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Devoted to the Past, Looking to the Future
Thirty Steps of the Be-JA Road

Viae ad Deultum: Spatial Perspectives on Roman Road Infrastructure in Southeastern Thrace

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ABSTRACT

This paper presents a comprehensive spatial analysis of Roman road infrastructure in Southeastern Thrace, focusing on the hinterland of *Deultum*. Based on six years of intensive field surveys (2018–2023) conducted as part of the "Archaeological Map of Bulgaria" project, we registered 109 archaeological sites across 32 sq. km within Sredets Municipality. Using Geographic Information Systems (GIS), we apply cumulative focal mobility network (CFMN) and central point network (CPN) analyses to examine the potential of the ancient communication networks in the region. Our methodology integrates archaeologically confirmed settlement sites with terrain-based modelling. The analysis reveals distinct mobility patterns across the diverse topography, from unconstrained movement in the Burgas Lowlands to channelled routes through the Strandzha Mountains. Key findings include the identification of previously undocumented links between *Deultum – Cabyle* and *Deultum – Hadrianopolis*, supported by strong correlations between modelled routes and archaeological site distributions. While acknowledging the limitations of purely topographical modelling, our results demonstrate that computational approaches can significantly enhance the understanding of Roman transport infrastructure, particularly in regions where direct archaeological evidence remains scarce.

KEYWORDS

Roman road network, spatial analysis, landscape archaeology, cumulative focal mobility network, central point network

Introduction

This paper contributes to the ongoing study of the hinterland of *Deultum*, a research initiative launched in 2018 as part of the project "Archaeological Map of Bulgaria" (Нехризов 2018), which aims to register new archaeological sites and update information on already registered ones.

After six years[1] of intensive field surveys (Чолаков, Георгиева 2019; 2020; 2021; 2022; in press) and with several forthcoming publications (Cholakov in press; Cholakov, Dakasheva in press), we now consider the accumulated data sufficient to shift our focus from data collection to landscape-scale spatial analysis. Specifically, we aim to examine the broader environment and its role in shaping the city's com-

1 This paper focuses exclusively on data collected during the field surveys conducted between 2018 and 2023. The 2024 surveys documented several new sites in the study area. As the analysis presented in this paper was completed prior to their inclusion, they are not part of the statistical dataset, as they do not significantly change it, but are referenced here in brief and will be incorporated in future work.

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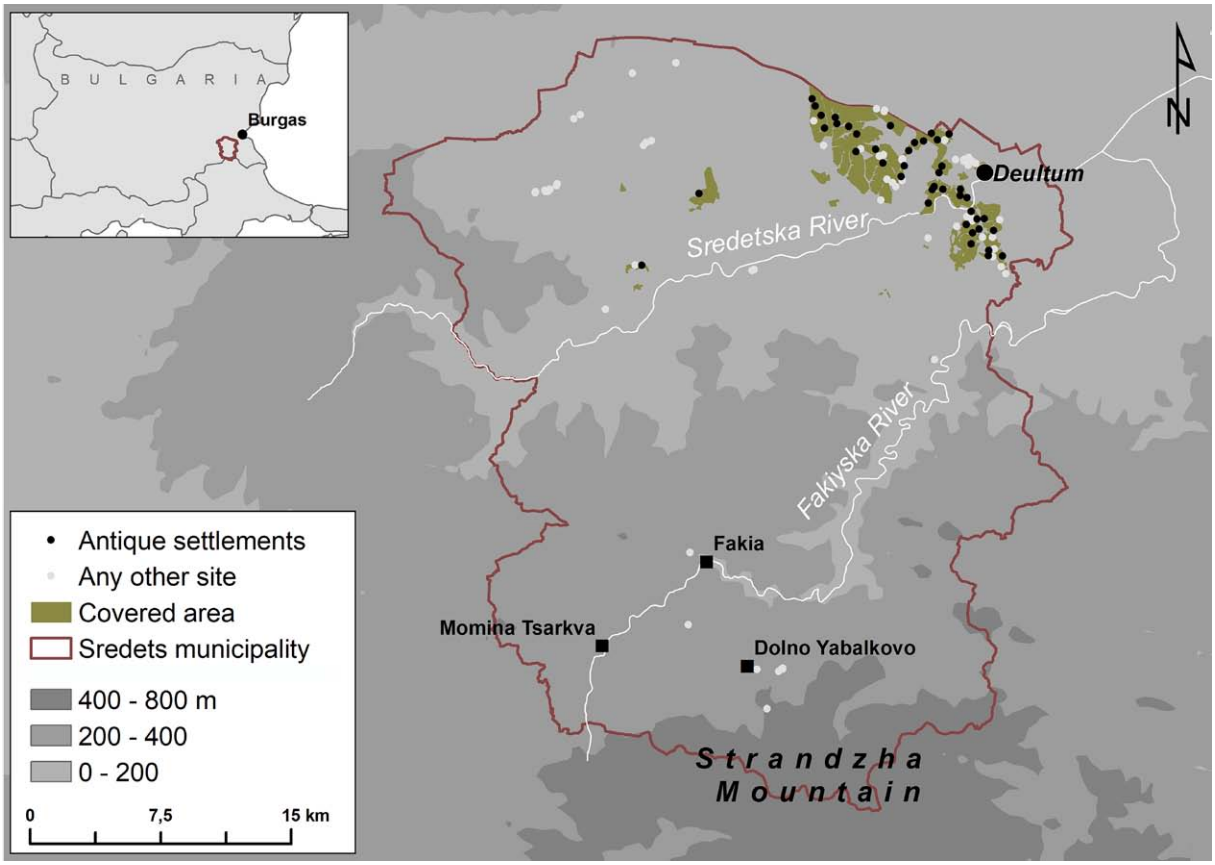


Fig. 1. The territory of Sredets Municipality (dark red) with the area surveyed during the expeditions between 2018 and 2023. Black dots represent all settlements dated to Antiquity (including villages, villae, and single buildings), distinguished from other archaeological sites, shown in light grey (map – Angel Grigorov)

munication networks during Antiquity, using Geographic Information Systems (GIS).

