Building a Model to Reconstruct the Hellenistic and Roman Road Networks of the Eastern Desert of Egypt, a Semi-Empirical Approach Based on Modern Travelers' Itineraries

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ABSTRACT

The Egyptian Eastern Desert, the part of the Sahara Desert that connects the Nile and the Red Sea, is rich in natural resources and meshed with multiple networks. The adoption of the camel as the main mode of transportation in the 1st millennium BC, faster and with a greater load capacity than humans or donkeys, dramatically changed the logistics used to cross this difficult terrain. Our objective, therefore, is to understand and reconstruct circulation in the region during Antiquity through location factors and the evolution of roads. For this purpose, a least-cost network specific to camel movements has been created for this arid and mountainous region.

The network is based on the reconstructed itineraries of modern travelers (18th and 19th centuries) who crossed the region under similar conditions to ancient ones. These routes and the travelers' diaries have enabled us to analyze the main travel constraints; they provide a set of data to calibrate the different movement factors of camel caravans and to validate the calculated least cost paths. The modeled network takes into account transport infrastructures, navigation conditions in plain areas, difficulties of the terrain surface, and the topographical constraints specific to camels.

This methodological paper details our approach from the description of movement factors, their mapping, and their use in least cost algorithms to the creation of a network covering 253 archaeological sites and 204 desert watering places. It aims to provide the archaeological and GIS communities with the method and tools to reproduce itineraries based on the hypotheses of movement and empirical data. For this purpose, the data is available and documented by a data paper.

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1 INTRODUCTION: RECREATING ANCIENT DESERT NETWORK ITINERARIES WITH SPATIAL MODELING

The Desert Networks project (DN) was started in 2017 as a way to study the networks that once meshed Egypt's Eastern Desert (on the region, see Brun et al. 2018; Sidebotham 2011), from the middle of the 2nd millennium BC (beginning of the New Kingdom) to the end of the 3rd century AD (Late Roman period). Our ultimate aim is to reconstitute the organization of human networks (e.g. state networks, such as those of the soldiers protecting the caravans, or which brought together the thousands of people employed in the great imperial quarries of Mons Claudianus, as well as the more tenuous solidarity networks which for decades linked the desert's inhabitants) and economic networks (by tracing the circulation of goods within the region, and their integration into the great contemporary economic networks, from the Mediterranean to the Indian Ocean). For this purpose, and as an initial step, we defined the spatial foundations of this study in order to focus on the reconstruction of the Eastern Desert's physical networks. In other words: how, when, and where did people travel in the region and what factors influenced the location and evolution of roads over the 2,000 years encompassed by the project?

Route modeling requires knowledge of a traveler's travel capacity in a given environment. (Verhagen, Nuninger and Groenhuijzen 2019) describe this as the notion of affordance: 'it is a set of environmental properties related to individual behavior'. These affordances are a combination of the capacity for movement relative to the mode of transportation and external factors, including the physical environment and human factors (infrastructure, safety, navigation). This approach to understanding human movement requires an analysis of the general movement factors of societies and archaeological evidence of mobility (Murrieta-Flores 2010).

The latter (faunal remains and textual sources found in the Eastern Desert forts) attest that camels[1] were introduced into the Eastern Desert during the first half of the 1st millennium BC (Agut-Labordère 2018: 181; Agut-Labordère and Redon 2020), and that their use in caravan transport became quickly widespread, from the beginning of the Hellenistic period (331–30 BC) (Chaufray 2020; Cuvigny 2020), at the expense of equids, and more specifically the donkey, which was used as a load-carrying animal during the Pharaonic period (Leguilloux 2020; Mitchell 2018). The camel remained overwhelmingly used as a pack animal throughout the Roman and Late Roman period (30 BC–640 AD) (Adams 2007; Leguilloux 2020).

An inventory of archaeological sites according to their function (security/surveillance, watering place, shelter, resting and supply site, quarry, mine) and by period also provides information on the infrastructures set up so that caravans (for supply or trade) and expeditions could cross the region. The sources also insist on the need for watering places along the documented routes. Navigation could be facilitated by the presence of guides (Cuvigny 2018, about the presence of guides mentioned in an ostracon found in the desert and reporting an elephant hunting expedition) and especially by the careful, but not systematic, marking of certain parts of the route with cairns (e.g. around Berenike, see Sidebotham 1999: 349–359). Few ancient roads are precisely mapped today, except for some very well developed communication axes (e.g. the Wadi Hammamat, used mainly in Roman times and equipped with 15 forts: Cuvigny et al. 2003). This lack of data, especially on the most difficult to access or least studied sectors, reduces our understanding of the choices that motivated the selection of one itinerary in preference to another, or the location of sites on these itineraries.

In order to overcome the lack of sources for determining the general factors of movement in the Eastern Desert in ancient times, this study proposes to extrapolate data from the analysis of the itineraries of modern travelers (18th to early 20th centuries), which can be documented more precisely, and then apply them to ancient routes. Indeed, despite the time separating these journeys, the travelers shared the same mode of transport and similar environmental constraints regarding navigation. Climatic conditions have changed little since the beginning of Egypt's aridification at the end of the African Humid Period about 5,800 years ago (Brookes 2003; Bubenzer and Riemer 2007) and no major climate change has been demonstrated for the last 5,000 to 4,500 years (Crépy 2016; Sanlaville 1997; Welc 2016), although minor fluctuations have occasionally been reported for the Roman period (Garcier and Bravard 2014).[2] Changes in the landscape since antiquity are mainly related to a gradual lowering of inherited aquifers (Gasse 2000) and anthropogenic activities. The evolution of the vegetation cover and of the water supply in the aquifers from antiquity to the present day has not yet been documented for the study area; however, field work, analysis of geological documentation, and the study of satellite images indicate that the surface conditions and hydrogeological configuration have not changed during that time. The fact that some water points have been exploited from the New Kingdom to the present day seems to confirm this (Crépy, Manière and Redon Forthcoming; Crépy and Redon Forthcoming). Despite the probable adaptations of camels in just over two millennia, travel conditions have remained similar, with a clear distinction between pack camels (slower but more resistant) and riding camels (faster but with a lower carrying capacity) in both Antiquity (Agut-Labordère and Redon 2020) and the 19th (Barron and Hume 1902: 3; Du Camp 1860: 259–260) and 20th centuries (Tregenza 1955). For example, crossings sometimes had to be made at night because of the heat in ancient times

(Strabon 16, 1, 45), which was also the case in the 19th (Belzoni 1820: 335, 344) and 20th centuries, especially during the summer (Tregenza 1955: 61). And when travelling in broad daylight, meridian breaks were often necessary during the hottest hours (Du Camp 1860: 270, 286–287; Flaubert 1910: 243, 245, 253; Tregenza 1955: 147). In the 1940s and 1950s, the wells were still without pumps and road construction was minimal, as in ancient times, consisting mainly of the clearing of the bigger and sharper stones (often linked purely to the repeated passage of caravans rather than a dedicated operation) and possibly reuse of old ramps on certain steep slopes or very uneven passages (Tregenza 1955: 141, 145–146).

Because of this continuity/permanence and environmental stability, affordances can therefore be described for trips involving pack camels, whether they were made in Antiquity or today. The descriptions contained in modern travel narratives are sufficiently diverse and well distributed to provide reliable data. It is therefore possible to propose maps of these transport constraints and to reproduce the travelers' journeys using the least cost analysis method, in order to calibrate the model. The model can then be used to reconstruct ancient routes, by applying the same calibrated least cost analysis method to the network of ancient sites.

The model presented here is eminently suitable for our study area, located approximately between Abu Shaar in the north and Bir Abraq in the south, an area of 110,000 km^2 (***Figure 1***). However, this is the first model ever proposed by both archaeologists and modelers intended to model routes primarily traversed by people with camels, and could therefore serve as a starting point for other projects. In order to make it reproducible and applicable to other areas and periods of study, we thought it useful to thoroughly describe the method used to build it. The data is available in the Data Accessibility Statement and described in the associated data paper (Manière, Crépy and Redon 2020). Thus, this article will primarily focus on method and methodological issues, with a presentation of the initial results obtained from the model's implementation, to show its potential uses. How the results impact on our knowledge of the Greco-Roman roads of the Egyptian Eastern Desert (a study that is still ongoing) will be discussed in forthcoming articles.

2 FROM EMPIRICAL MODERN TRAVELER DATA TO ANCIENT NETWORK RECONSTRUCTION

2.1 THE EGYPTIAN EASTERN DESERT AND THE USE OF THE CAMEL IN ANTIQUITY

The Eastern Desert is hyper-arid: apart from its northernmost region (from the Mediterranean Coast to the area between Beni Suef in the Nile Valley and Zaafarana on the Red Sea Coast) and the Red Sea Coast, the average annual rainfall is less than 5 mm (Embabi 2004). It is made up of two distinct zones that follow one another from west to east: an extensive sedimentary plateau and the Red Sea Hills. From the eastern edge of the Nile Valley, one first crosses the plateau, with no obvious natural landmarks to facilitate movement. To the north, the plateau consists mainly of Eocene limestone; to the south, the main outcropping formation is dated to the Upper Cretaceous and is mainly sandstone (Nubian sandstone). The waters from the Nile are easily accessible for the first 20 km, through exploitation of the near-surface water table. Further on, it is necessary to dig deeper into the wadi alluvium to exploit the water tables, which are episodically recharged, and to continue digging in the underlying geological formations to exploit deeper water tables (fracture porosity in limestone, interstice porosity in sandstone) whose water supply is greater, more regular, and less directly correlated to current rainfall. In the early years of the 20th century, in an area less than 50 km from the Nile, there were still indications of the presence of ancient artesian springs and wells related to the Nubian Sandstone Aquifer System in low altitude sandstone areas, e.g. at Laqeita (Ball 1927) or El-Kanais (Murray 1955). Continuing westward, one is less likely to observe this phenomenon; apart from localized hydrogeological conditions there is no alternative to manually or mechanically pumping water up from wells, often over several tens of meters.

Beyond this plateau, to the east, one encounters the hills of the Red Sea, a high massif made of heterogeneous rocks, mainly metamorphic and magmatic, intensely fractured and faulted, which belong to the Arabian–Nubian Shield. These elevations, within which the watershed between the Mediterranean and Red Sea Basins is located, are cut by wadis, dry valleys which, during phenomena of intense rainfall, are transformed into powerful rivers which can flood the surrounding areas through flash floods, easily degrading all unprotected installations and considerably modifying the geometry of the valleys. The relief and geological changes are numerous, providing obvious natural landmarks, but they also present obstacles for crossing from east to west, as only a limited number of passes are easily practicable.

