. She elaborated that several other significant aspects must be taken into account.

A rapid increase was witnessed following the establishment of Comilla University in 2006. Prior to it, the rate was rather low. A recent study indicates that in 2023, the anthropogenic structure expanded to 17.11 sq km in the studied area, compared to a negligible extent in 2000 (Ridoy, 2023, p. 51). Majumder (2023) concentrated on the recent rapid land use and land cover changes in the Lalmai-Mainamati region in her study. Here, the DEM from the year 2000 was utilised due to the absence of the DEM in the study area for earlier years.

### *2.1.2. Waterways*

Waterways, including rivers and ponds, profoundly impacted ancient transportation and spatial configurations, making them essential to LCPA in archaeology. Ponds supplied vital water supplies and obstructed direct pathways, but rivers typically served as natural corridors that enhanced trade, communication, and transportation. Hydrological data, encompassing river networks and water bodies, are mapped for LCPA to assess their influence on cost surfaces.

Moreover, rivers may function as barriers necessitating diversions, or they may lower transportation costs by providing navigable pathways, contingent upon the context. The delineation of aquatic bodies commences with the river, followed by the ponds and water streams. This will aid in achieving a comprehensive understanding of the waterways in our study region and will be employed in the development of the friction layer of LCPA.2.1.2.1. Reclassifying the Probable Paleochannel

It is important to note that all the raster layers (parameters) must be reclassified for LCPA calculation. Actually, reclassification is a common GIS methodology that transforms complex raster data into a standardised cost surface that the algorithm uses to compute movement trajectories. Here, all the vector polylines of the potential paleochannels, from a recent study of Ridoy (2025), have been amalgamated into a singular vector (.shp) polygon designated as Surrounded Water Channels. This has since been transformed into the raster format GEOTIF (.tif) and classified into two categories. 1 denotes the primary water (paleochannel) region, whereas 2 signifies the periphery of the expanded study area (Table 3).

This approach efficiently transformed the dataset into an easier binary classification, emphasising only the pertinent features. Missing or undefined values were replaced with NoData to prevent interference in the spatial analysis. After reclassification, the output raster (Surrounded Water Channels) consequently yielded a standardised layer and similar to the paleochannels raster data, the other water-based parameters have also been reclassified.

**Table 3:** Reclassification value of all probable paleochannels

| Attribute | Value |
|---|---|
| Input Raster | Surrounded_Water_Channels_union_raster.tif |
| Output Raster | Surrounded_Water_Channels_union_raster_reclass.tif |
| Reclass Field | Value |

| | |
|---|---|
| Reclassification | 0 as 1<br>2 as 2 |
| Change Missing Values to NoData | DATA |

### *2.1.2.2. Reclassifying the Reservoirs Data*

Reservoirs and water tanks are either impermeable or challenging to shift. Aquatic formations induce detours, resulting in increased travel costs. Integrating these elements into the cost surface improves terrain modelling by precisely depicting mobility restrictions. Their existence may indicate regions where energy-intensive bypassing takes place, affecting route selection. LCPA emulates natural restrictions by assigning elevated difficulty ratings to these structures, hence enhancing precise route planning through complex terrains. This method improves the precision and pertinence of analysis. This analysis identifies all the oldest ponds and water tanks, from Ridoy (2025), in the area as impediments to calculating LCPA. Following the aforementioned reclassification process, this data has also been reclassified (Table 4).

**Table 4:** Reclassification value of the water tank shapefile

| Attribute | Value |
|---|---|
| Input Raster | Reservoir_Dissolve_Union_raster.tif |
| Output Raster | Reservoir_Dissolve_Union_raster_reclass.tif |
| Reclass Field | Value |
| Reclassification | 0 as 1<br>1 as 2 |
| Change Missing Values to NoData | DATA |

### *2.1.2.3. Reclassifying all the Water Streams*

Water streams can be frequently considered obstacles in LCPA, particularly when their flow, depth, or width hinders mobility. These natural features result in crossings, which increase travel costs and influence route selections. Streams may be assigned elevated resistance values to signify the energy or resources needed for traversal around or over them. Integrating water streams as obstacles in LCPA enhances modelling precision, as they function as natural impediments to direct flow. This parameter facilitates the identification of feasible pathways while accounting for the constraints imposed by hydrological parameters in the study area. It is noteworthy that certain ponds are situated within the watercourse observed during the field visit.

Nevertheless, the literature contains no information concerning the water stream in the study area, commonly known as *Khari* or *Jala*. Following the execution of multiple field surveys utilising a GPS device to gather data and delineate the area as a shapefile. This summary Table 5 of consolidated or eliminated water streams. Nevertheless, a comprehensive long-term field study will be essential to record the intricate details. Similar to the data from the water tank or paleochannel, this has also been reclassified (Table 6) to provide the aggregated friction cost.

**Table 5:** Combined data of the water stream

| Name | Area(m2) |
|---|---|
| Water Stream | 3113666 |

**Table 6:** Reclassification value of the water stream

| Attribute | Value |
|---|---|
| Input Raster | WaterStream_Khari_Clipped_Union_raster.tif |
| Output Raster | WaterStream_Khari_Clipped_Union_raster_reclass.tif |
| Reclass Field | Value |
| Reclassification | 0 as 1, 1 as 2 |
| Change Missing Values to NoData | DATA |

## *2.2. Calculating The LCPA*

Upon the preparation of all parameters, it is time to calculate and visualise the cost distance path. However, before this, it is essential to finalise various other procedures, including the formulation of aggregated charges and the support of raster data, among others.

### *2.2.1. Creating Cost Surface*

In Esri's ArcGIS, the weighted overlay tool facilitates the uncomplicated creation of a composite cost surface (Figure 1.ii). The

Table **7** summarises the weighting of all parameters.