We integrate a combination of well-established analytical methods that have proven highly effective in similar archaeological studies. These include cumulative focal mobility network (CFMN) analysis (Déderix 2016; Fábrega-Álvarez 2006), and central point network (CPN) analysis (see Herzog 2013, 246–248 and references therein). Together, these computational approaches enable us to explore potential ancient mobility corridors and test existing hypotheses about Roman road networks in southeastern Thrace through reproducible spatial methodologies.

Historical Background

Deultum is located on the western shores of the Black Sea, in the former Roman province of Thrace, in what is now modern-day Bulgaria. Today, the ancient city lies buried beneath the eastern outskirts of the village of Debelt, Sredets Municipality, approximately 15 km from the city of Burgas (figs 1–2).

It was one of the two Roman colonies established in the 1st c. AD in the newly founded province of Thrace, and the earliest colony in present-day Bulgaria. The ancient city, which continued to exist throughout Late Antiquity and the Middle Ages, has been under archaeological investigation since the 1980s. The most significant features excavated include *thermae*, sections of the street network and the fortifications, as well as a representative building with public functions and possibly a temple (Vagalinski 2024).

Despite the ongoing archaeological excavations at *Deultum*, surprisingly little is known about

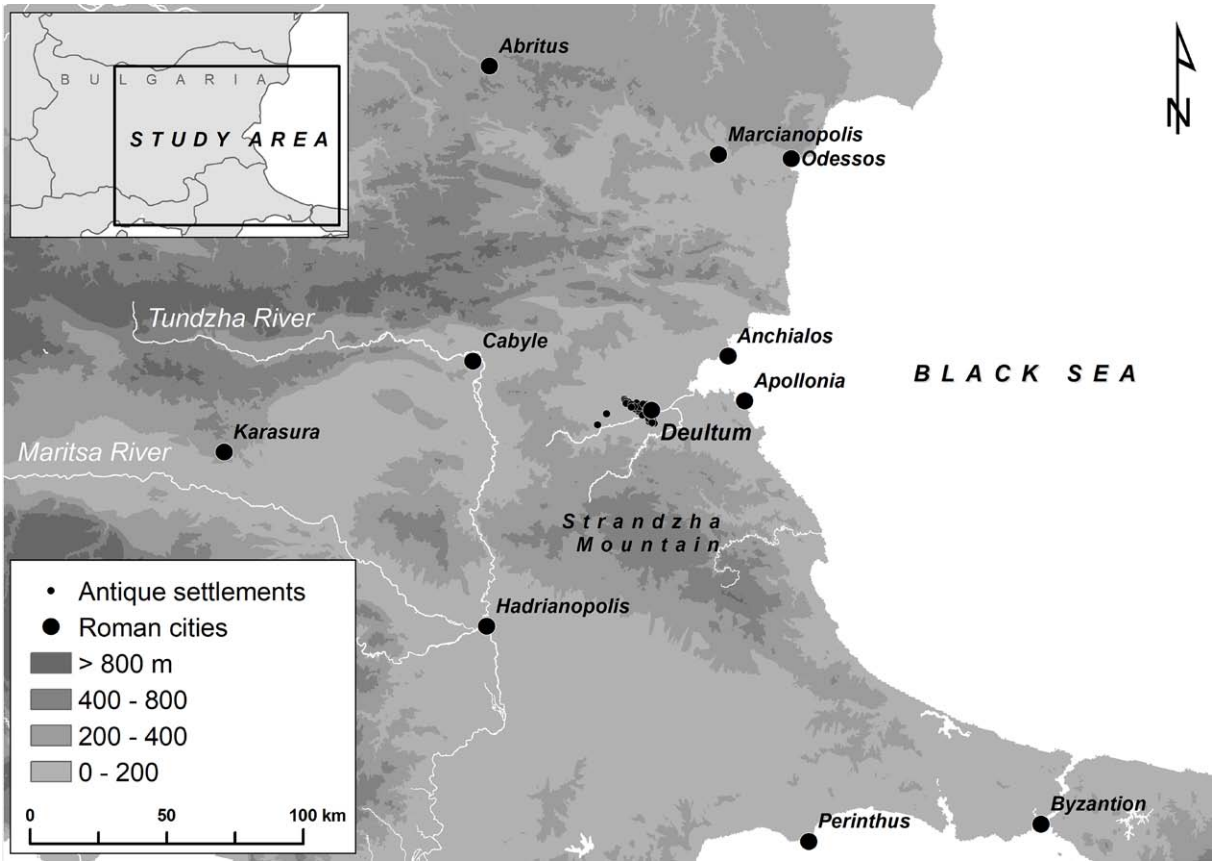


Fig. 2 The study area and its surroundings, displaying the neighbouring regional centres (large black dots) and the Antique settlements registered during the field surveys conducted between 2018 and 2023 (small black dots). The regional centres serve as origins and destinations for modelled roads leading into and out of the territory of Deultum (map – Angel Grigorov)

its surrounding territory. This gap in knowledge becomes particularly striking when contrasted with the broader archaeological attention that the Strandzha Mountain region has attracted for over a century starting with the early explorations by Škorpil (Шкорпил 1913) and Ayanov (Аянов 1938) in the early 20th c. followed by the last expeditions of the Bulgarian–Turkish Summer University (from 2002), and recent projects by Sofia University focussed on historical routes and cultural heritage (Цветкова, Емилов 2022).