Despite being a hostile environment for millennia, the region has continued to attract a diverse range of people. If we concentrate on the so-called historical periods, it was gold that initially attracted people from the valley (Klemm and Klemm 2013) during the Predynastic era and the Old Kingdom (3rd millennium BC). The region was also crossed by expeditions (in search of copper from Sinai or spices and incense from the Land of Punt) heading to the Red Sea (Gasse 2006), whose shore ports were developed during the Old and Middle Kingdom (Wadi Jarf, Ayn Sukhna, Mersa Gawasis). The peak of

Figure 1 General map of the Egyptian Eastern Desert.

the region's occupation, however, dates back to the first century of the Hellenistic period (332–31 BC), when the desert became equipped with permanent or semi-permanent posts to facilitate its crossing (Gates-Foster 2012; Redon 2018). As in the Pharaonic period, it was the exploitation of its materials, primarily gold, which was of interest to the Ptolemaic kings, who constantly needed to finance their wars in the Mediterranean (Faucher 2018; Redon and Faucher 2020). The equipment of the desert was also done to facilitate the access to the new ports founded on the Red Sea Coast, notably the port of Berenike (Sidebotham 2011), from where they could import spices, incense, and especially elephants, the essential war machines of the 3rd century BC battlefields, which were hunted on the African coasts (Cuvigny 2018; Thiers 2001). The Roman period was the second apogee of the region, which saw it endowed with a tight network of forts and stations (20 to 30 km apart) along three main routes: Coptos–Myos Hormos, Coptos–Berenike, commissioned in the 1st century AD, and, in the following century, Antinoopolis–Berenike (Brun 2018). When gold mining in the area ceased, the Romans turned their attention to the region's hard granite and porphyry stones (Maxfield and Peacock 2007; Peacock and Maxfield 1997). As a result, commercial traffic intensified and the exchange networks between the Indian Ocean, the Red Sea, and the Mediterranean Sea became increasingly dynamic (De Romanis 1996; Sidebotham 2011).

It should be noted that the increase in human presence in the region, between the Pharaonic and Greco-Roman periods, can be partly explained by a revolution in Egypt at this time, the introduction of the "ship of the deserts"—the camel (Agut-Labordère and Redon 2020). Although it is still difficult to precisely date when camels arrived on Egyptian soil, it was certainly before the Ptolemaic period, during the 1st millennium BC. Perhaps they were introduced by nomadic Arab populations, specialized in their breeding, who we know supplied the Ptolemaic state with transport animals in the Hellenistic period (Cuvigny 2020). Camels enabled the convoys to move at a quicker pace, even though they were now more heavily loaded. The logistics were therefore different from those previously employed when the donkey, horse, and human foot were the only means of crossing the region. From the end of the 4th century BC, camels became the main means of transport in the Eastern Desert, and they remained so until the first half of the 20th century.

This revolution creates a unique opportunity for the Desert Networks project. These animals are an excellent modeling object and form the basis of our work reconstructing ancient tracks in the Hellenistic and Roman periods (we exclude the New Kingdom because this model is based on the use of the camel). Thanks to the analysis of camels' transport constraints, we are now able to reconstruct the network of their routes throughout the project area. This modeling process complements and improves the method developed in a previous publication (Crépy, Manière and Redon Forthcoming), and is based on the analysis of modern travelers' itineraries (18th to early 20th centuries) as they traveled through the desert in similar conditions to ancient times. They have provided valuable data on travel conditions and the calibration of friction layers used in the determination of Least Cost Paths (LCP).

2.2 LEAST COST PATH FOR CAMEL TRANSPORTATION

LCP analysis is used to find the best possible route from a specific starting point to one or more destinations. It is frequently used in archaeology to find ancient roads, model networks, or assess the accessibility of a site (recent studies include: White and Barber 2012; Güimil-Fariña and Parcero-Oubiña 2015; Groenhuijzen and Verhagen 2017; Carreras, De Soto and Muñoz 2019; Seifried and Gardner 2019). The cost of the journey is defined by the conditions (mode of transportation, type of road, type of travelers, time of year) and the purpose of the journey (goods transport, military expedition, postal service, etc.), with priority given to minimizing the distance, time, or money spent, etc. This analysis can be performed directly on a vectorized network or on a cost grid, with each pixel of the grid representing the difficulty of crossing a portion of territory. The least cost path therefore depends on the combination of travel capacity and external constraints that apply to the traveler.

This technique can be used to generate routes between one or more sites or to create a network. For the latter, depending on the assumptions of the network structure, different methods can be implemented (Herzog 2014).

The LCP method consists of creating a cost grid for each factor influencing the movement of the traveler and then producing a grid which cumulates all the factors. This new grid can then be used to represent the cost of the distance traveled from a starting point to the rest of the territory. A least cost path algorithm (Dijkstra 1959, in this study) can then be used to find the optimal route from the starting point to the destinations.

2.3 MODELING APPROACH WITH MODERN TRAVELER DATA

In this study, we sought to represent both the camels' ability to move according to the topography, the difficulty of the terrain, and navigation in the specific context of the Eastern Desert, as well as the logistical factors related to infrastructure. With the exception of the latter, each of these movement factors was represented by a raster grid of the same spatial resolution. The values of each grid representing travel costs were calibrated and tested by two sets of training and validation data from modern travelers' itineraries under conditions close to those of Antiquity. Finally, a network was created to link all the sites on the basis of these calibrated grids.

Regarding the topographical factor, many functions exist for determining the slope cost of travel for human walking, but these result in paths that are too far from camel routes (Crépy, Manière and Redon Forthcoming), showing that travel involving camels (especially loaded ones) has its own constraints. This might seem obvious; however, too many studies on ancient routes still disregard the heuristic and methodological problem of using the functions of Tobler (1993) or Minetti et al. (2002), especially when human walking is not relevant to the reconstructed route. Similarly, the impact of terrain on human walking speed can be determined (Lejeune, Willems and Heglund 1998; Soule and Goldman 1972) but remains unknown for a heavily loaded camel. In general, the lack of experimentation on the walking ability of a loaded camel according to various parameters does not allow us to quantify their movement using pre-established functions — only generic information uncorrelated to the terrain conditions (slope, surface condition, etc.) is available in the literature (e.g. Schwartz 1986).[3]

Faced with these limitations, the model published here has been developed using a theory-driven approach (Verhagen 2018). Travel factors or assumptions were initially determined and mapped on the basis of the analysis of travelers' itineraries. In the absence of parameters allowing the use of a function, the relative costs of these factors were adjusted by a process of trial and error, to ensure that the results corresponded as closely as possible to the training route dataset chosen for the reliability of their reconstruction. The model was

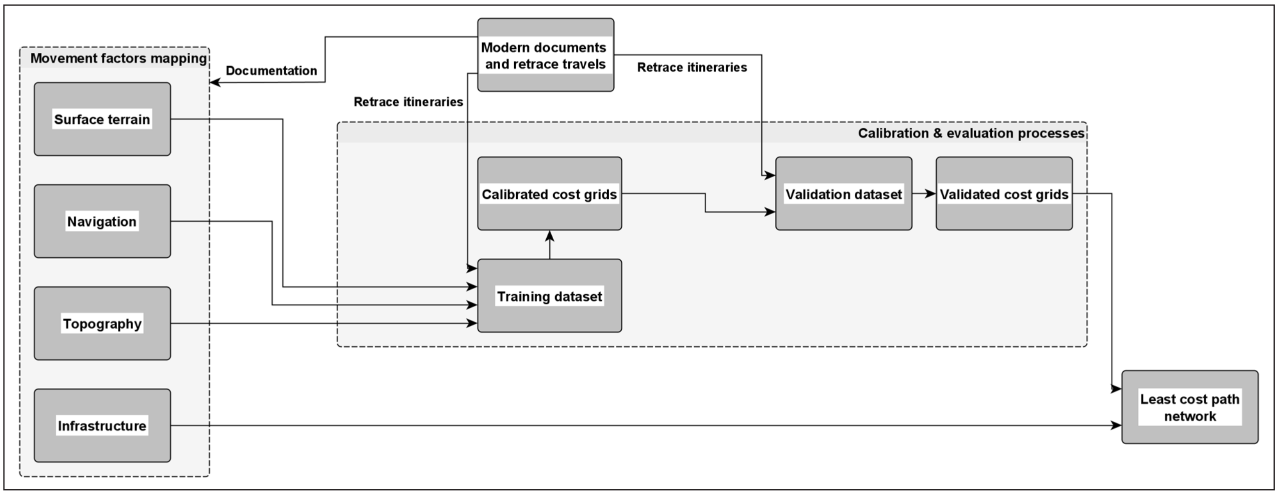

Figure 2 Network modeling process.

then evaluated for its ability to replicate alternative routes to analyze travel assumptions, mapping, and costs. Finally, the calibrated and validated costs were applied to the ancient data in order to extrapolate routes between sites to form a network (*Figure 2*).

This approach has the advantage of freeing itself from cost functions, which are often developed in an environment and conditions that are very different from those of an arid desert, and also of facilitating the introduction of additional variables, such as the terrain surface condition or navigation. The disadvantages of this method are that cost values are not estimated by experimentation but represent the weight of factors relative to each other in order to reproduce routes; subsequently, they cannot be reused outside the environment in which they were established and do not reflect a cost in measurable units. The result is therefore not directly transferable or generalizable, although the approach is still replicable for other environments and regions.

The infrastructure necessary for travel cannot be represented by a cost grid, so this component is taken into account through their function as nodes in the development of the network. The choice to favor certain infrastructures on a route can therefore be made on the basis of the modeled network. Although this approach does not allow for the direct determination of travel speeds or times, it has the advantage of taking more parameters into account for the definition of the model and identifying several possible routes, depending on the period under consideration, instead of producing the best route.

Territorial security and infrastructures for travelers are variable components in the time interval studied (between the middle of the 1st millennium BC and the end of the 4th century AD). Nevertheless, in order to represent the network of possible routes, these factors of passable areas or usable infrastructures can be removed in the definition of the network but can also be integrated in its use.

Spatial data processing operations were carried out using ArcGIS 10.5 software. In spite of the loss of accuracy in route calculations, due to the use of the spreading algorithm D8 instead of D16 (Bevan 2013), this software allowed the easy creation of the custom made cost functions required for the model as well as the optimization of the necessary computing power. This lack of accuracy can nevertheless be put into perspective in relation to a mode of transportation where many routes can coexist within the same valley. Even if the desired result is a network of lines, the reality is that each line generally represents a transport corridor.

3 THE TRAVELERS' PATH DECISION FACTORS

3.1 RETRACING THE STEPS OF TRAVELERS' ITINERARIES

In order to retrieve the decision factors, it was necessary to identify sufficient routes taken by expeditions and trips that included camels. With the exception of the so-called Myos Hormos route in the Wadi Hammamat (*Table 1*), only two ancient road sections could be used for the model. They belonged to the road linking the Nile Valley to Porphyrites (Roman porphyry quarries located in the Gebel Dokhan area) which were identifiable in the field thanks to cairns on both sides of the road section (Sidebotham 1996; Scaife 1935).

The accounts of Western travelers and explorers who had traversed the desert, as well as some of the maps they produced, were meticulously scrutinized in order to increase the corpus of data. By retracing their journeys, seven routes were reconstructed (*Table 1*). This work, and the reconstitution of the itineraries, feeds into the design of the model's factors in two ways: first, by what is explicitly mentioned by the travelers (favorable or unfavorable terrain conditions, avoidance of certain passes, duration, distances and archaeological sites), and secondly, by trends that appear throughout all of the itineraries (favorable slopes, wadis that appear advantageous on satellite images but were not used).