**Table 7:** Weighted overlay value

| Raster | % Influence | Field | Scale Value |
|---|---|---|---|
| Slope | 50 | Value | |

| | | | |
|---|---|---|---|
| | | 1 | 1 |
| | | 2 | 2 |
| | | 3 | 3 |
| | | 4 | 4 |
| | | 5 | 5 |
| | | 6 | 6 |
| | | 7 | 7 |
| | | 8 | 8 |
| | | 9 | 9 |
| | | NODATA | NODATA |
| Surrounded Water Channels | 35 | Value | |
| | | 1 | 10 |
| | | 2 | 4 |
| | | NODATA | NODATA |
| Reservoir | 5 | Value | |
| | | 1 | 10 |
| | | 2 | Restricted |
| | | NODATA | NODATA |
| Water Stream | 10 | Value | |
| | | 1 | 10 |
| | | 2 | Restricted |
| | | NODATA | NODATA |
| Total Influence (%) | 100 | | |

It is important to mention that the percentage influence attributed to each layer was determined using empirical data and field observations focusing on the analytical necessities of weighted overlay analysis. The slope received the highest weight (50%) since the steep terrain of the Lalmai-Mainamati region poses the principal constraint for movement and development. Paleochannels, comprising 35%, were designated secondary significance due to their function as barriers and potential aquatic pathways in the pre-medieval era. Reservoirs (5%) and streams (10%) were assigned lesser weights, as they constitute localised barriers but have a diminished impact on the wider environment. The description is provided in the sections 2.2.1.1 to 4.

The weighted overlay analysis amalgamates various raster layers to produce a cohesive cost surface, with each layer imparting a designated percentage of influence according to its significance. This methodology provides a fair assessment of the elements influencing movement or growth within the research domain. The investigated parameters encompass slope, neighbouring water channels, reservoirs, and water streams, each having distinct influence and cost scale values.

#### *2.2.1.1. Slope (Influence: 50%)*

The slope layer is an essential element, important for the Lalmai-Mainamati research region. Due to its mountainous terrain, the elevation exceeds 250 feet above sea level. The fifty per cent influence has adversely affected the overall weight. The slope values range from 1 to 9, with each numeral representing a certain terrain type, where elevated values indicate steeper areas. Steeper gradients lead to increased costs or challenges for movement or building, signifying that terrain steepness is the principal limitation in this assessment.

#### *2.2.1.2. Surrounded Khiroda Paleochannels (Influence: 35%)*

This layer exerts the second-greatest influence in the analysis. Regions designated with a value of 1 are allocated a high scale value of 10. The value of 1 denotes the non-aquatic region of the raster, which was automatically produced following the union of the paleochannels vector with the vector of the expanded research area. The non-water area is allocated a high value of 10 when the maximum slope cost value is 9. This is to ensure that the non-aqueous region is disregarded as a communication pathway. In contrast, places designated with a value of 2, mainly the waterbody or paleochannel zones, are considered less restrictive. A scale value of 4 indicates a moderate effect on mobility or appropriateness. The value 4 was designated due to the recognition that travelling by boat is more arduous than by road, specifically for very short distances. However, during the pre-medieval period, it was perhaps the most rudimentary method of long-distance communication due to the lack of a modern transportation system.

#### *2.2.1.3. Reservoir/Water Tank (Influence: 5%)*

The reservoir layer exerts a minimal influence, yet it aids in the analysis. Consistent with the preceding non-reservoir area, area 1 was designated a value of 10. The water area, field value 2, was classified as restricted due to its designation as an impediment. These are the regions that are neither accessible nor suitable for mobility. The non-reservoir area was allocated a high cost of 10, as it is essential to assign a value in ArcGIS; otherwise, the combined cost surface will not be accurately generated.

### *2.2.1.4. Water Streams (Influence: 10%)*

The existence of water streams exerts a moderate influence on the overall surface cost. Non-stream regions designated with a value of 1 are allocated a high scale value of 10, signifying that they should not be regarded as walking routes. Value 2 (primary water stream area) is designated as 'Restricted', indicating its function as an impediment to movement or access.

This weighted overlay analysis generates a comprehensive cost surface that incorporates