Meanwhile, several major works have addressed the road system in the studied area, though often only partially. These include the "Tabula Imperii Romani" (TIR 1928), the "Tabula Imperii Byzantini" (Soustal 1991), the "Barrington Atlas" (Talbert 2000), Wendel (2005), Madzharov (2009), "ORBIS" (Scheidel, Meeks 2012), and the "Digital Atlas of the Roman Empire" (Åhlfeldt 2012). Most of these studies adopt an imperial, over-regional perspective, while Škorpil, Ayanov and Gospodinov provide the most direct engagement with this specific region (Шкорпил, Шкорпил 1885; Шкорпил 1888; Аянов 1946; Господинов 1985; 1995; 2014).

Study Area and Geographical Characteristics

The need for greater clarity about *Deultum*'s territorial extent and its settlement system development prompted us to initiate systematic field surveys aimed at investigating the city's hinterland. While the exact boundaries of *Deultum*'s ancient territory remain uncertain, and some suggestions exist in the literature (Soustal 1991, 234; Господинов 2014, 78), further clarification is required. Although it

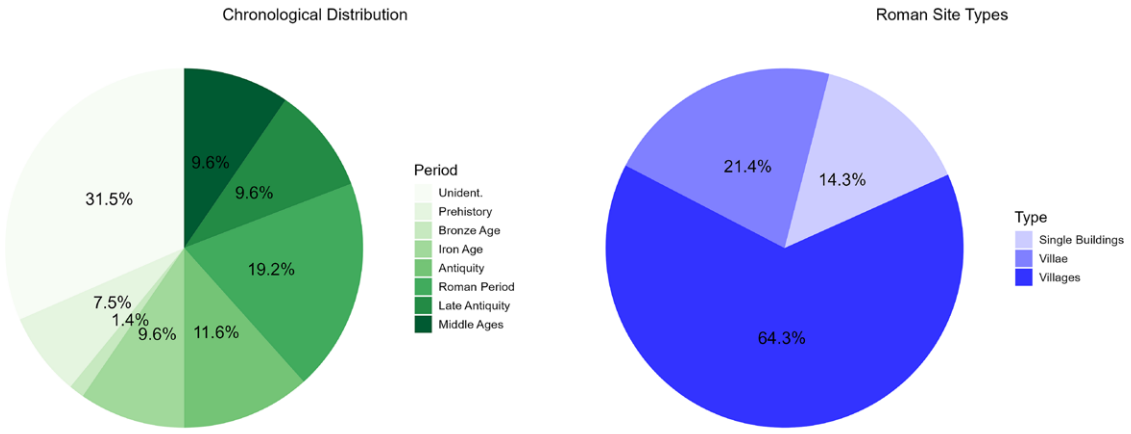


Fig. 3 Two pie charts showing the results of the field surveys. The green pie chart illustrates the chronological distribution of the materials collected during the surveys. The blue pie shows the proportion of different Roman site types. From the lightest to the darkest these are single buildings, villae and villages, identified on the basis of surface materials (chart – Angel Grigorov)

is unlikely that the ancient city's territory corresponds directly to modern administrative boundaries, for practical and logistical reasons, our field surveys were limited to the administrative boundaries of Sredets Municipality (fig. 1).

Situated in the southwestern part of Burgas Province, Sredets is the largest municipality in the region, covering approximately 1,150 sq. km. The municipality's terrain exhibits considerable topographical diversity: roughly two-thirds of the territory, south of the Sredetska River, lies within the northernmost slopes of the Strandzha Mountains, where elevations reach up to 680 m above sea level near the Turkish border, while the northern third encompasses the hilly southwestern edge of the Burgas Lowlands, dropping to just 4.5 m above sea level near Lake Mandrensko. This varied landscape is well-watered by several major rivers and their tributaries that flow eastward into Lake Mandrensko (fig. 2).

Approach

While we build upon previous scholarship, our approach is deliberately independent and data-driven. We do not incorporate earlier hypotheses into our modelling to avoid preconditioning the results. Instead, we rely exclusively on archaeologically confirmed sites and terrain-based analyses. This methodology allows us to evaluate ancient mobility networks objectively while simultaneously assessing the plausibility of previous interpretations through reproducible spatial methodologies.

The Field Survey Stage

Our fieldwork follows the well-established Mediterranean field survey methodology, which has been successfully adopted in Bulgarian archaeological research for decades (see Кечева 2024 and references therein). This approach involves full-coverage pedestrian survey in which the entire area under investigation is walked and recorded – also referred to as total coverage.

The survey methodology consists of several integrated components. During fieldwork, the area is systematically divided and mapped using polygons to ensure comprehensive coverage (fig. 1). All identified archaeological features and findspots are thoroughly documented through multiple recording methods: collection of ceramic fragments and other diagnostic artefacts, detailed photographic documentation, and precise spatial recording using GPS technology.

Data Processing Stage

The post-survey stage involves the processing and classification of collected data, followed by their integration into a GIS-compatible database. These steps allow the team to delineate the boundaries of newly identified archaeological sites and, through analysis of the collected material, to determine their typology and chronology (fig. 3).