ROUTE	DATE	BIBLIOGRAPHY	MAPS	USE
Belzoni's journey	1818	Athanasi 1836, Belzoni 1820	Belzoni 1820, pl. 38	Training
Colston's journey	1873	Colston 1886		Training
Couyat's travels	1907–1910	Couyat 1910		Training
Bisson de la Roque's journey	1922	Bisson de la Roque 1922	Bernand 1977, pl. 48	Training
Coptos-Myos Hormos road	Roman period	Cuvigny et al. 2003		Validation
El Saqqia – Bab El Mukheniq cairn road	Roman period	Sidebotham 1996		Validation
Wadi el Atrash cairn road	Roman period	Sidebotham 1996		Validation
French Expedition in Egypt's route	1799	Denon 1802, De Rozières 1813	Jacotin 1818, f. 5–8	Validation
Du Camp and Flaubert's journey	1850	Du Camp 1860, Flaubert 1910		Validation
Floyer's travels	1887–1891	Floyer 1887	Floyer 1887	Validation

Table 1 Ancient and modern journeys used in the constitution of the training and validation datasets.

Unfortunately, the georeferencing of maps did not provide much assistance due to the survey methods used (lack of systematic triangulation for Floyer's and the Description of Egypt maps), because the representation is too imprecise (Bisson de la Roque's map), or because they do not have a uniform coordinate system (Description of Egypt map). However, thanks to hydrographic and toponymic information, their content was nevertheless valuable in confirming and supplementing the accounts. Floyer's route, used in the analysis, does not really correspond to the steps made during a single voyage by the explorer but to routes he spotted during different journeys, which we have cut into sections from site to site. Similarly, the Description of Egypt map describes a route rather than steps; however, De Rozière (1813) and Denon (1802) undertook this route and described it, making it possible to divide into steps.

Reconstructing itineraries from heterogeneous textual sources (the objectives of the journeys being variable as well as the accuracy of the accounts) whose authors had not initially foreseen such a use—with a few exceptions (for example, Bisson de la Roque 1922)—is delicate and requires the cross-referencing of several sources: cartographic and textual data from travelers; toponymy; location of water points and archaeological sites (for this, we used the DN database, which brings together all the archaeological data of more than 300 sites occupied from the New Kingdom to the Roman period due for online release in 2021, and the Trismegistos database); geology (geological maps); and recognizable landmarks described by travelers that are visible on satellite images (hills, passes, confluences, etc.). The accounts selected were therefore chosen on the basis of the quality, quantity, and accuracy of their information.

This method is based on the definition of a succession of steps that allows the route to be progressively refined. First of all, we noted all of the toponyms (in particular the names of wadis, i.e. dry rivers, wells and gebels, i.e. mountains) mentioned in the narrative, as well as the archaeological, geological, and topographical landmarks. This information, when combined with that of the Desert Networks and Trismegistos databases and satellite images, allowed us to set up the first mesh of points in the Google Earth Pro software. By returning to the text and cross-referencing, where possible, with the accounts of other travelers who took part in the expedition (for example, d'Athanasi (1836), to refine Belzoni (1820), for whom he was the interpreter during the expedition), made it possible to consolidate these points and gradually refine the itinerary. It was therefore possible, for the best cases, to reconstruct the entire journey to the scale of the wadi and the pass (for example, for Bisson de la Roque 1922). On the other hand, in cases with particularly wide wadis or passes that can be crossed by several distinct paths, it was rarely possible to be certain of the route taken. The scale and resolution of the reconstruction, therefore, depends largely on the width of the wadis and passes, and is more accurate in the mountainous area (wadis and passes are more circumscribed) than on the plateau (the Wadi Qena, for example, is more than 2 km wide).

The choice of path was based on the example of caravan routes still visible on current satellite images (Appendix B), keeping in mind that camels do not always follow straight paths due to surface conditions: 'It was not a straight walk, for both men and animals were winding a little as they avoided stones and surface irregularities' (Tregenza 1955: 4). In order to test the effectiveness of this method, we compared Bisson de la Roque's itinerary, reconstructed solely from his account (Bisson de la Roque 1922) with the plan he drew up for his expedition. Only one minor error in the route reconstruction was found, which made it necessary to replace a faulty 10.7 km long section with a corrected section of 8.7 km; the faulty section thus represented only 2.04% of the total corrected route (525.8 km). Steps for which there were doubts about the exact route were not included in the model, either at the training or validation stage (***Figure 3***).

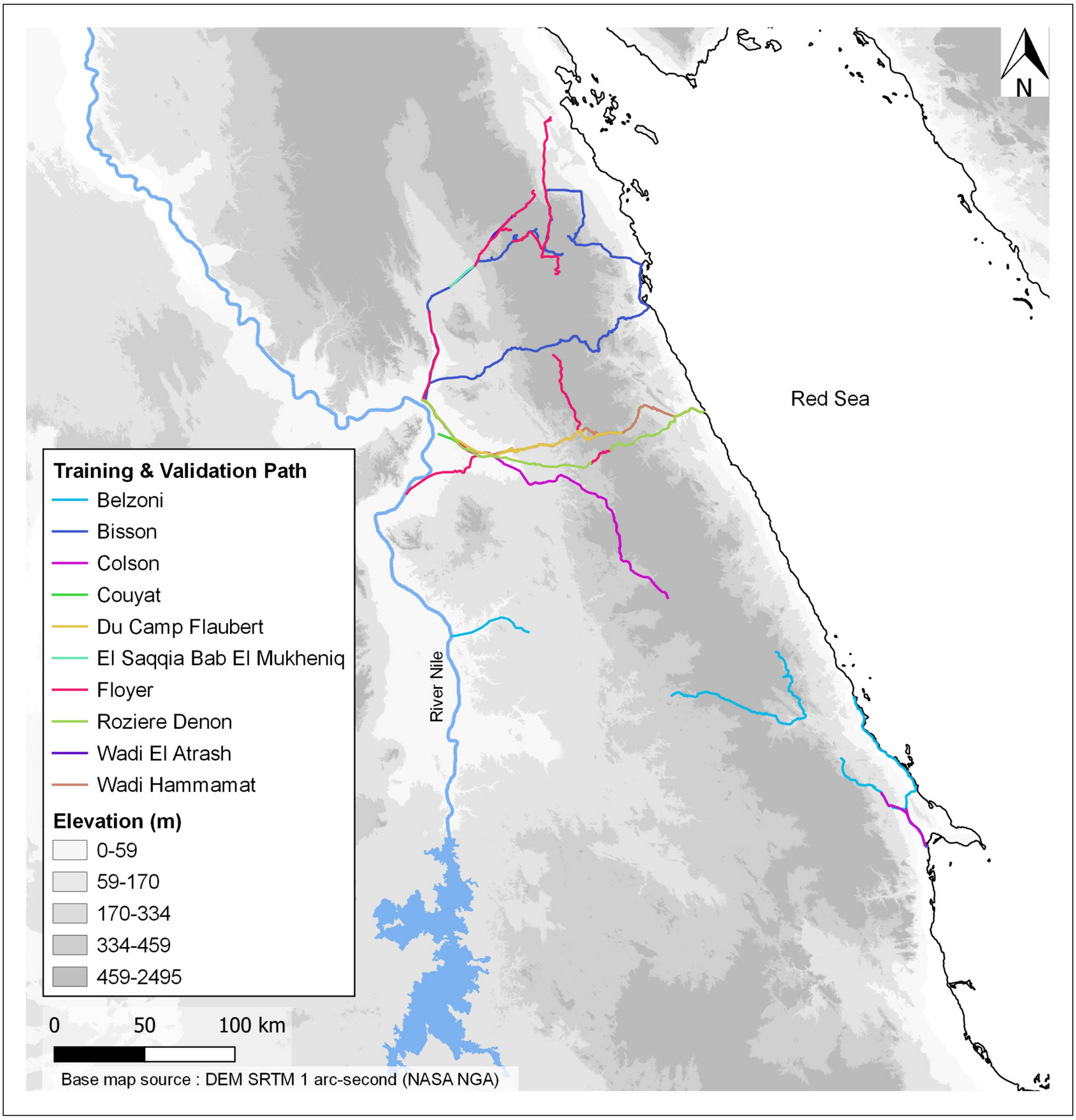

Figure 3 Travelers' itineraries used for model training and validation.

3.2 TRAVELERS' INFORMATION ABOUT THEIR ITINERARY CHOICES

Analysis of the slopes crossed by travelers during the steps shows a strong preference for gentle slopes (+/– 5%), and a high sensitivity to slopes greater than 10%. Travel by loaded camel is much more sensitive to the topographical factor than that by a person on foot; however, the lack of reoccurring data on the duration and distances travelled makes it impossible to propose a slope/speed travel model for these camel trips. An average speed of 3.9 km/h (+/– 1.45 km/h) can nevertheless be calculated over the 30 steps studied in a previous article (Crépy, Manière and Redon Forthcoming). These values agree with the 3 to 4 km/h described in the Arabian Desert for loaded camels (Rennell 1791), a speed that was also compared to other means of transport by Bevan (2013), as well as with the 4 to 5 km/h for pack camels recorded in the 1980s (Schwartz 1986). This is also consistent with the reference value of 4 km/h taken by geologists and topographers from the Survey of Egypt at the beginning of the 20th century to map the Eastern Desert, when no surveyor's wheel was available (Barron and Hume 1902: 3–4).

In the accounts, the travelers recount their experience of the trip, the difficulties of the terrain, and sometimes the choices that motivated their journey. This information makes it possible to qualitatively characterize the different factors leading to camels' movements in the Eastern Desert. Some accounts mention a camel's difficulty to move over certain surfaces or on certain slopes; that they were likely to slip and injure themselves on angular and smooth surfaces, such as rocky outcrops (Du Camp 1860: 270; Flaubert 1910: 244–245); and that areas of coarse sedimentary deposits were unsuitable for them to walk across (Tregenza 1955: 4). Conversely, the surfaces that were most suitable for walking were areas of sandy-gravelly deposits of wind or river origin. Belzoni (1820: 317) sums up the situation of surfaces and slopes admirably: 'A steep and craggy road over a mountain is no more adapted to a camel than the deep sand of the desert to a horse'.

In the plateau sectors, where landmarks were rare, travelers or their guides made the wadis their preferred means of travel, even at the cost of long detours, and referred to constructed markings (Crépy, Manière and Redon Forthcoming; Cailliaud and Drovetti 1821: 59). These valleys offered safe orientation corridors, especially for night walks, with good terrain conditions. Similarly, near the Red Sea Hills, in areas of the plateau where the wadis followed by travelers were very steep (to the point of giving Floyer (1887: 663) the impression of being at the bottom of a trough), markers (cairns or masonry blocks) were placed on either side of the tributary to be followed to indicate the preferred route for penetrating the mountains, thus limiting the risk of reaching a dead end (Cailliaud and Drovetti 1821: 59). On the contrary, some roads were considered easily passable, especially between Qena and Quseir, because there were many landmarks, few junctions, and many wells (Browne 1799: 146–147; Floyer 1887: 661–663).