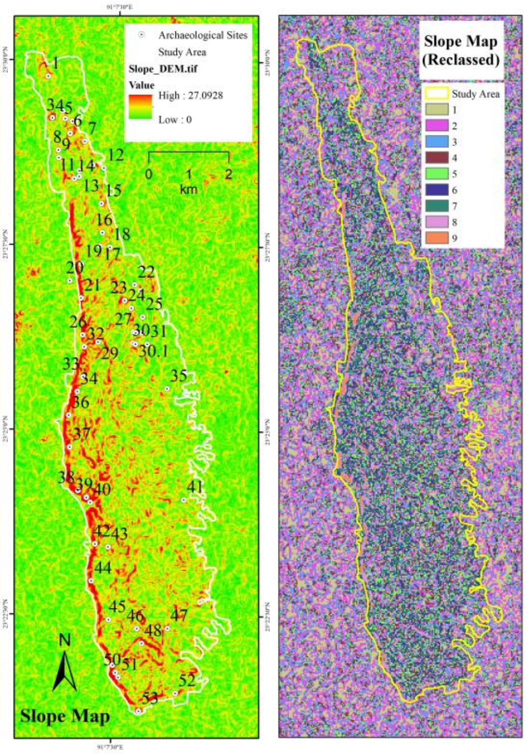


**Figure 1**.i

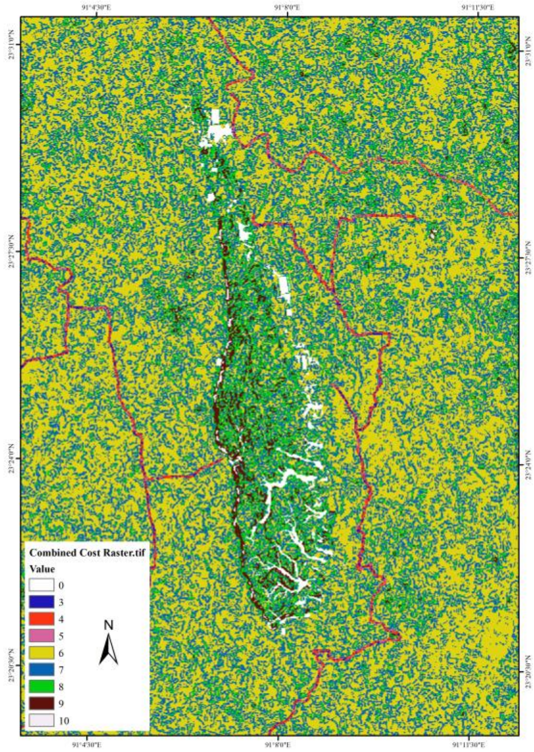


**Figure 1**.ii

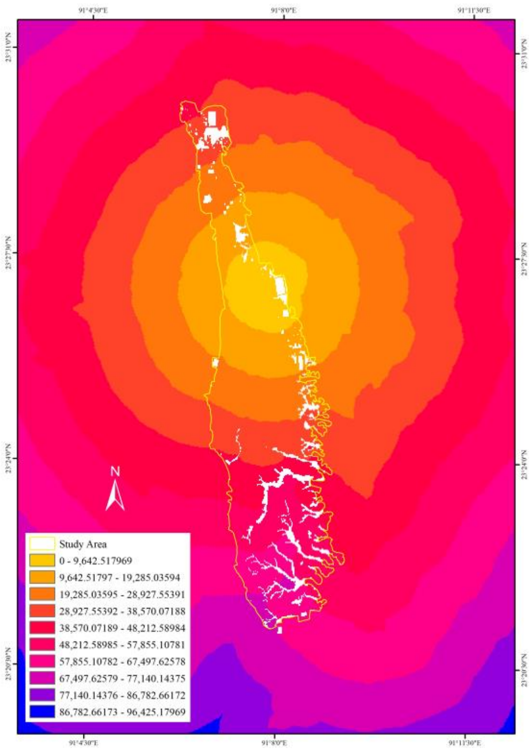


**Figure 1**.iii

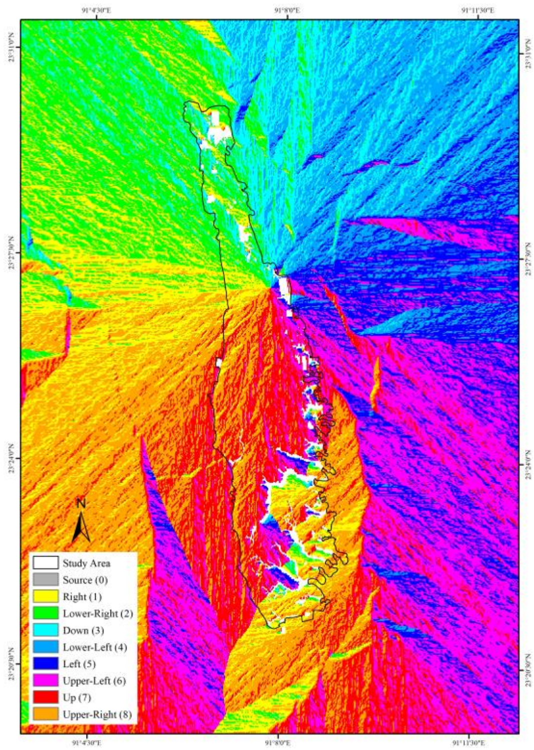


**Figure 1**.iv

**Figure 1: i.** Slope before and after reclassification, ii. Combine cost raster, iii. Distance raster, iv. Backlink raster

variables such as topography gradient, proximity to water bodies, and impediments like reservoirs and streams. The slope layer is the principal element of the analysis, with adjacent water paleochannels being of secondary relevance, while reservoirs and water streams possess minimal value.

### *2.2.2. Cost Raster, Distance Raster and Backlink Raster*

Upon completion of the aforementioned weighted overlay, the integrated cost raster has been generated (Figure 1.ii). The distance raster, in LCPA it is a raster layer that illustrates the cumulative cost from a source to each cell in the landscape, signifying the most cost-effective way for traversal, (Figure 1.iii) was subsequently generated to focus on the location of Ananda *Vihara,* the largest *vihara* in the Lalmai-Mainamati region. The backlink raster, in LCPA that mainly indicates the optimal direction to return to the source via the most efficient route, (Figure 1.iv) was ultimately produced, focusing on the same place as the last stage of the LCPA computation.

So, the Cost Raster indicates the ease or difficulty of traversing the landscape. Consequently, the model generates a Distance Raster that illustrates the cumulative travel cost from the origin to all other destinations. The Backlink Raster thereafter documents the direction to traverse from each cell towards the source via the most efficient path. Collectively, these essential rasters enable the model to delineate the most efficient route between two locations.

## *3. Output of the Least Cost Path Analysis*

Upon completion of all processes, the resultant cost polyline, together with the associated attribute data, was generated. This is illustrated in Figure 2 and Table 8. In the data table, Dist. (km) represents the distance of each site from Ananda Buddhist Monastery Complex (ABMC), Dist. (h) indicates the distance in km/h from Ananda *Vihara* according to the Tobler hiking function, and Dist. (m) denotes the corresponding value in meters of the previous measurement. The range between ID 1-2... and so on (km) pertains to the distance between the objects (OBJ). ID 1 to 2 denotes the distance from the Palace of Queen Mainamati to Banyan Tree Mound, applicable in its entirety; conversely, (+) Dist. Between ID 1-2.......so on (km) is merely the positive value of the preceding entry, as Excel computed it using the specified formula (OBJ. ID 1-2). Consequently, when the prior value is substantial, the resulting figure seems negative. KM/H (according to the Tobler Function) represents the value of walking distance in km/h from OBJ. ID 1-2. The last Dist. In minutes (ID 1-2 and so on…) show the walking distance (OBJ. ID 1-2/2-3/3-4………) in minutes.

It is noted that, due to the water stream's raster pixel resolution and the geographical location of a specific site, which is located in a water stream, the cost path for two out of fifty-six sites could not be calculated. And these two sites are 40. Valley Site below Madina Mound and 16. Mainamati Mound 2A. The first limitation identified for the 'Valley Site below Madina Mound' in this study is due to the pixel size (30-meter resolution) of raster data.

Although vector shapefiles accurately represented the water streams, their conversion to raster format resulted in an alignment issue. Specifically, one location of the archaeological site was set into at the intersection of a corner of raster pixel of the water stream, which had been classed as an obstacle. The pixel was omitted from the cost surface, hence obstructing the computation of cost distance for that location. On the other hand, the site location of Mainamati Mound 2A is situated in a water stream.

The establishment of the site probably occurred during a later period when the stream had dried up. Although further archaeological study is required here.