Spatial Analysis

For the analysis we employ all archaeologically identified settlement sites – including *villae*, isolated buildings, and villages – that were primarily inhabited during the Roman period, as input data (fig. 1).

We also incorporated the coordinates of the regional centres *Abritus*, *Marcianopolis*, *Odessos*, *Karasura*, *Cabyle*, *Anchialos*, *Hadrianopolis*, *Perinthus*, *Apollonia Pontica*, and *Byzantion* (fig. 2). These external nodes allow us to anchor potential roads entering and exiting the investigated area (Whitley, Burns 2008; Murrieta-Flores 2012). As a topographic basis, we employed a 25-metre resolution EU digital elevation model (DEM) v1.1 of the Balkans, provided by the European Environmental Agency (2022).

The analysis was conducted using the movecost package in R (Alberti 2023) in which we applied Tobler's (1993) hiking function over the DEM to simulate the most efficient walking route across the landscape through least cost path (LCP) calculations (Conolly, Lake 2006, 252–262; Kantner 2012). The cost model is anisotropic, meaning that the effort required to travel from point A to point B differs from the reverse journey due to slope influence.

We applied these parameters in two complementary analytical approaches:

Cumulative Focal Mobility Network (CFMN) Analysis

For our CFMN implementation, we computed multiple LCPs connecting each archaeological site to all others in our dataset, treating every location as both potential origin and destination. This approach identifies natural corridors that channel movement toward given endpoints across the entire landscape, revealing the directional preferences an individual would follow when travelling to any destination from any starting point within the study area. The method describes landscape potential for movement toward archaeological sites through a procedure that combines cost-distance and hydrological modelling tools, specifically by performing hydrological analysis on accumulated cost surfaces (Fábrega-Álvarez 2006; Déderix 2016; Pažout 2017a).

The analysis enables extraction of route hierarchies by ranking corridors based on their density values. According to some scholars, corridors with higher density values may represent major preferential routes, potentially corresponding to historical highways, while those with lower values likely reflect local paths used for routine daily movement (Pažout 2017b).

Central Point Network (CPN) Analysis

CPN analysis models how movement and interaction patterns radiate from key locations (central points), such as settlements, markets, or ritual sites. This method helps reconstruct past mobility systems, territorial organisation, and socioeconomic hierarchies (see Herzog 2013, 246–248 and references therein). The approach exhibits high centrality as routes radiate from a single focal point.

We modelled it by establishing *Deultum* as a central endpoint and calculating multiple LCPs connecting it to all other sites (the settlement sites and the regional centres). This approach reveals what the regional road system might have looked like if it had developed with *Deultum* as its primary hub, potentially identifying major arterial routes that served the colony's broader territorial connections.