3.3 MAPPING COST LAYER (PATH DECISION FACTORS)

Path computation requires the mapping of identified movement factors. In Antiquity, like in modern times, camel caravans have been able to pass through narrow passages if allowed by travel conditions. The accuracy and resolution of each mapping must therefore be as fine as possible in order to reflect this reality in the calculations. The reference spatial resolution was set at 11 m in accordance with the resolution of the Digital Elevation Model (DEM) that covers most of the mountainous areas in our study. The DEM is a combination of the TanDEM-X 0.4 arcsec (~11 m over our study area) provided by the German Aerospace Center (©DLR 2019), and the SRTM 1 arc second (NASA and NGA) reworked by ATDI at 25 m and resampled at 11 m in the sectors not covered by the former (***Figure 4***).

3.3.1 Mapping the preferential surface for camels

Two types of surface that could influence a camel's walk were distinguished: the easy sandy-gravel walking surfaces, mainly found in the lowland areas near the Nile Valley, the coast and the wadis; and the difficult rocky outcrops and coarse deposit surfaces that the travelers sought to avoid. Identifying all these surfaces depends on various geological, topographical, and erosional dynamics parameters, but it is through photo-interpretation of textures and arrangement that they are best identified; thus, although a meticulous cartography based on satellite images allowed us to obtain very good results, it was also exceptionally time consuming.

The proposed method for terrain mapping is a compromise between efficiency and the accuracy needed to identify narrow sandy-gravel valley bottoms (***Figure 5***). The first step is to roughly map large mountainous areas using satellite images, the DEM, and geological maps (Geological Map of Egypt, 1978, 1:500,000), making it possible to distinguish the most coherent rocky areas from the looser sectors derived from Tertiary limestone rocks, Cretaceous clastic rocks, and areas of Quaternary alluvial and aeolian sedimentary deposits. Manually mapping the edges of these areas, especially where rock outcrops and sandy deposits mix, is time consuming; however, they can be mapped more easily using Landsat8 OLI panchromatic images (NASA, 15m resolution), with the shadow they produce on sandy deposits minimizing mapping inaccuracies. The edges of mountainous areas and outcropping rocks can be identified by filtering the satellite images with a reflectance threshold below 11,000. Areas identified in this way are vectorized and then merged to the general delimitation of mountainous areas and corrected locally if necessary.

The valley bottoms were identified by the construction of a theoretical hydrographic network, generated by calculating the flow and accumulation directions using the DEM. Sandy-gravel deposits in valley bottoms can be distinguished to a minimum watershed size of 0.1 km^2. This value was used in the stream definition determining the basic section of the network. Each fragment of the network was characterized by its Strahler rank (Strahler 1957), a method of hierarchizing river networks, in which each section without a tributary has a value of 1 and a section of order n+1 is generated by the confluence of two sections of value n. A buffer around the sections of the network has been developed so that the elementary sections are two pixels wide (where each pixel represents 11 m) and each buffer is twice as wide as its Strahler rank. Thus, the area covered by the valley bottoms increases from upstream to downstream from the confluences. This value, of twice the Strahler rank, allows a good representation of the narrow valleys at the head of the watershed and avoids covering too large areas downstream, on rocky zones. The large mountainous areas are then cut by these areas of the hydrographic network. This method has the advantages that it can be carried out quickly; plus, it allows the easy identification of sandy-gravelly valley bottoms with little manual correction, even in narrow passages. However, this technique lacks precision because it simplifies the wadi bottoms and turns them into corridors of fixed width (***Figure 6***).

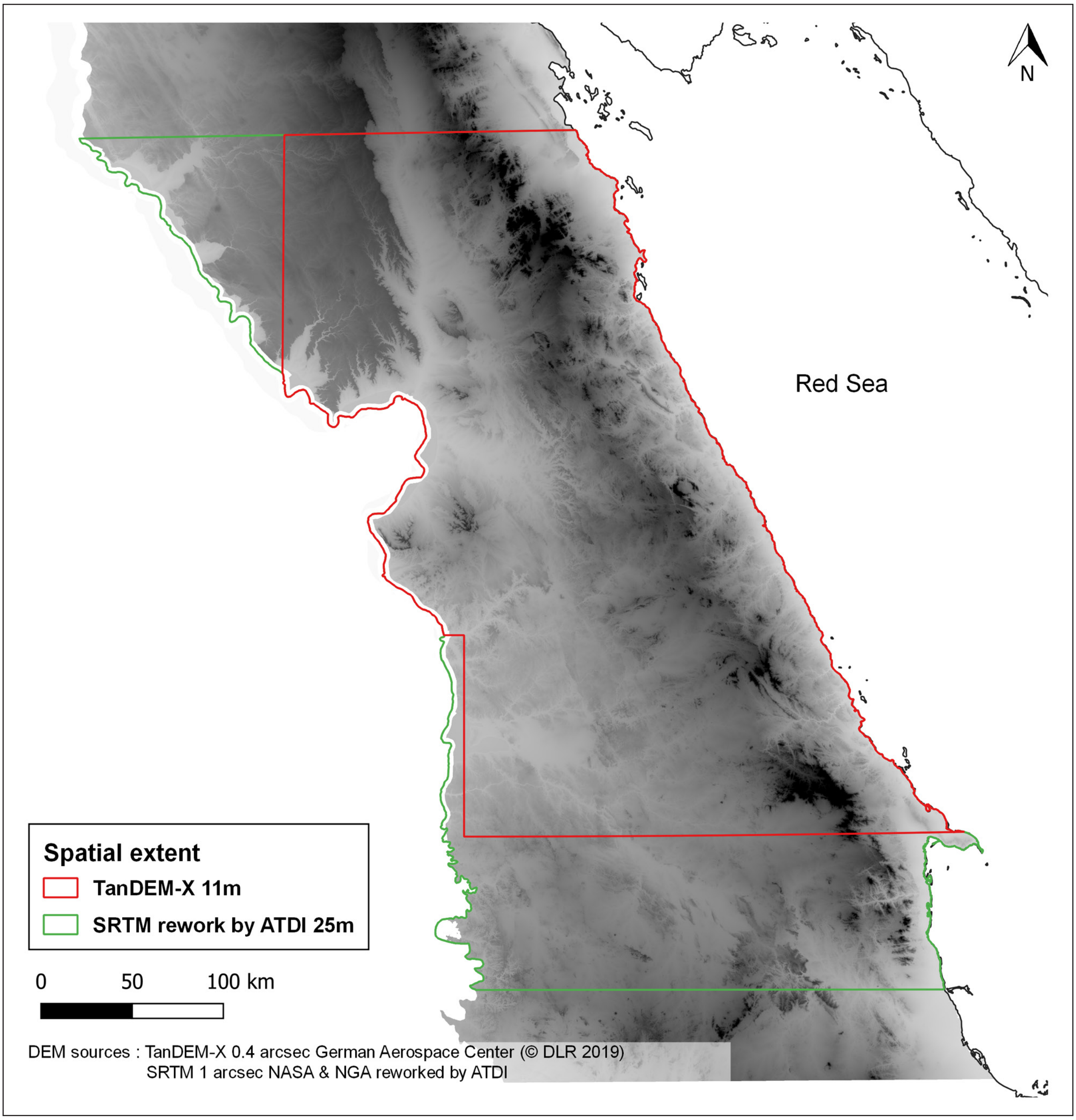

Figure 4 Spatial extent of the respective DEMs.

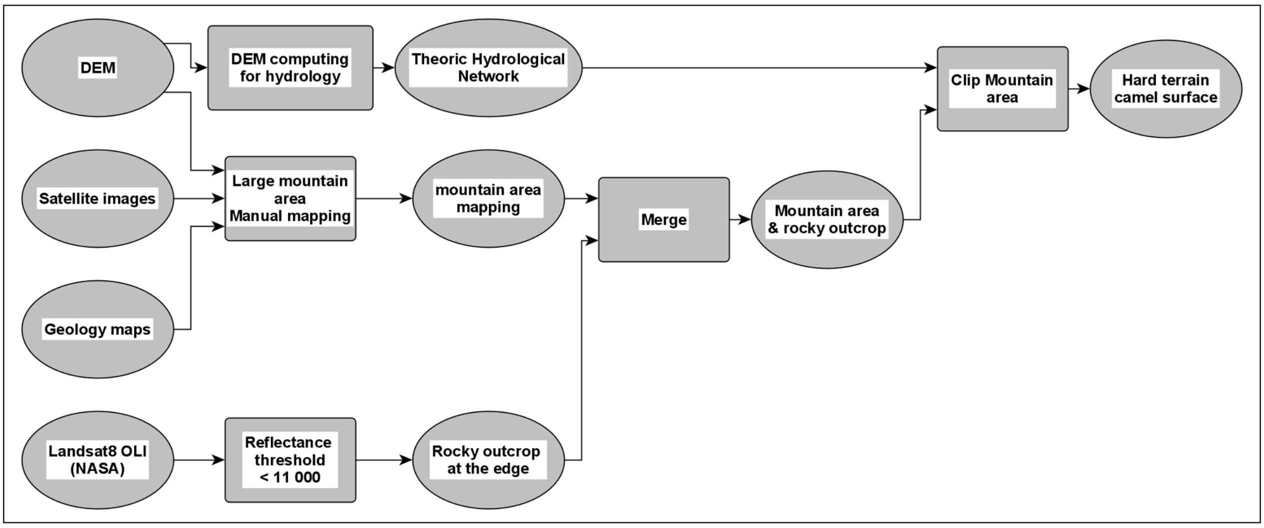

Figure 5 Workflow for mapping difficult terrain surfaces for camels.