**Table 8:** Result of the combined least cost path analysis with statistical calculation of 15-minute walking distance

| OBJ. ID | From | To (SL No., Name) | Dist. (km) | Dist. (h) | Dist. (m) | Dist. Between ID 1-2.......so on (km) | (+) Dist. Between ID 1-2.......so | KM/H (according to the Tobler Function) | Dist. in munities (ID 1-2 and so on....) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | ABMC | 1. Palace of Queen Mainamati | 6.19 | 1.23 | 74 | | | | |

| | | | | | | | on (km) | | |
|---|---|---|---|---|---|---|---|---|---|
| 2 | ABMC | 2. Banyan Tree Mound | 5.21 | 1.03 | 62 | 0.98 | 0.98 | 0.19 | 11.7 |
| 3 | ABMC | 3. Mainamati Mound 1 | 5.19 | 1.03 | 62 | 0.02 | 0.02 | 0.00 | 0.2 |
| 4 | ABMC | 4. National Cemetery Mound | 5.07 | 1.01 | 60 | 0.12 | 0.12 | 0.02 | 1.4 |
| 5 | ABMC | 5. Gab Tree Mound | 4.8 | 0.95 | 57 | 0.27 | 0.27 | 0.05 | 3.2 |
| 6 | ABMC | 6. Army Bungalow Mound | 4.52 | 0.9 | 54 | 0.28 | 0.28 | 0.06 | 3.3 |
| 7 | ABMC | 7. Mainamati Mound 1A | 4.16 | 0.83 | 50 | 0.36 | 0.36 | 0.07 | 4.3 |
| 8 | ABMC | 8. Singara Mound | 4.31 | 0.86 | 51 | -0.15 | 0.15 | 0.03 | 1.8 |
| 9 | ABMC | 9. Officer Bungalow Mound | 4.21 | 0.84 | 50 | 0.1 | 0.1 | 0.02 | 1.2 |
| 10 | ABMC | 10. Mainamati Mound 1B | 3.48 | 0.69 | 41 | 0.73 | 0.73 | 0.14 | 8.7 |
| 11 | ABMC | 12. Abbas Ali Mound | 3.3 | 0.66 | 39 | 0.18 | 0.18 | 0.04 | 2.1 |
| 12 | ABMC | 11. Chulla Mound | 3.59 | 0.71 | 43 | -0.29 | 0.29 | 0.06 | 3.5 |
| 13 | ABMC | 13. Charpatra Mound | 3.51 | 0.7 | 42 | 0.08 | 0.08 | 0.02 | 1.0 |
| 14 | ABMC | 14. Fakir Mound | 3.61 | 0.72 | 43 | -0.1 | 0.1 | 0.02 | 1.2 |
| 15 | ABMC | 15. Mainamai Mound 2 | 2.52 | 0.5 | 30 | 1.09 | 1.09 | 0.22 | 13.0 |
| 16 | ABMC | 17. Boiragi Mound I | 1.36 | 0.27 | 16 | 1.16 | 1.16 | 0.23 | 13.8 |
| 17 | ABMC | 18. Kotila Mound | 1.21 | 0.24 | 14 | 0.15 | 0.15 | 0.03 | 1.8 |
| 18 | ABMC | 19. Borogach Mound | 1.54 | 0.31 | 18 | -0.33 | 0.33 | 0.07 | 3.9 |
| 19 | ABMC | 20. Southwest Foot of Borogach Mound | 1.69 | 0.34 | 20 | -0.15 | 0.15 | 0.03 | 1.8 |
| 20 | ABMC | 22. ABMC | 0 | 0 | 0 | 1.69 | 1.69 | 0.34 | 20.1 |
| 21 | ABMC | 22.1. South of Ananda Vihara | 0.21 | 0.04 | 3 | -0.21 | 0.21 | 0.04 | 2.5 |
| 22 | ABMC | 21. Niranjan Mound | 1.44 | 0.29 | 17 | -1.23 | 1.23 | 0.24 | 14.6 |
| 23 | ABMC | 23. Rupban Kanya's Monastery | 0.46 | 0.09 | 5 | 0.98 | 0.98 | 0.19 | 11.7 |
| 24 | ABMC | 24. Hilltop Sites West of Bhoj Monastery | 0.59 | 0.12 | 7 | -0.13 | 0.13 | 0.03 | 1.5 |
| 25 | ABMC | 25. Bhoj Monastery | 0.87 | 0.17 | 10 | -0.28 | 0.28 | 0.06 | 3.3 |
| 26 | ABMC | Big Itakhula Mound | 1.23 | 0.24 | 15 | -0.36 | 0.36 | 0.07 | 4.3 |
| 27 | ABMC | 27.1. Eastern Foot of Big Itkhola Mound | 1.24 | 0.25 | 15 | -0.01 | 0.01 | 0.00 | 0.1 |
| 28 | ABMC | 28. Latikot Monastery | 1.29 | 0.26 | 15 | -0.05 | 0.05 | 0.01 | 0.6 |
| 29 | ABMC | 26. Khachar Mound | 1.9 | 0.38 | 23 | -0.61 | 0.61 | 0.12 | 7.3 |
| 30 | ABMC | 29. Kotbari Monastery | 1.87 | 0.37 | 22 | 0.03 | 0.03 | 0.01 | 0.4 |
| 31 | ABMC | 30. Rupban Mound | 1.53 | 0.3 | 18 | 0.34 | 0.34 | 0.07 | 4.0 |
| 32 | ABMC | 30.1. Rupban Mound Hall | 1.53 | 0.3 | 18 | 0 | 0 | 0.00 | 0.0 |
| 33 | ABMC | 31. BARD's Artefact Finding Spot | 1.61 | 0.32 | 19 | -0.08 | 0.08 | 0.02 | 1.0 |
| 34 | ABMC | 32. Hatigara Mound | 2.17 | 0.43 | 26 | -0.56 | 0.56 | 0.11 | 6.7 |
| 35 | ABMC | 33. Ujirpur Mound | 2.8 | 0.56 | 33 | -0.63 | 0.63 | 0.13 | 7.5 |
| 36 | ABMC | 35. Salban Buddhist Monastery | 2.92 | 0.58 | 35 | -0.12 | 0.12 | 0.02 | 1.4 |
| 37 | ABMC | 34. Dhan Mound | 3.22 | 0.64 | 38 | -0.3 | 0.3 | 0.06 | 3.6 |
| 38 | ABMC | 36. Pakka Mound | 3.91 | 0.78 | 47 | -0.69 | 0.69 | 0.14 | 8.2 |
| 39 | ABMC | 37. Hugni Mound | 4.71 | 0.93 | 56 | -0.8 | 0.8 | 0.16 | 9.5 |
| 40 | ABMC | 38. Adina Mound | 5.71 | 1.13 | 68 | -1 | 1 | 0.20 | 11.9 |
| 41 | ABMC | 39. Madina Mound | 5.78 | 1.15 | 69 | -0.07 | 0.07 | 0.01 | 0.8 |
| 42 | ABMC | 41. Chila/Ghila Mound | 5.9 | 1.17 | 70 | -0.12 | 0.12 | 0.02 | 1.4 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 43 | ABMC | 42. Little Itakhola Mound | 7.02 | 1.39 | 84 | -1.12 | 1.12 | 0.22 | 13.3 |
| 44 | ABMC | 43. Sabura/Bokshi Mound | 6.94 | 1.38 | 83 | 0.08 | 0.08 | 0.02 | 1.0 |
| 45 | ABMC | 44. Rupbani Mound | 7.95 | 1.58 | 95 | -1.01 | 1.01 | 0.20 | 12.0 |
| 46 | ABMC | 45. Arjunakhola Mound | 8.8 | 1.75 | 105 | -0.85 | 0.85 | 0.17 | 10.1 |
| 47 | ABMC | 46. Colonel Mound | 9.13 | 1.81 | 109 | -0.33 | 0.33 | 0.07 | 3.9 |
| 48 | ABMC | 47. Balagazi Mound | 11.49 | 2.28 | 137 | -2.36 | 2.36 | 0.47 | 28.1 |
| 49 | ABMC | 48. Takka Mound | 9.72 | 1.93 | 116 | 1.77 | 1.77 | 0.35 | 21.1 |
| 50 | ABMC | 49. Kalidas Mound | 9.95 | 1.97 | 118 | -0.23 | 0.23 | 0.05 | 2.7 |
| 51 | ABMC | 50. West Foot of Minarkhil Mound | 10.13 | 2.01 | 121 | -0.18 | 0.18 | 0.04 | 2.1 |
| 52 | ABMC | 51. Bairagi Mound II | 10.29 | 2.04 | 122 | -0.16 | 0.16 | 0.03 | 1.9 |
| 53 | ABMC | 52. Lalmai Mound 1 | 12.68 | 2.52 | 151 | -2.39 | 2.39 | 0.47 | 28.5 |
| 54 | ABMC | 53. Chandi Mound Complex | 13.84 | 2.75 | 165 | -1.16 | 1.16 | 0.23 | 13.8 |