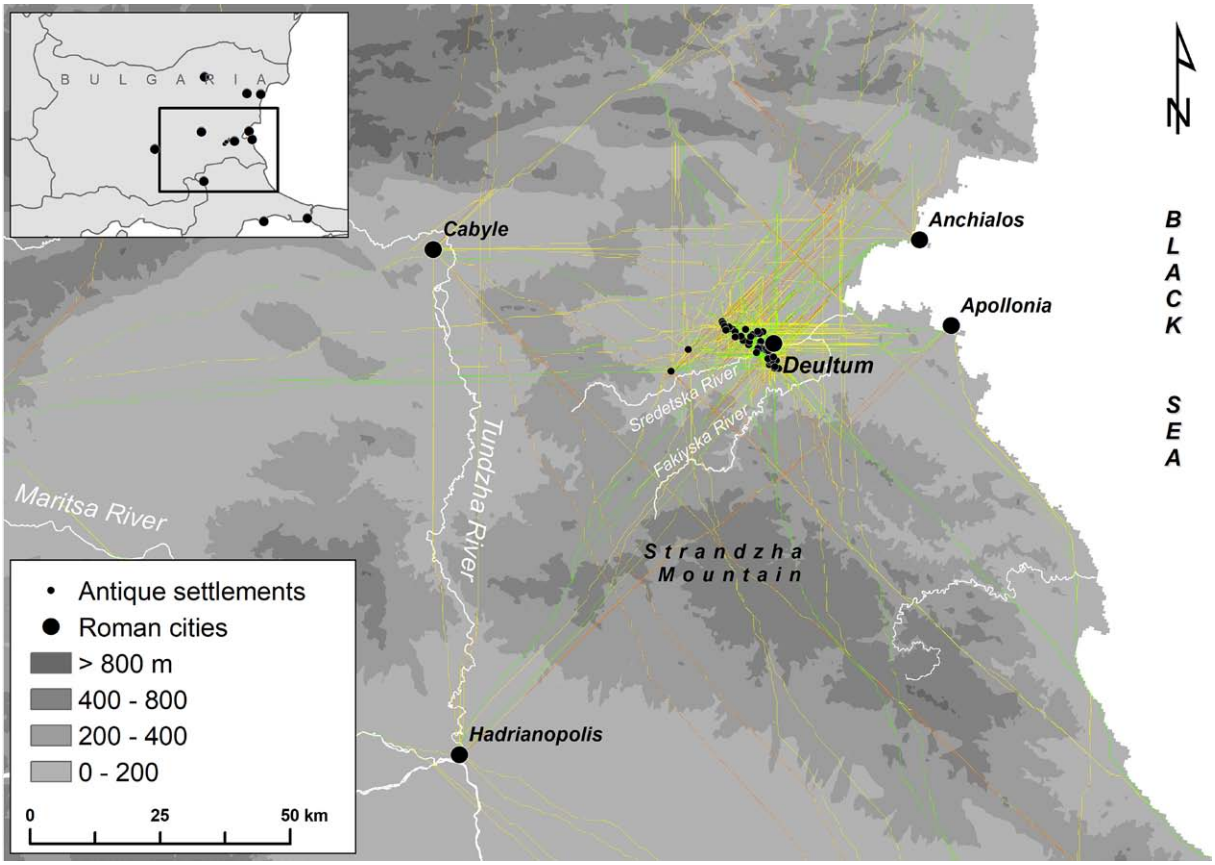


Fig. 4. Close-up of the study area presenting the results of the CFMN analysis. The map visualises the density of modelled travel routes: high-density corridors (represented in green) indicate areas where multiple LCPs converge, suggesting zones of enhanced movement potential. Medium-density corridors (yellow) reflect moderate path convergence, whilst low-density corridors (red) show areas where fewer modelled routes overlap (map – Angel Grigorov)

Results

Over the course of six years, the team covered an area of 32 sq. km. Within this area they registered 109 archaeological sites (settlements, mounds, fortresses, etc.), averaging approximately 3 sites per sq. km. Of these, 45 can be securely identified as settlement sites[2] dated to the Antiquity and Roman period (figs 1, 3). All these 45 settlements are included into the analysis.

Terrain-Based Mobility Patterns

The CFMN analysis reveals distinct mobility patterns across the diverse topography of the study area (fig. 4). In the flat terrain of the Burgas Lowlands, the results demonstrate considerable homogeneity, suggesting that roads could theoretically be routed almost anywhere across the landscape. As Hochstetter (1871, 193) states for his journey from *Constantinopel* (*Byzantion*) to *Adrianopel* (*Hadrianopolis*), "where there are no paths because everything is a path."[3] This phenomenon reflects mostly the absence of significant terrain constraints in the DEM used, as well as the lack of natural barriers incorporated into the input data.

2 Including *Deultum* in this database.

3 "...wo es keinen Weg gibt, weil alles Weg ist."

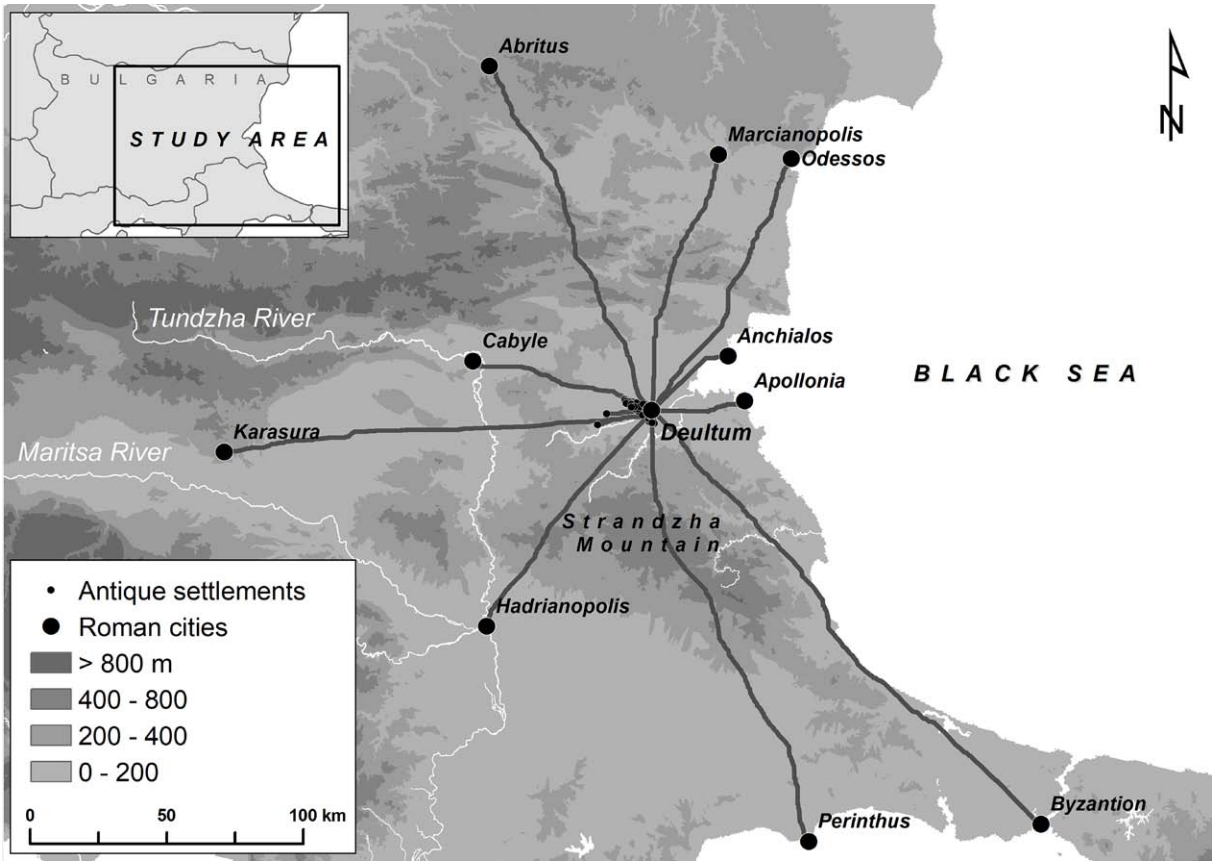


Fig. 5. Central point network analysis with Deultum set as the destination for all points. The map shows the relative accessibility of the surrounding settlements and locations, indicating how travel routes converge towards Deultum across the study area (map – Angel Grigorov)

In contrast, when analysing the mountainous southern regions within the Strandzha slopes, the modelled routes become significantly more constrained. Here, the CFMN analysis identifies specific corridors that channel movement through mountain passes and river valleys, following the natural topographical grain of the landscape.