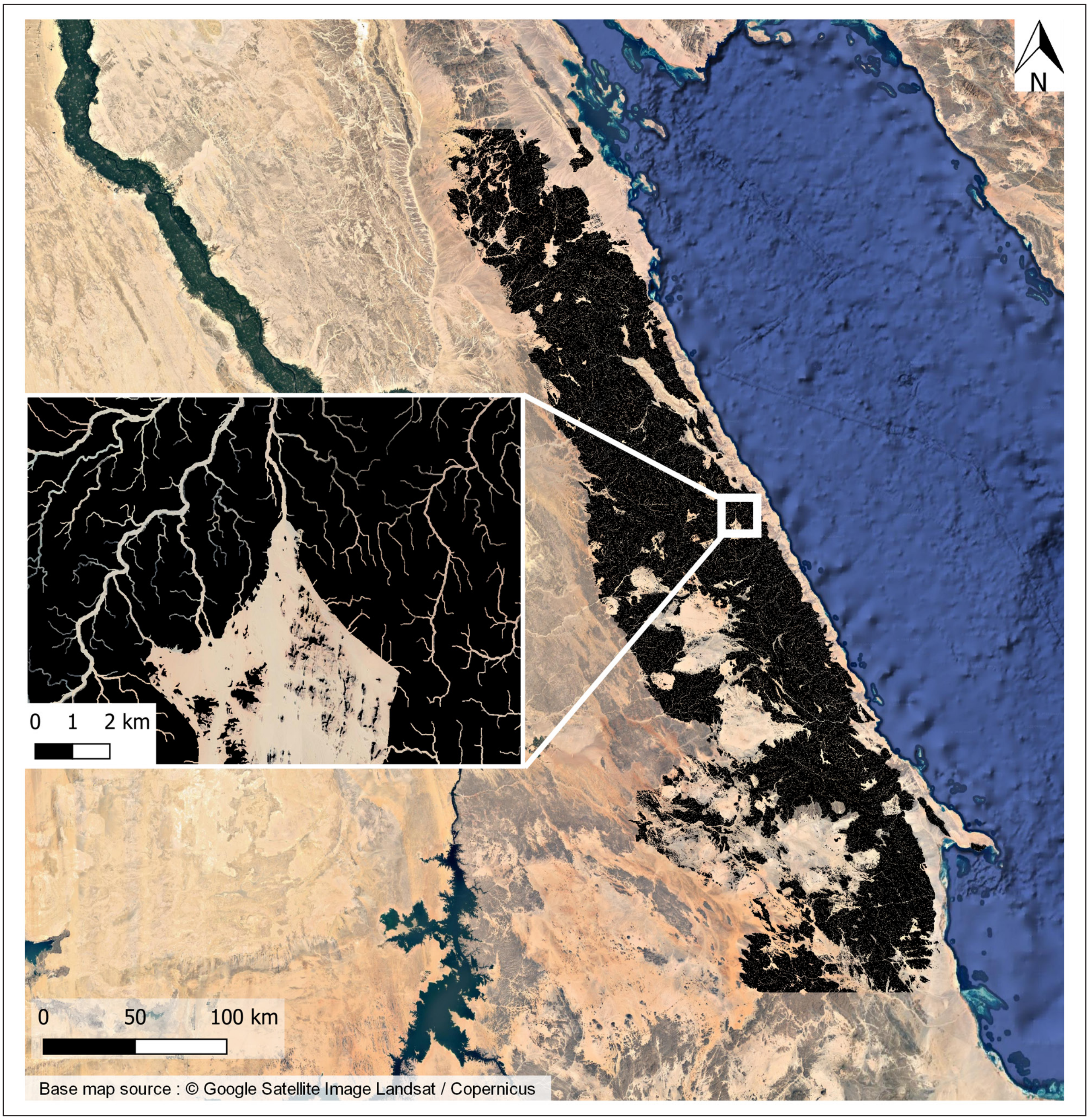

Figure 6 Map of difficult walking terrain for camels (in black).

3.3.2 Mapping navigation

In the absence of a built road (no ancient roads were paved in the Eastern Desert, except perhaps some small portions of the Via Nova Hadriana), the natural paths preferred by travelers were the wadi valleys. To identify these in the non-mountainous part of the desert, i.e. in the essentially sandy-gravel plain to the west of the region and on the Red Sea Coast, the theoretical hydrographic network was used in the same way as for defining the sandy-gravel valley bottom areas in the mountainous sector. A buffer of twice Strahler's rank for the hydrographic section was used to obtain a walking surface proportional to the size of the valley. The mountainous area was not considered because of numerous landscape landmarks and because natural paths in the valley bottom were already preferred for their walking surface (***Figure 7***).

Outside the wadis, routes were traced using cairns that were regularly present to guide travelers (Cailliaud and Drovetti 1821; Sidebotham 1996). In the highly frequented zones, traces of earlier caravans were also elements of orientation outside the valleys. These paths were not taken into account in this first cartography. At present, too few of these routes (ancient or modern) are listed but analysis of those already known will enable interpretation of their benefits on the concerned routes. Systematic mapping of these roads could complement this orientation representation and thus improve the results produced by route calculations.

3.3.3 Mapping logistics

According to modern travelers, the crossing of Egypt's Eastern Desert can last from three and a half days

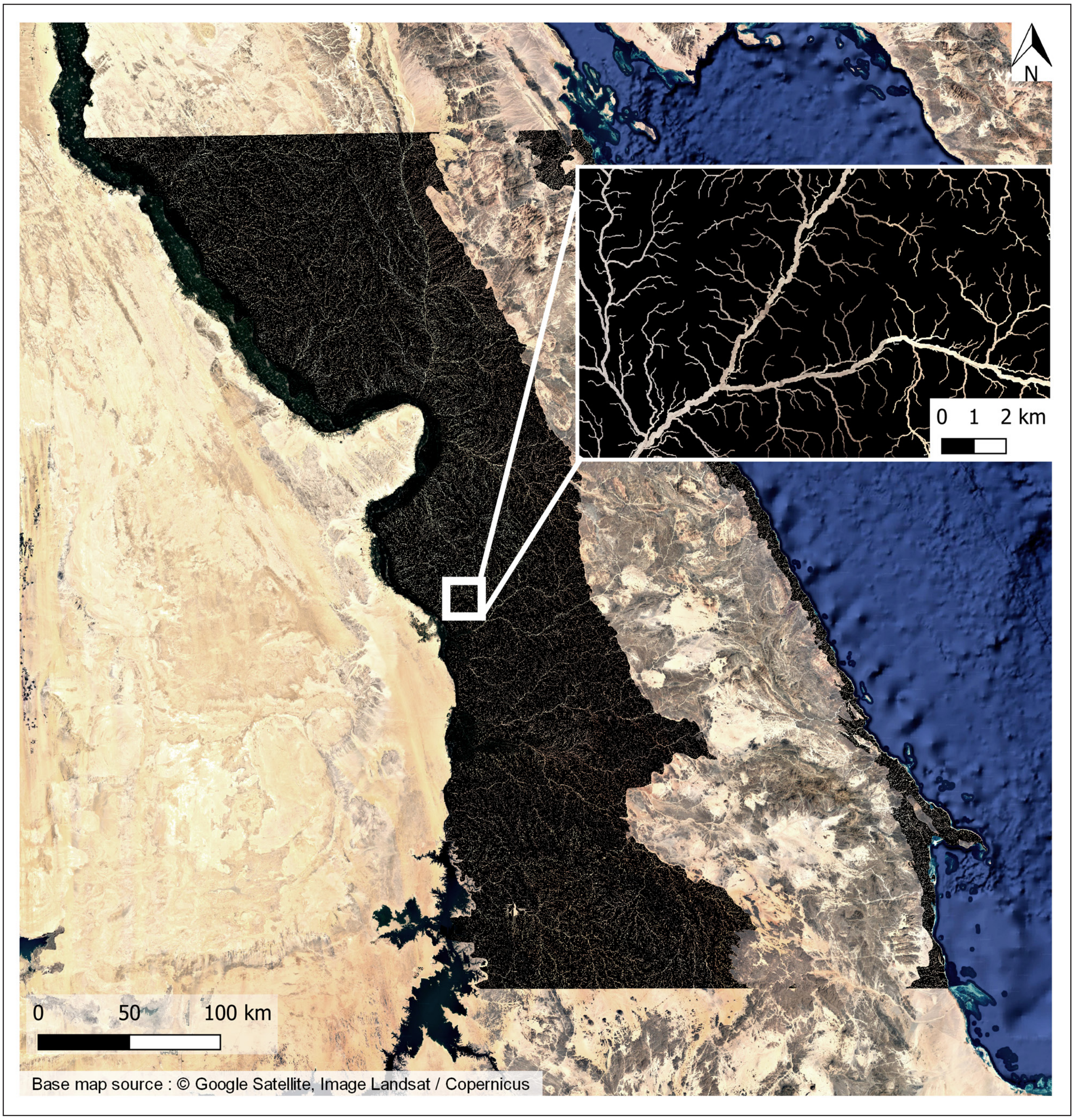

Figure 7 Map of difficult navigation (in black).

to several weeks, depending on the purpose of the trip and the route chosen. Logistics are organized around infrastructures designed to ensure the rest, water (and sometimes food) supply, and safety of passengers and their animals. Archaeological sites, usually including a water supply source, and water points (ancient and modern) have been inventoried and located within the archaeological database of the Desert Networks project. The mapping of ancient water points was complemented with modern data provided by the Egyptian topographic maps 1/50,000 (Egyptian General Survey Authority, 1989–1990) and 1/250,000 (Army Map Service, Corps of Engineers, U.S. Army, 1953–1960). Many of the watering places present are indeed rehabilitated old wells that show a variable use over time, between closure and reopening (Crépy, Manière and Redon Forthcoming; Crépy and Redon Forthcoming). The watering places in this context reflect possible itinerary steps depending on whether or not the road was used, and materialize the availability of water resources that has probably not changed since Antiquity (Crépy and Redon Forthcoming). A total of 457 infrastructures were used in the development of the network, i.e. 253 archaeological sites and 204 watering places, both natural and man-made (*Figure 8*).

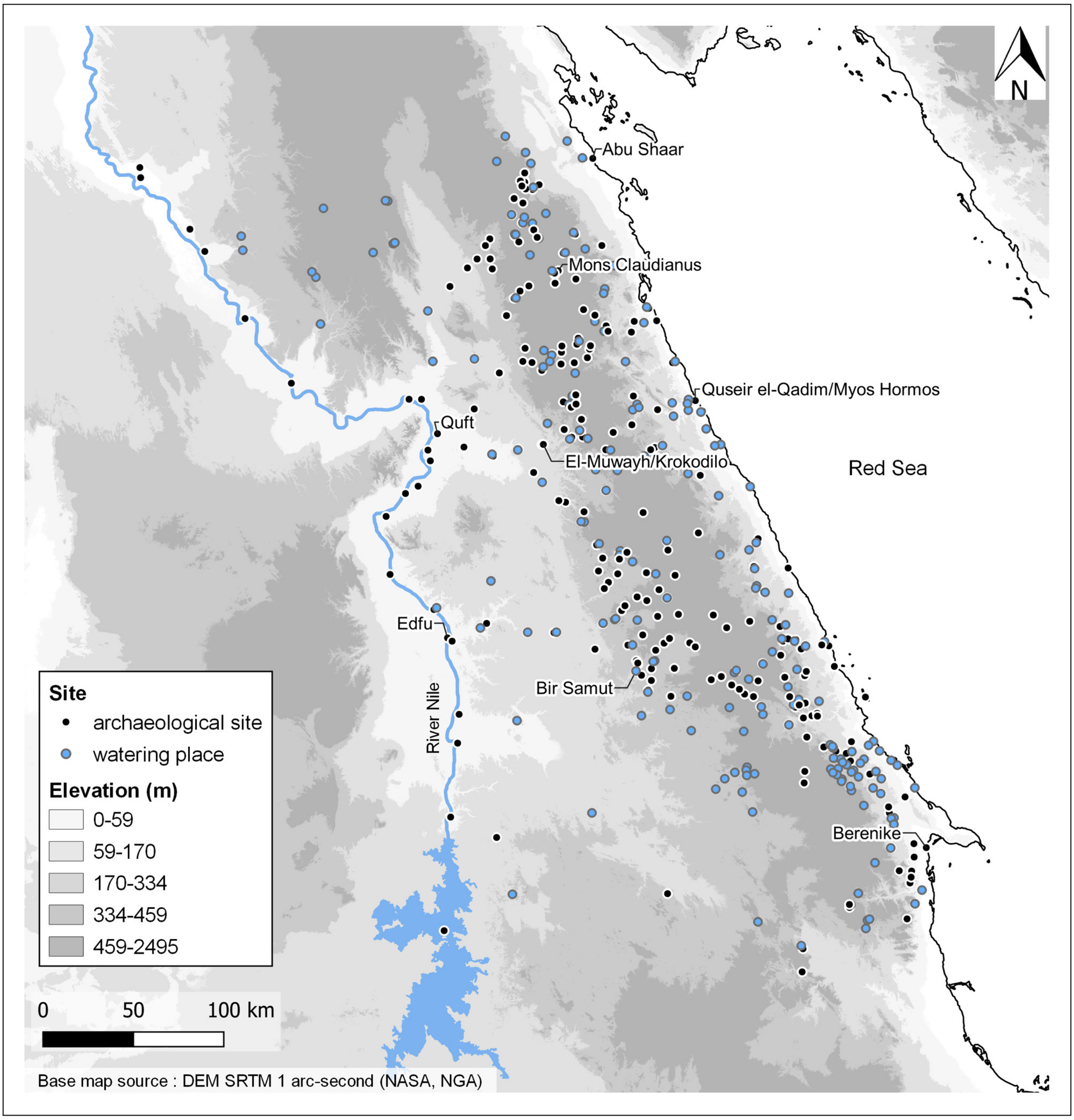

Figure 8 Sites and watering places.