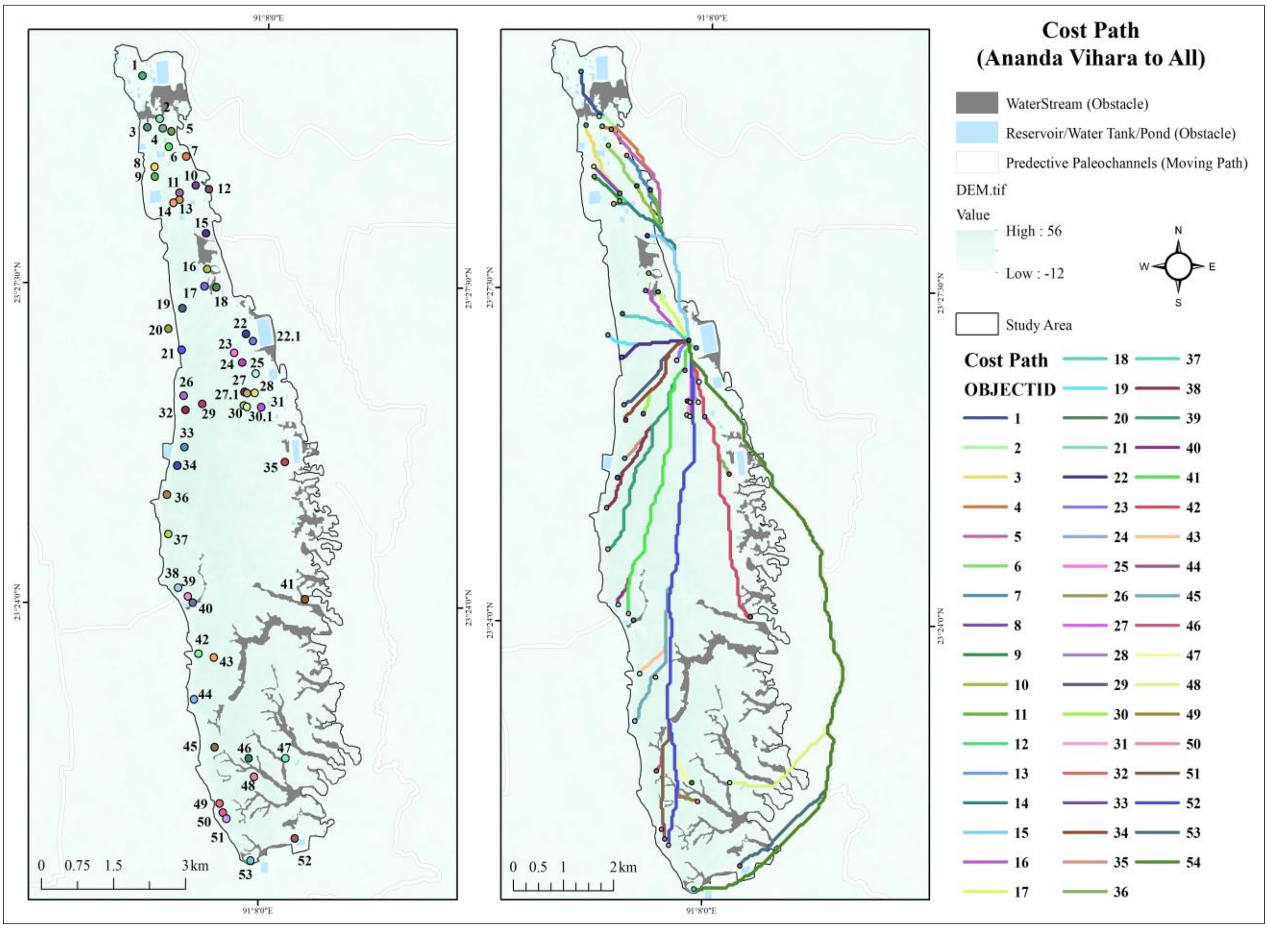


**Figure 2:** Cost path (Ananda *Vihara* to all sites)

## 4. *Analysis*

The Ananda Buddhist Monastery Complex is a pivotal site for investigating the historical and archaeological importance of the Mainamati region because, according to Ridoy (2025), it is situated as the central monument of the Devaparvata. This analysis section will evaluate the distances and journey durations to proximate locations, emphasising their accessibility and significance.

### *4.1. Nearby Sites (0-2 Km)*

A multitude of historically significant sites are reachable within a 2-km radius. The closest spot, located south of Ananda *Vihara*, is merely 0.21 km apart, requiring a short 3-minute walk. The

Rupban Kanya Monastery is located 0.46 km distant and is accessible in roughly 5 minutes. It functions as a crucial supplementary location. Likewise, the Hilltop Sites situated west of Bhoj Monastery and Bhoj Monastery itself, which are 0.59 and 0.87 km away respectively, provide significant insights into the interrelations of the religious edifices. Moreover, Big Itakhula Mound, the Eastern Foot of Big Itkhola Mound, and Latikot Monastery are situated within a distance of 1.2 to 1.3 km and can be accessed in roughly 15 minutes, underscoring the region's organised configuration of religious and residential zones. Figure 3 is representing nearby, short-distance, moderate-distance, and long-distance sites.

### *4.2. Short-Distance Sites (2-5 Km)*

The locations located within 2 to 5 kilometres exemplify the broader spatial patterns and cultural significance of this region. The Salban Buddhist Monastery is an important location, located 2.92 km distant. This site is acknowledged as one of the most significant and well-conserved archaeological sites in the region, with an estimated journey duration of 35 minutes to reach it. Hatigara Mound is situated 2.17 km away and necessitates 26 minutes for access. Other notable sites, such as Abbas Ali Mound, Chulla Mound, and Pakka Mound, situated within this area, augment the understanding of spatial patterns and the evolution of religious activities in the region.

### *4.3. Moderate Distance Sites (5-10 Km)*

Sites located 5 to 10 kilometres from the Ananda Buddhist Monastery Complex offer insights into the historical evolution of Buddhism in the region. The Palace of Queen Mainamati is situated 6.19 kilometres distant and takes 74 minutes to arrive. Adina and Madina Mounds are located roughly 5.7 to 5.8 km away and can be reached in approximately 70 minutes. They provide significant insights into the diverse cultural and religious dynamics of the region. Sabura/Bokshi Mound, situated 6.94 km distant, takes around 83 minutes to reach.