Route Hierarchy and Corridor Density

The CFMN analysis enables extraction of density-based classifications of modelled corridors indicating areas where multiple LCPs converge, suggesting zones of enhanced movement potential (fig. 4). This concentration in specific areas provides valuable insights into natural movement constraints. The correlation between these modelled corridors and the distribution of archaeologically identified settlements suggests that topographical movement potential played a meaningful role in shaping ancient transportation patterns, even while recognising that the final road network reflected complex interactions between environmental possibilities and cultural choices.

Connectivity Patterns and Strategic Regional Integration

The CPN analysis, with *Deultum* established as the central destination, demonstrates the colony's exceptional connectivity potential (fig. 5). The results indicate that the city could maintain efficient communication links with both its immediate rural settlements and distant regional centres without requiring significant detours. This pattern suggests that the location selected for the colony was strategically optimal from a communication perspective.

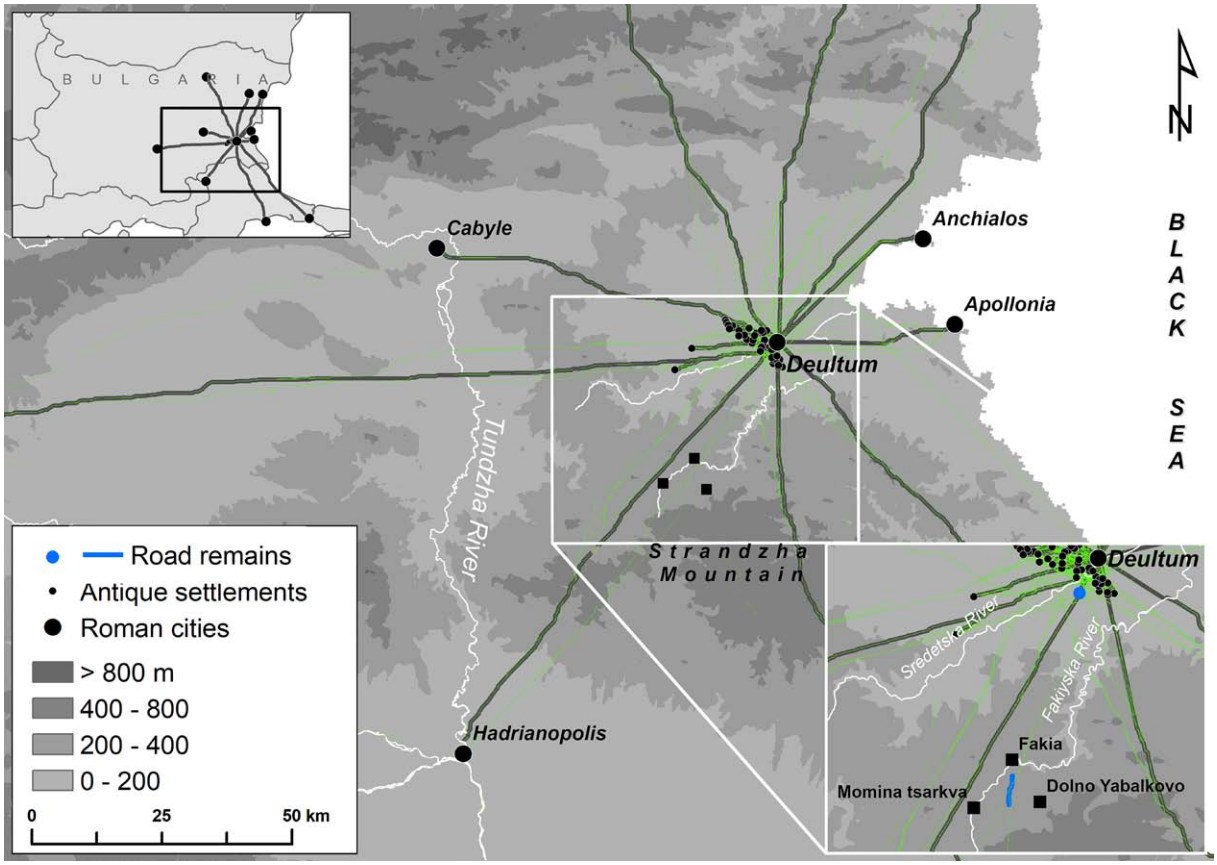


Fig. 6. The study area showing the combined results of the high-density CFMN and CPN corridors. In the lower right corner, the inset shows a close-up of the region with the two registered roads (in blue) alongside the high-density CFMN results (map – Angel Grigorov)

The analysis further demonstrates direct connectivity with major centres such as *Apollonia*, *Anchialos*, *Cabyle*, *Hadrianopolis*, and *Byzantion*, underscoring *Deultum*'s capacity to function as a key node within regional transportation networks.

Specific Connections Discoveries

Several significant link patterns emerge from the combined analyses that warrant detailed examination:

Deultum – Cabyle

The models consistently reconstruct a well-defined link between *Deultum* and *Cabyle*, despite the absence of explicit textual and archaeological evidence for this route (fig. 6). The modelled path follows a logical trajectory across the landscape, avoiding major topographical obstacles while connecting the two strategic centres efficiently. Archaeological sites discovered during our field surveys show notable concentration along this predicted axis, providing independent validation for the corridor's plausibility.