4 CALIBRATION AND VALIDATION PROCESS USING TRAVELERS' PATHS

4.1 CALIBRATION AND VALIDATION DATASET

The calibration and validation of the costs represented by each of the trip factors was carried out by comparing modeled itineraries with the reconstructed legs of travelers' journeys. Two sets of data were created. A training dataset of 56 stages from the Belzoni, Bisson, Colston, and Couyat trips corresponding to a cumulative distance of 1,343 km. A validation dataset of 50 steps using the voyages of Floyer, Du Camp and Flaubert, Rozière, and Denon, and also from the known ancient routes of Wadi Hammamat, Wadi El-Atrash, and between El-Saqqia and Bab El-Mukheniq (*Table 1*). These routes have a cumulative distance of 1,103 km.

Calibrating or verifying the least cost paths using actual journeys requires that these steps correspond to the best possible journey between the starting point and the destination, with no intermediate stages influencing the trajectory. The steps were therefore selected for the reliability of their reconstruction, but also according to their distance and purpose. The distances traveled should not be too long (the maximum distance travelled is 72 km), in order to avoid the need for travelers to make detours to water points or rest areas. Also, the route of each step should not be influenced by particular points of interest or by tourism that would force the traveler not to take the best possible route (e.g. presence of archaeological sites, inscriptions, or geological curiosities).

4.2 COST LAYER CALIBRATION AND VALIDATION PROCESS OF THE MODELED PATH

The objective of camel walking surface and orientation constraint mapping is not to prohibit areas considered as non-preferred but to assign a higher travel cost to them. Thus, from this perspective, the traveler can choose to cross them but, depending on the cost value, they will only be able to do so over limited distances. In the same way, travel costs are assigned to slope value intervals for DEM between –25 and 25 degrees of inclination. A critical slope of 20 degrees (or 37%) can be deduced from the analysis of travelers' documents and itineraries (Crépy, Manière and Redon Forthcoming); therefore, a higher threshold of 25 degrees was chosen in order to take into account slope uncertainties and spatial representativeness.

Calibration of these three factors is carried out through a succession of trial and error by varying the cost values so that the modeled routes correspond as closely as possible to the training dataset. Between –25 and 25 degrees, an arbitrary cost is initially assigned to each degree of the slope and to navigation and terrain surface factors. The cost values are gradually adjusted so that a calculated least cost path fits as closely as possible to a traveler's step in the training dataset. Further adjustments are made to the cost values to simulate another step. These modifications then need to be checked to ensure that they still allow the first step to be reproduced, before proceeding with all calibration data so that the correct valleys are followed by the LCPs. The choice to change one cost value rather than another among the travel factors was made by studying LCP variation and by understanding the travelers' decisions to reach their destinations. Analysis of the sectors and slopes crossed by the unsatisfactory part of the LCP allowed us to identify the factor or slope to be refined.

The cost grid was generated by adding navigation to the terrain surface minus one, in order to keep a value of one for the best travel conditions. This grid was multiplied by using the topography as a vertical factor. In the absence of a camel cost allocation function for slope intervals from experimentation, their calibration was achieved in an isotropic way. As the routes are highly influenced by logistical steps, the outward and return paths are mainly slope variants within the same valley. This choice also facilitates the calibration process and the readability of the results by avoiding the direction of the slope.

Uncertainties in training and validation routes as well as travel constraint mapping are difficult to quantify. This information is based mainly on the analysis of landscape morphology, desert toponymy, i.e. the valleys, passes and places that have been traveled, rather than on the accuracy of distances. Thus, it can be ascertained that the traveler has taken one valley, not another, but generally it is not known whether they traveled on a particular slope, at the bottom of a valley, or alternately in these different positions. Nevertheless, the analysis of caravan tracks observed on satellite images indicates that, barring major obstacles (incision), the valley bottom and alluvial terraces were crossed at the shortest possible distance. The most important gaps were found in the large wadis tributaries of the Nile (in particular the Wadi Qena and its direct tributaries) and in the Nile Valley itself. Possible trajectories are more numerous in these low-slope areas and the Nile's development (canals and dikes) was not taken into account in the displacement factors. Travelers' routes have the characteristic of moving rapidly away from the river, along the edge of the desert. Agricultural developments, especially the Nile Valley irrigation canal systems, hamper travelers' ability to follow the river, as highlighted by Floyer (1887: 663): 'the surface of the fields themselves is baked into deep crevasses, making them dangerous to ride over, so that short cuts cannot be made. The banks which control the inundation wind about so much as to sometimes nearly double the distance from point to point'. This explains why travelers ride across the desert between Qena and Bir Ambar, almost parallel to the Nile (Bruce 1790; De Rozière 1813), even though it takes them away from the river. In proportion to the uncertainties, the accepted deviations from the training and validation data are therefore higher in the wide valley bottoms of lowland areas than in steep mountain areas.

The quality of the calibration and validation results was evaluated by measuring the differences between the route taken by a traveler and the route modeled by the least cost path algorithm (***Figures 9*** and ***11***). Quantitative information allows the uncertainties of the reconstructed paths to be evaluated according to the areas crossed, but only a visual diagnosis can assess the errors. Indeed, the working scale being the wadi, a road is considered valid as soon as it follows the right valley, independently of its width.

This procedure for calibrating and evaluating lower cost routes resulted in a combination of cost values for each trip factor where the entire training dataset could be validated (Appendix A). Using this combination, we were able to replicate the validation dataset with the same validation criteria.

The mean lengths of training routes and LCPs were 24.0 km (Standard Error (s.e.) ± 1.7 km) and 25.6 km (s.e. ± 1.8 km) respectively, an overestimation of LCPs by 1.7 km (s.e. ± 2.4 km) (***Figure 9***). However, when studying length deviations, it is important to take into account that two routes may have similar lengths for different trajectories. For a better estimate of the differences between each LCP and its training route, the area of deviation between them was calculated (***Figure 10***). In order to obtain a variation of area per kilometer of route (defined here as normalized area deviation) the area of deviation is related to the length of the training path, allowing for comparison of data.

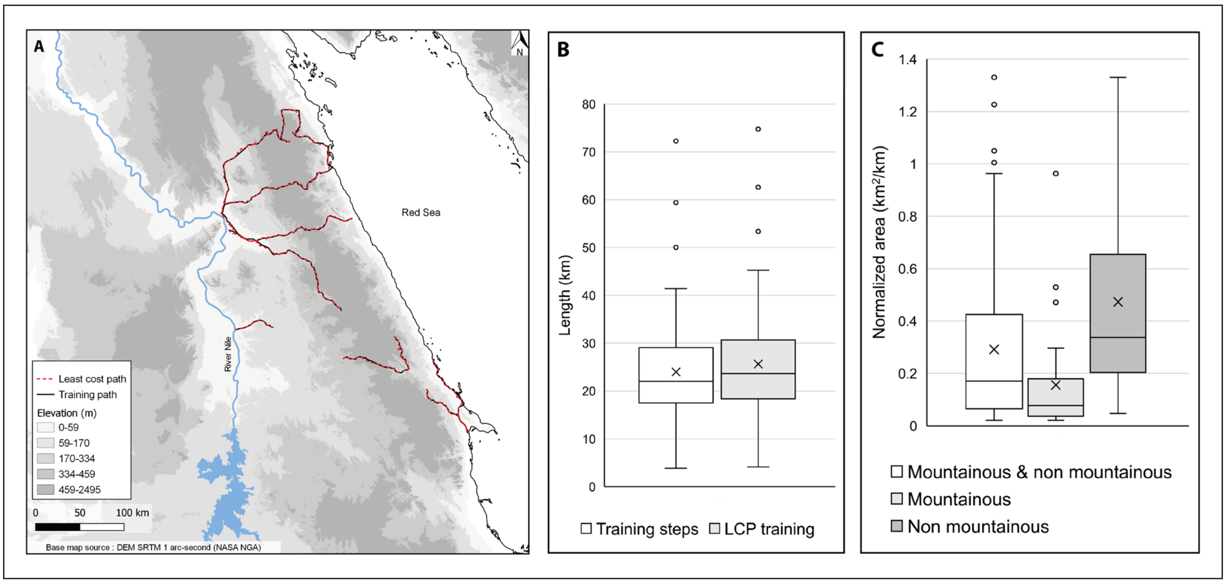

Figure 9: Training and least cost path with movement factor cost combination (Appendix A). **A:** LCP results (after movement factor grids calibration on training path dataset). **B:** Training paths and LCP lengths. **C:** Normalized deviation area between training paths and LCP.

Figure 10 Area deviation example on Couyat's training step path.

This method to compare trajectories between several paths is similar to the Path Deviation Index developed by Jan, Horowitz and Peng (1999), except that the denominator of our index is the length of the training or validation path rather than the shortest path (Equation 1). Our objective was therefore to always compare the deviation surface with the reference path. An index of 0 means that the paths are identical, and the value of the index increases with the deviation of the modeled path.

$$\text{normalized deviation area} = \frac{\textit{deviation area } (km^2)}{\textit{training or validation length } (km)} \quad (1)$$

This normalized area deviation shows that 50% of the LCPs have deviation areas of less than 0.17 km^2 and 75% have deviations of 0.43 km^2 per training path kilometer. In order to characterize the highest uncertainties in the wider valleys and on the banks of the Nile, the routes were characterized by the majority of the terrain they crossed from the delineation of the mountainous areas used for the travel factors. Thus, among the largest differences observed, the latter are mainly found in the non-mountainous routes with medians of 0.18 km^2/km and 0.65 km^2/km respectively.

The mean lengths of the validation routes and the corresponding LCPs were 23.0 km (s.e. ± 2.3 km) and 24.7 km (s.e. ± 2.5 km) respectively, an overestimation of the LCPs similar to that of the training data of 1.7 km (s.e. ± 2.5 km) (***Figure 11***).

The normalized area of deviation shows that 50% of the LCPs on the validation runs have deviation areas of less than 0.12 km^2 and 75% have deviations of 0.36 km^2 per kilometer. For the majority, the deviations are therefore slightly smaller than those observed on the training data. Nevertheless, some high values were observed on the routes near the Nile and for some sandy areas within the mountain ranges (***Figure 11***). The difference between mountainous and non-mountainous routes is reflected in the deviations from the validation routes; the medians were 0.06 km^2/km and 0.44 km^2/km, respectively.