### *4.4. Long-Distance Sites (10+ Km)*

Locations exceeding 10 km from the Ananda Buddhist Monastery Complex delineate the peripheral boundaries of the region's historical geography. Colonel Mound is located 9.13 km away and necessitates 109 minutes for access, signifying its prominence yet remoteness. Balagazi Mound, situated 11.49 km distant, has a walk duration of 137 minutes and exemplifies the extensive spread of archaeological features in the area. The Chandi Mound Complex, the farthest site analysed, is situated 13.84 km away and requires 165 minutes of travel, making it a significant yet challenging location to reach.

### *4.5. Accessible Connectivity's 15 Minutes Walking Distance Standard*

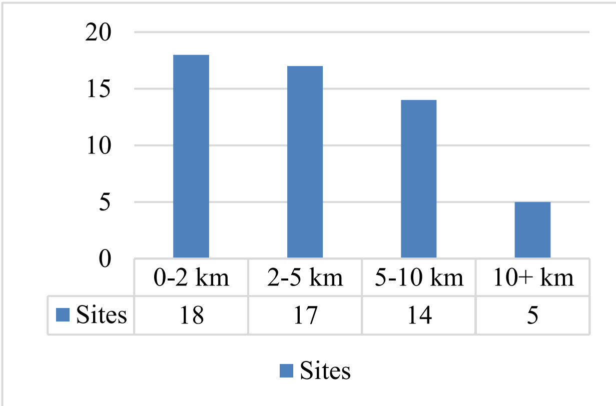


**Figure 3:** Sites quantification; based on LCPA cost path distance from Ananda *Vihara*

Examining Table 8, the final column titled 'Dist. In minutes' (ID 1-2, etc.) reveals that the distance to each site, from north to south, is primarily within a 15-minute walking range, based on the calculated least cost route from Ananda *Vihara* to all locations, except four sites (OBJ. ID 20, 48, 49, 53). In the ancient period, the people attempted to construct their settlement houses within a 15-minute walking distance of one another; it is a standard walking distance concept that is accepted all over the world (Caselli, 2021; Caselli et al., 2022; Zhang et al., 2023). Nazneen and Huda (2024) also discussed this topic.

It has been identified a pattern that indicates the application of accessible connectivity in the Lalmai Mainamati region. A matter to address in order to arrive at Balagazi Mound, Lalmai Mound 1, and the Chandi Mound Complex from the previously referenced site in Table 8. Both the river and land-based routes have been utilised. Through using a 30m resolution DEM, we identified some inaccuracies in the calculations, including the distance from Salban Buddhist Monastery to Dhan Mound; however, the overall accuracy rate is judged to be satisfactory.

*4.6. River-Based Communication*

Analysing Figure 2, the most cost-effective route from Ananda *Vihara* to Lalmai Mound 1 and Chandi Mound is through the waterway, particularly the anticipated Khiroda River's paleochannel. This suggests that accessing the location by water is simpler than by road. The layout and organisation of these sites demonstrate a systematic network of monasteries, towns, and mounds designed for interconnection and shared religious practices. Areas within a 2-kilometre radius are the most accessible, with walking being the most feasible option. Locations within a 5-kilometre radius are reasonably accessible, while those at further distances may require additional planning and effort.