The CPN analysis, with *Deultum* as the focal point, reveals three potential configurations for this connection: 1) a direct route between the two cities; 2) a northern trajectory (traced by the CFMN as well) that intersects with mentioned in *Tabula Peutingeriana* road "*Ancialis* (*Anchialos*) – *Aquis calidis* – *Cabilis* (*Cabyle*)" (Anon., seg. 8), at an intermediate point; 3) or a routing that prioritises *Deultum* as the primary coastal destination before continuing to *Anchialos*. Each scenario reflects different priorities in network organisation, from topographical efficiency to administrative hierarchy, and these configurations may well have coexisted simultaneously.

Deultum – Hadrianopolis

Both analytical approaches delineate a passageway extending toward *Hadrianopolis*, creating a communication axis that spans from the Black Sea coast to this important inland centre (fig. 6). Archaeological evidence along several points of this predicted route supports the existence of such a connection. Toponymic analysis also reveals place names that may preserve traces of ancient road infrastructure in this area (Шкорпил, Шкорпил 1885, 12–15; Шкорпил 1888, 68–71; Аянов 1946; Господинов 2014). During our surveys, we also registered individual road sections that we assume are from this road. The first is located approximately 5 km southwest of *Deultum* (Cholakov 2019). The second lies south of the village of Fakiya, between Momina Tsarkva and Dolno Yabalkovo villages, and can be traced for about 4 km in a south-southwest direction (Cholakov 2024) (fig. 6). Although its endpoint remains unknown, its trajectory points toward *Hadrianopolis*. The road is also depicted on the Russian Imperial map from 19th c. (Де-Ливрон 1880), where it leads to "*Adrianopol*" (*Hadrianopolis*).

Discussion

The results should not be taken without concerns. They have to be carefully investigated and tested. In general, the study of the Roman road system in this area is fraught with numerous challenges. Some of these issues have been addressed within the scope of our analysis, while many others inevitably remain not covered.

Interpretation of Spatial Analysis Results

Although areas of high corridor density, executed by the CFMN model, may suggest greater route importance, this relationship cannot be considered deterministic. CFMN density patterns represent mathematical convergence shaped exclusively by topographical constraints and the distribution of input sites, without incorporating cultural, political, or economic factors that often dictated the placement of Roman roads (Fonte et al. 2017; Verhagen et al. 2019). High-density zones should therefore be understood primarily as regions offering favourable topographical conditions for movement rather than as direct reflections of road hierarchy (McLean, Rubio-Campillo 2022, 3–4).

Comparison with Previous Scholarship

The *Deultum – Cabyle* Connection

The absence of clear evidence for a *Deultum – Cabyle* corridor in both historical sources and the archaeological record leaves open questions about how *Deultum* was connected to the Thracian interior? The closest reference is the *Cabyle – Anchialos* road, which appears in the *Tabula Peutingeriana*, but no archaeological confirmation exists for it (Шкорпил, Шкорпил 1885, 14–15), creating wide scope for interpretation. For example, Wendel (2005, 97–108) proposed two alternative routes: (1) *Cabyle – Anchialos* via *Aquis Calidis*, and (2) *Cabyle – Deultum – Apollonia*, with the *Deultum – Anchialos* segment running through the Burgas Lake region. Madzharov (2009, 68, fig. 42) followed the *Tabula Peutingeriana* strictly, reconstructing a direct *Cabyle – Anchialos* road that bypassed *Deultum*.

A similar approach: *Cabyle – Anchialos* via *Deultum*, appears in the Barrington Atlas (Talbert 2000, Map 22) and several digital projects such as ORBIS (Scheidel, Meeks 2012) and the Digital Atlas of the Roman Empire (Åhlfeldt 2012), all strongly influenced by Poulter's (1995, 9) model.

Ayanov's reconstruction of the regional road system offers yet another perspective. He suggested a northern route intersecting *Tabula Peutingeriana*'s route, thereby maintaining connectivity between *Deultum*, *Cabyle*, and *Anchialos* (Аянов 1946, 96–97). This interpretation resonates closely with the second scenario generated by our "*Deultum – Cabyle*" connection analysis, suggesting an optimal integration of *Deultum* within the broader regional road infrastructure.

The *Deultum – Hadrianopolis* Route

A similar situation arises with the model-generated connectivity between *Deultum* and *Hadrianopolis*. This route is absent from the itineraries: *Itinerarium Antonini* mentions only a road linking *Deultum* with *Sadame*, *Tarpodizum*, and *Ostodizum*, without directly going to *Hadrianopolis* (It. Ant., 110). Kiepert (after Господинов 2014, 75) was the first to propose a direct *Debelt – Hadrianopolis* connection, based on the assumption that such a route must have existed. Both Ayanov and Gospodinov, drawing on historical, archaeological, and topographical data, accepted this reconstruction (Аянов 1946; Господинов 2014). Their model envisions a route from *Deultum* to *Ostodizum*, with a branch toward *Hadrianopolis* – an interpretation that complements our computational and field survey results.