The increase in uncertainty with the widening of valleys and the multiplication of paths through areas is reflected in the quantification of discrepancies between the LCPs and the training and validation data. An intermediate solution to taking into account the size of these transport zones may be the analysis of a lower cost corridor (Surface-Evans 2012); however, the creation of preferential travel zones is incompatible with our objective of creating a network.

5 NETWORK COMPUTING

Building the network requires multiple low cost path calculation operations to be carried out on all the sites to be linked. In this study, we built a network based on 253 archaeological sites and 204 watering places. The low cost itineraries, generated with the three calibrated travel factors, were created by iteration from each point to the other 456 sites (***Figure 12***). This network connects all the sites in pairs with no prior assumptions about the structure or hierarchy of the network, in order to obtain the fastest and most direct routes possible (Waugh, 2000).

This method generates many duplicates and micro-sections, and several lines can form a segment between two nodes of the network. These routes were therefore processed and generalized to remove duplicates and sub-routes within 40 m of each other, and create continuous edges between each node. The total travel costs for each edge were then recalculated to estimate the difficulty of the route. More details about the process and data used are available in the associated data paper (Manière, Crépy and Redon 2020).

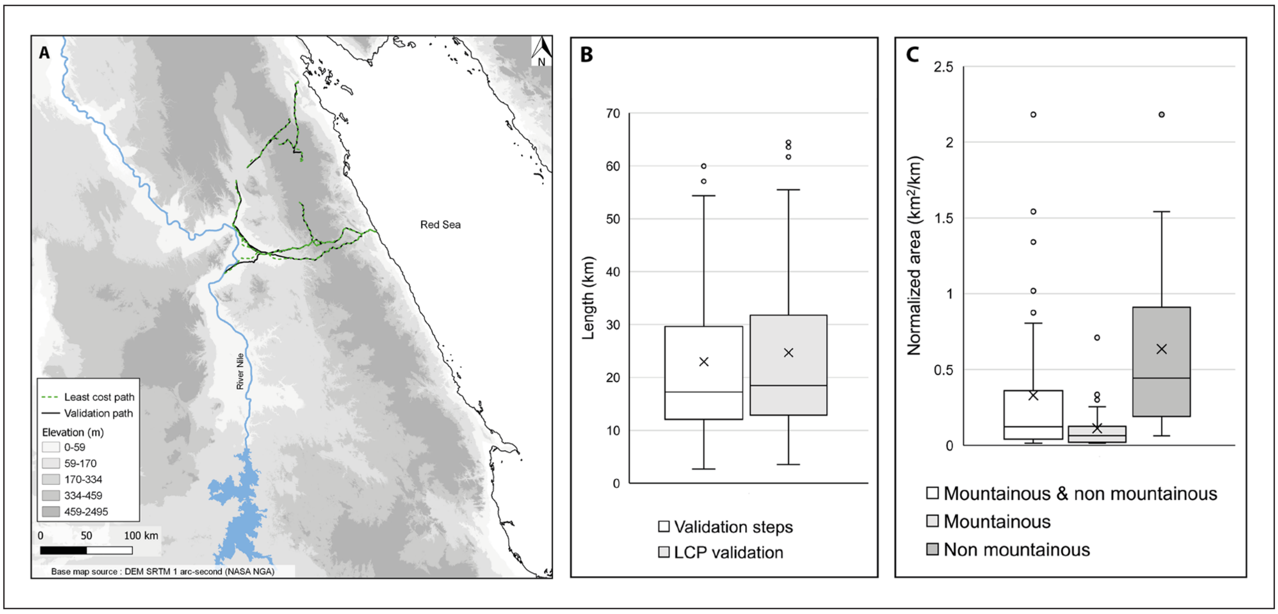

Figure 11 Validation and least cost path with movement factor cost combination. **A:** LCP results (after movement factor grids calibration on training path dataset) and validation paths. **B:** Validation paths and LCP lengths. **C:** Normalized deviation area between validation paths and LCP.

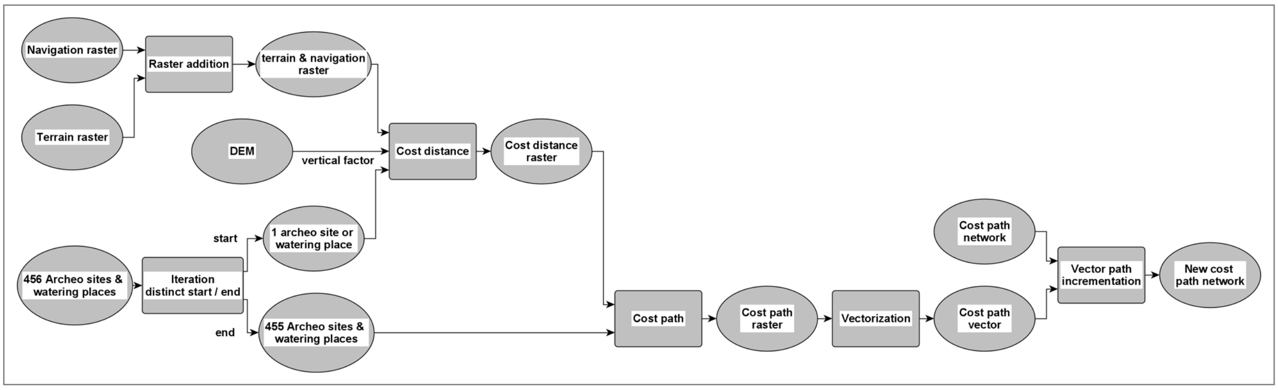

Figure 12 Network computation workflow.

6 RESULTS AND PERSPECTIVES

The current DN network provide routes reflecting the reality of the terrain between many archaeological sites, rather than a virtual and largely simplified network, which can be used in a variety of ways (***Figure 13***). Below we present the first achievements and studies carried out since its creation during the summer of 2020; however, as previously mentioned, how the results impact on our knowledge of the Greco-Roman roads of the Egyptian Eastern Desert will not be addressed within the scope of this article.

The first application of the DN project has been in assisting the photo interpretation of satellite imageries by visualizing the terrain crossed by these roads. In only eight hours of photo interpretation, on images provided by Google Earth Pro and Microsoft Bing Maps, 57 new points of interest have been identified, ranging from isolated tombs to multi-building sites that were previously unreported, as well as 14 new road sections—including 8 sections (total length: 4418 m) corresponding to an ensemble covering approximately 10 km as the crow flies (***Figure 14***). As with all the new sites and roads we anticipate will be identified over the coming months thanks to this model, field prospection will be launched to qualify them and their potential archaeological value.

The second application is the classic GIS use of a network to generate routes with lower cost (for example the shortest path tool developed within the QGIS software). With our model, for example, it is possible to establish paths minimizing the distance travelled between two ancient sites, or the difficulty of the journey by varying the intermediate steps of the road, making it possible to test different hypotheses for a route and the occupation of sites. This method can be used to support hypotheses on infrastructure dating, which is the case for dozens of signal towers (*skopeloi*) identified by different surveys between Coptos and Myos Hormos (sixty-three towers have been securely located by us so far). Various dates have been proposed, mainly in favor of the Roman period, although the medieval period was also suggested, but the lack of archaeological material has made dating impossible (Brun, Cuvigny and Reddé 2003). However, using this application, the study of all possible routes between Coptos and Myos Hormos has established that the shortest route linking the two cities through the well-dated Roman sites and the watering places exactly follows the tower path, supporting a Roman chronology (Crépy, Manière and Redon Forthcoming).

Besides being a validation tool for research hypotheses on the chronology of road infrastructures, the DN model can also be used to verify assumptions made on the roads' layout. An initial test was carried out on the access road to the Porphyrites quarries (quarries of porphyry) in Roman times, which was originally placed by the scholars in the Wadi Atrash, which passes through Bab el-Mukhenig, Deir el-Atrash, Qattar, and the Wadi Belih. The work carried out in 2020 by the MAFDO[4] in Ghozza, located in a small tributary wadi of the Wadi Atrash, demonstrated that another route to the Porphyrites was possible. The excavations uncovered a previously poorly known Roman fort, built on the site of an important gold mining village and dated to the Hellenistic period. The fort dates from the early Roman period, when the porphyry quarries were activated, but was abandoned quickly, probably at the end of the 1st century AD, when the peak of porphyry exploitation was reached in the following century. The archaeologists assumed that the initial route to the Porphyrites was opened in the 1st century AD, through the Wadi Ghozza. When this proved too complicated to cross it was replaced by the Wadi Atrash "highway", where a new fort, the Deir el-Atrash, was built. The reconstructed network makes it possible to confirm this hypothesis and the Wadi Ghozza as one of the routes reconstructed between the Nile Valley and the porphyry quarries (***Figure 15***). It is probable that the first route passed via Ghozza because the site was known to the desert travelers and was rich in water resources. However, when it became clear that the Wadi Atrash was easier to cross for the porphyry