It may be concluded that for long-distance travel beyond 12 kilometres (>12km), people of that era likely utilised river-based transportation. Because walking will require approximately 151 minutes or 2.52 hours to traverse the 12.68 km distance from Ananda *Vihara* to Lalmai Mound 1 (Table 8). In ancient times, people travelled on foot along land routes (Ahmed, 2023, p. 78). The Lalmai-Mainamati region, being encircled by channels, facilitated navigation through the waterway. The accessibility of transportation is believed to have facilitated the advancement of Buddhist architectural edifices in this area. Ahmed (2023) indicates that in the realm of water transport, numerous vessels, including Vela, Dingi, Dishi, and Dongga boats, were employed, as evidenced by terracotta plaques found at archaeological sites. Evidence suggests the use of ox carts for land transportation. Moreover, elephants and horses were employed for transporting purposes. The kings utilised elephants and horses for transportation alongside their armies.

*4.7. Land-Based Communication*

For distances likely under 12 km (<12km) from the destination, they utilise land-based communication methods. Figure 2 and the output data in Table 8 indicate that for distances over 12 km (from Ananda *Vihara* to Lalmai Mound 1 and Chandi Mound), people utilised the water-based route. However, at a distance of 12 km, the data and map indicate land-based communication according to the Tobler walking function (5.04 km/h).

In literature, it is mentioned that King Balabahtra constructed an exquisite royal pathway and gardens within the city. According to Rashid (2015), the capital city of Devaparvata had the magnificent palace of King Balabhadra in Kakatshila, from whence the Mainamati Copperplate Inscription was promulgated. This inscription provides a comprehensive account of Devaparvata and its river, Khiroda. The capital was augmented by the establishment of a royal highway *(Rajpath)*, enhancing its overall grandeur, in conjunction with other architectural endeavours. It indicates that Devaparvata ought to possess an exquisite royal road within it, necessitating further investigation to ascertain the way of the route.

*4.8. Water Stream Sideway as Land-Based Communication*

Fieldwork observations indicate that the existing land-based communication in the hilly region is situated near the water streams, locally known as *Khari* or *Jala*. Upon examining the LCPA data, it was verified that the trajectory from Ananda *Vihara* Road No. 49 towards Takka Mound is comparatively congruent with the water streams. Certain authors, including Herzog

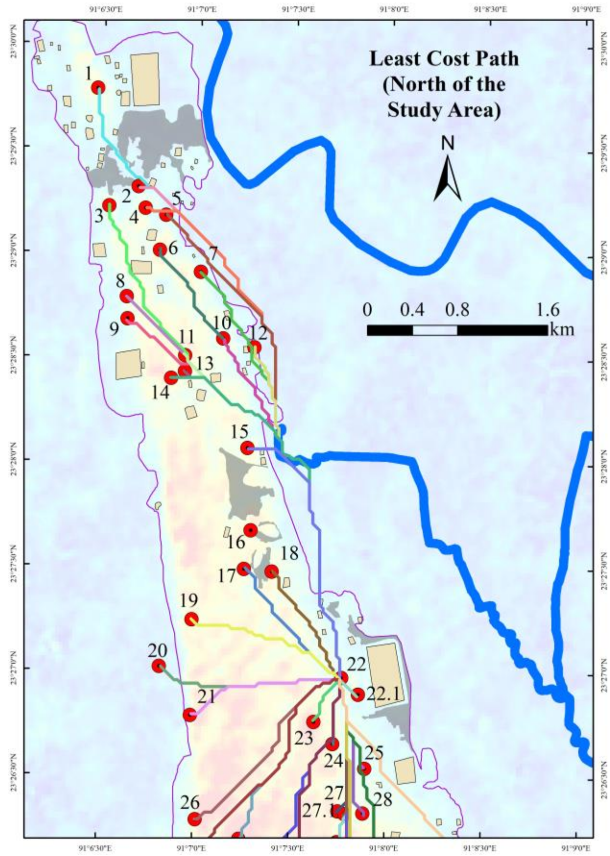


**Figure 4.**i

(2014b), do not rely solely on slope for the LCPA computation. Nevertheless, due to the mountainous terrain, it is essential to consider slope as a component. Figure 4.i-4.iv illustrates the