The diversity of these scholarly reconstructions reflects the likelihood that multiple viable routes coexisted (Торбатов 2004, 79). Our models similarly indicate a dense network of major, intermediate, and local routes that would have facilitated communication at multiple scales, linking not only major centres but also the wider system of villages (Господинов 2014, 73). The relative importance of these routes could shift over time in response to political, economic, or environmental changes. Yet this should not be understood as implying the extinction of certain roads. Once established, roads tend to persist as enduring features of the cultural landscape, even if their level of use fluctuates. The critical question is therefore not whether a road existed, but which routes were more intensively used in a given period. While major arteries could gain or lose strategic significance, local populations often continued to rely on long-established paths for everyday mobility, ensuring a continuity of movement even when broader historical dynamics redirected traffic flows (Григоров 2024).

Methodological Limitations and Critical Considerations

The numerous opportunities for road reconstructions are due to the fact that most of the terrain is suitable and convenient for tracing a road. But while our computational approach yields valuable insights, it is essential to acknowledge significant limitations that affect the interpretation of the results. The models rely exclusively on the relief and the location of archaeological sites, potentially overlooking key factors that influenced the location and use of ancient roads.

Unpredictable Socio-political and Environmental Factors

In lowland regions, CFMN models may suggest that routes could be traced almost anywhere, but such scenarios are unrealistic. Roads could not simply cut indiscriminately across cultivated fields or private land; their courses were necessarily constrained (Herzog 2013, 240). Cost-surface models based solely on terrain characteristics cannot capture the social, cultural, or political factors that often governed route alignment. Ancient roads did not always follow topographically optimal paths. Political boundaries, land ownership patterns, religious considerations, and even the ideological confidence of Roman engineering could all result in substantial deviations from least-cost pathways (Verhagen 2013; Herzog 2014; 2016; Verhagen et al. 2019; Seifried, Gardner 2019).

Environmental factors also played a critical role. The current DEM-based approach does not adequately represent variables such as dense forests, seasonal marshlands, flooding patterns, or the practicalities of river crossings. The integration of paleoenvironmental data – including vegetation cover, wetland extent, and historical hydrological changes – would significantly improve model accuracy and plausibility.

Archaeological Data Limitations

The model relies on currently identified archaeological sites as origins and destinations, but this dataset represents only a fraction of ancient settlements. Future discoveries may significantly alter the

distribution of input points, potentially changing the modelled corridors[4]. The 32 sq. km surveyed, while substantial, represents a relatively small sample of the broader regional territory, and expansion of the survey area may reveal new patterns not captured in the current analysis.

Model Validation and Future Research

The strong correlation between modelled corridors and the distribution of archaeological sites provides encouraging validation of the computational approach, yet further testing remains essential. The predicted routes can be systematically evaluated through targeted field surveys designed to identify physical traces of road construction, milestones, or related infrastructure, as well as to expand the database of sites. Two methodological strategies may be envisioned. The first involves selective sampling: partial survey coverage can generate meaningful tests of the models, with subsequent refinement possible through iterative comparison. The second option entails total coverage, which would yield a more comprehensive picture of settlement distribution to be used as origin–destination inputs in the models. This latter strategy, however, is considerably more demanding in terms of time, money and labour, and moreover depends on the capacity of intensive pedestrian survey to detect all the sites now lying beneath the ground surface (Ammerman, Feldman 1978; Davis 2004; Fentress 2000; Terrenato 2000).

Integration of additional data sources promises to enhance model accuracy. Historical cartographic evidence could be employed to identify road traces that may serve as "attractors", channelling modelled networks around verified arterial routes. Natural barriers such as the Sredetska and Fakiyska rivers should be explicitly incorporated, with bridges and fords defined as focal points to guide predicted flows. Additional fixed points – such as toponyms and confirmed archaeological evidence – could likewise act as anchors for constraining the models. Paleoenvironmental reconstructions would provide further refinement: marshy zones can be detected through the detailed Russian (Де-Ливрон 1880) and Austro-Hungarian (Generalkarte 1910) maps of the region, which not only record wetlands but also document river crossings (bridges and fords) and old roads. These cartographic sources are especially valuable, as they predate the major landscape transformations initiated during the massive industrialisation of Bulgaria after 1944; the terrain prior to this period is believed to have remained largely stable (Събкова 2018; Sabkova 2019, 51–52).

The incorporation of maritime transportation analysis would provide a more complete picture of connectivity, as near the coast sites like *Deultum* certainly participated in both terrestrial and maritime networks. Modelling the integration between land and sea routes could reveal additional aspects of the site's strategic importance.

Conclusion

This study demonstrates the potential of computational spatial analysis to illuminate ancient transportation networks in southeastern Thrace while highlighting the methodological challenges inherent in reconstructing Roman road systems. Through the integration of CFMN and CPN analyses with extensive field survey data, we have identified plausible links and routes that align with both archaeological evidence and topographical constraints, providing new insights into the strategic importance of *Deultum*'s location. The site demonstrates exceptional connectivity potential, capable of serving as a crucial hub between maritime and terrestrial transportation networks while maintaining efficient links to both local settlements and major regional centres. The identification of the *Deultum – Cabyle* and *Deul-*

4 During the 2024 and 2025 seasons, 51 additional sites were recorded, 15 of which are settlements. The field surveys will continue in 2026.

tum – Hadrianopolis connectivity, though absent from ancient sources, appears highly probable based on our modelling and the distribution of archaeological sites along the predicted routes.

However, our research also underscores the limitations of terrain-based modelling. The models rely exclusively on topographical features, mainly relief, and cannot account for the social, political, and economic factors that significantly influenced ancient road placement. Future research should integrate paleoenvironmental data, historical cartographic evidence, and systematic field validation to enhance model accuracy.

As field surveys continue and new archaeological data become available, the models can be refined and validated, contributing to our evolving understanding of ancient mobility systems in this crucial region.

Acknowledgments

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