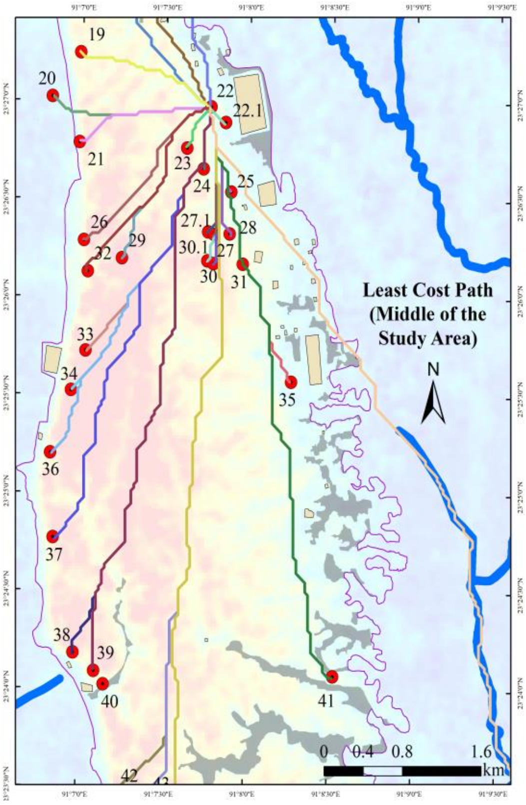


**Figure 4**.ii

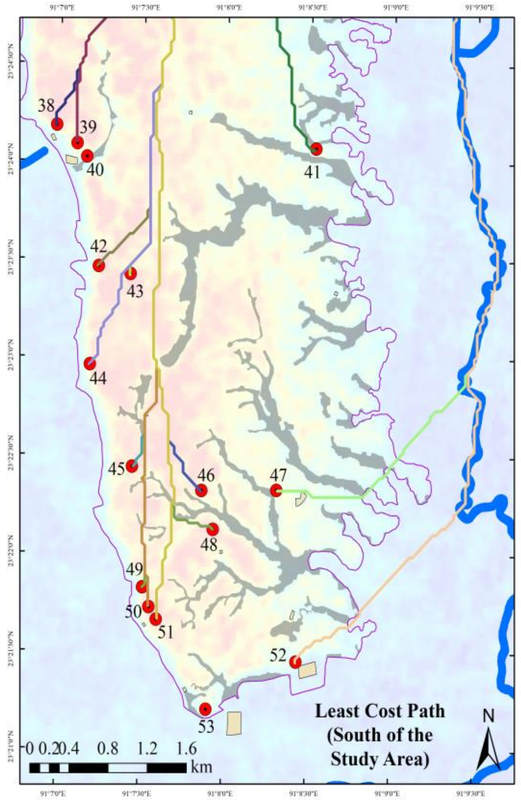


**Figure 4**.iii

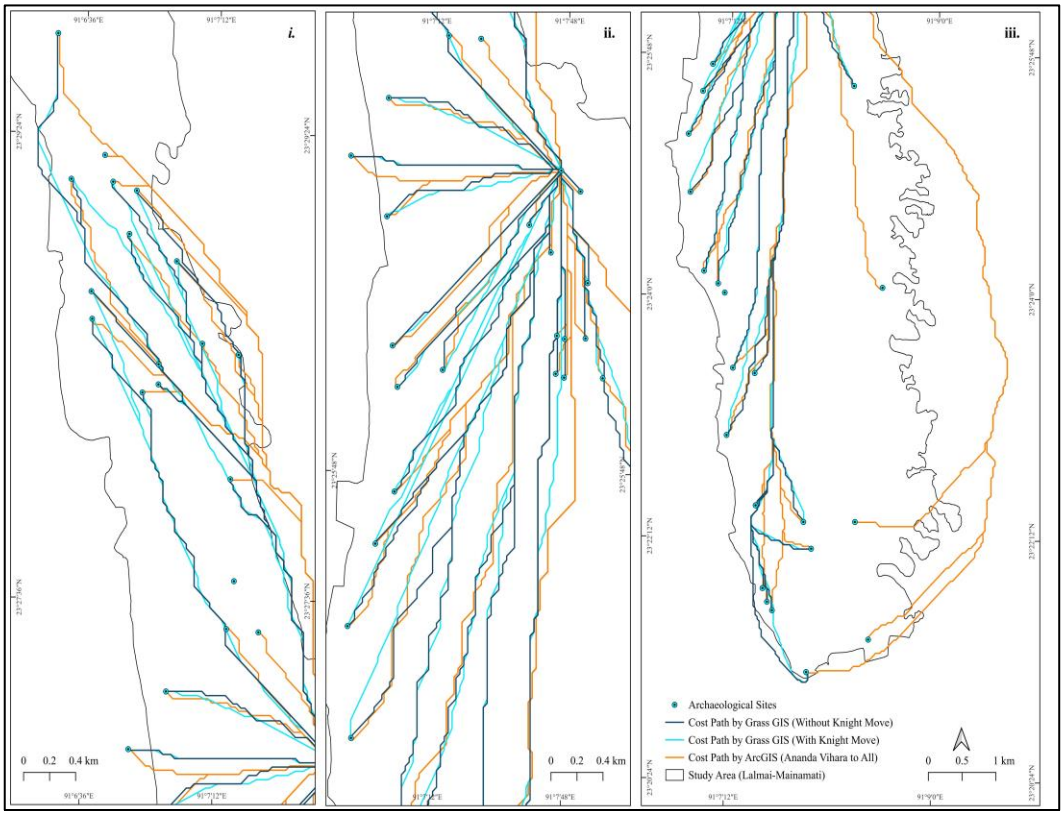


**Figure 4**.iv

**Figure 4:** LCPA maps of the study area; i. North, ii. Middle, iii. South, iv. Comparison map of cost path with and without knight move algorithm in Grass GIS versus Dijkstra's algorithm in ArcGIS

LCPA output, concentrating on the northern, central, and southern regions of the study area, respectively

It has been observed that various software employing distinct algorithms yield slightly divergent values. A further attempt has been conducted using GrassGIS, both with and without the Knight move algorithm, wherein all water bodies are designated as barriers to analyse solely the terrestrial cost path. The provided map (in Figure 4. iv) is indicating the output.

## *5. Conclusion*

The Least Cost Path Analysis or the LCPA of the Lalmai-Mainamati region has yielded significant insights into the spatial arrangement of its archaeological sites, demonstrating a systematic settlement distribution pattern shaped by terrain and aquatic connectivity. The research indicates that the majority of locations were intentionally situated within a 15-minute walking distance of one another, implying careful design for accessibility and social engagement. The Khiroda River's paleochannel undoubtedly functioned as a vital transportation corridor for greater distances, promoting trade and cultural interaction. This research highlights the efficacy of computational methods, such as LCPA, in reconstructing ancient mobility networks, notwithstanding limitations related to DEM resolution and parameter weighting. The results correspond with historical records of Devaparvata as a prosperous Buddhist cultural hub, highlighting the relationship between landscape and human habitation. Although with some limitations, the study is also expanding future research scopes. Such as the utilisation of the 30-meter resolution DEM can be addressed as a limitation, specifically for the micro-regional area such as Lalmai-Mainamati, since it may mask micro-relief differences that influence fine-scale movement. Likewise, the lack of historical road data, coupled with limited archaeological field validation, may indicate some uncertainty in the model. Although the research presents a step-by-step sequential structural model, which is the first use in Bangladesh archaeology, it yields significant geographical insights. On the other hand, this study concentrates on environmental parameters, excluding socio-cultural or ritual aspects that may have influenced site placement. The future incorporation of high-resolution DEM, historical data, social or religious parameters may yield a more comprehensive understanding of movement and settlement trends. Additionally, it should utilise vegetation as an additional parameter, as vegetation density and type can substantially affect mobility. Although it was eliminated as a variable in this analysis due to the lack of suitable historical data for the research period. Overall, this research work enhances comprehension of Lalmai-Mainamati's cultural environment, providing a basis for further investigation of South Asia's archaeological history, specifically via computational and digital methodologies.

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