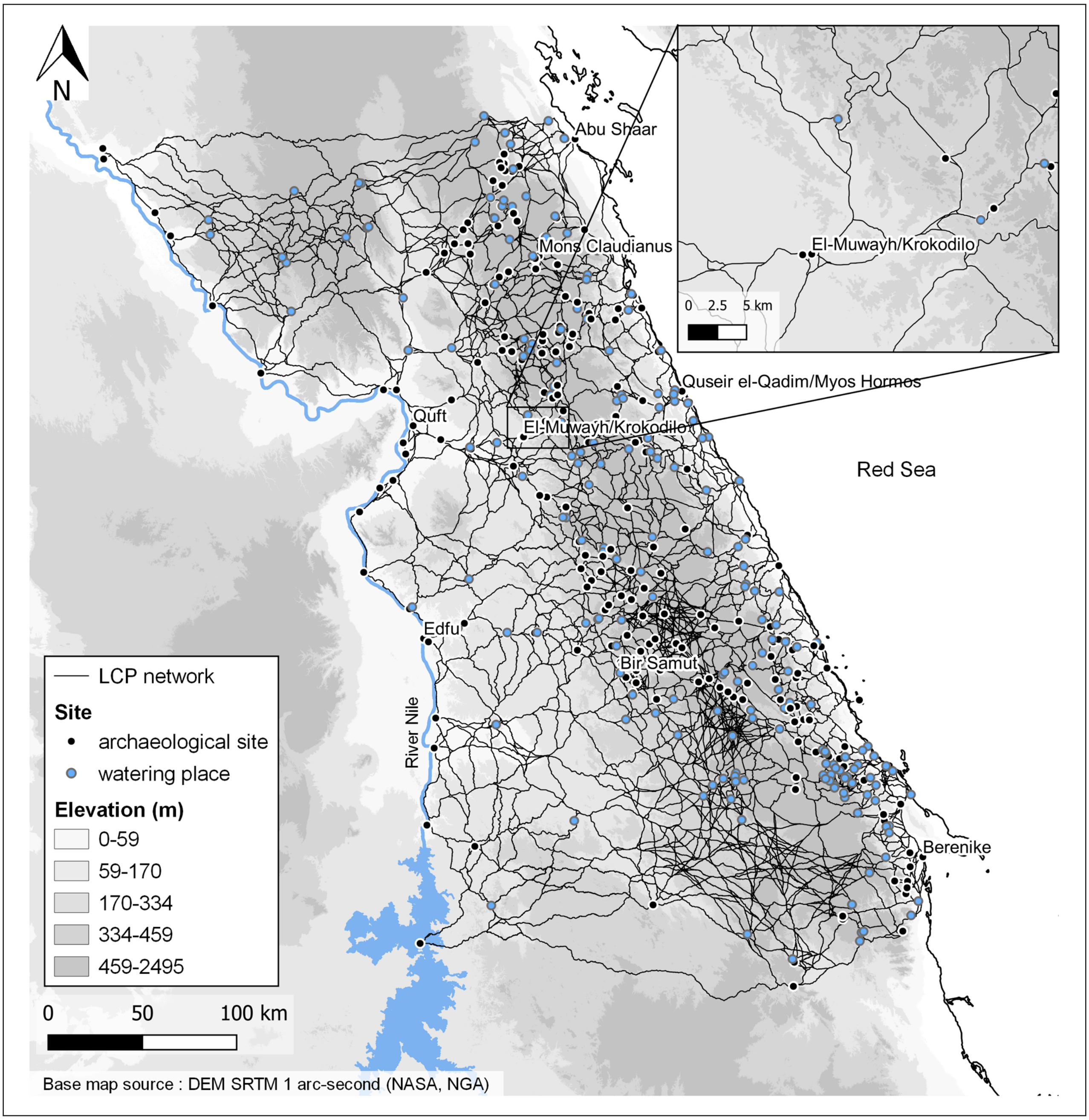

Figure 13 Least cost path networks of the Eastern Desert sites occupied from the New Kingdom to the Roman period.

loaded chariots, a new road was constructed (Gates-Foster et al. in preparation). The new road, activated by the Roman administration in the 2nd century AD, follows almost exactly the least cost path reconstructed by our model, highlighting once again the incredible ability and expertise of Romans engineers to find the shortest routes to build their roads.

The discrepancy between the DN network traced by the model and the roads determined by ancient sources can also be questioned. A good example comes from the Hellenistic route reconstructed between the sites of Abu Midrik and Abu Rahal: wadi navigation forces the DN model to draw a long route through the valleys, while a field survey conducted in the 2000s showed that the ancient route was shorter (Sidebotham and Gates-Foster 2019: Figure 3.178). Ancient travelers took this navigation constraint into account by setting up dozens of cairns to guide them out of the valleys, saving them a long detour. The cairns route can be effectively retraced by removing the navigation constraint from the model in this area. It also makes it possible to propose an alternative path to the one retraced by our colleagues on the second half of this road where the cairns are no longer preserved (Crépy, Manière and Redon Forthcoming).

Finally, the diachronic evolution of the routes over time can be studied in order to understand the original parameters in place for the creation of different networks during specific periods of occupation, enabling the choice of routes according to history, politics, and safety, as well as the aims of the intra-desert traveler to be questioned.

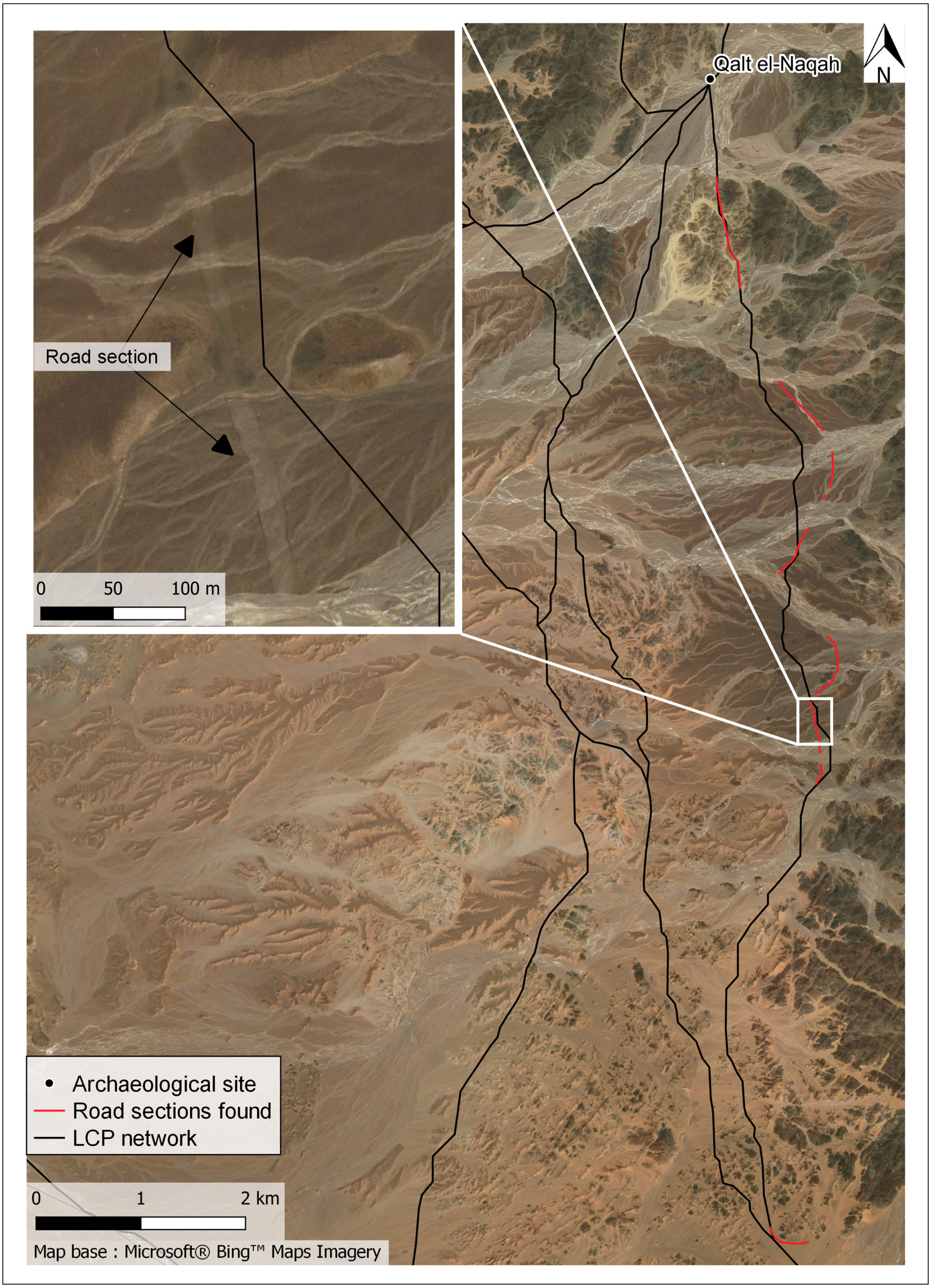

Figure 14 Road sections identified by photo interpretation for Qalt el-Naqah.

Work in this area is, however, yet to start; however, these analyses, which will involve comparing the modeled network with archaeological surveys, will be the subject of future publications, alongside more detailed case studies on each of the fields briefly mentioned in this paragraph.

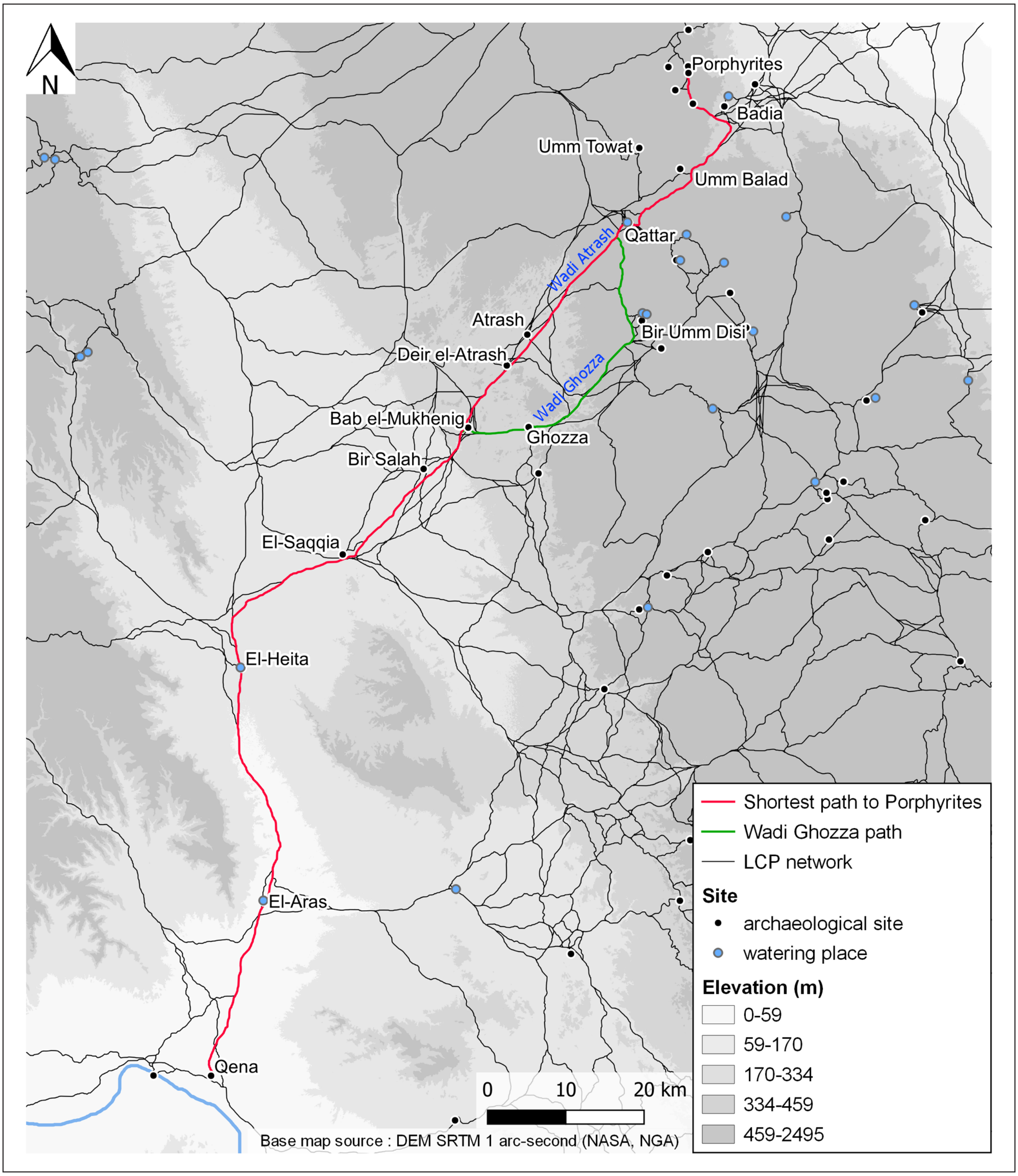

Figure 15 Shortest route from Qena to Porphyrites using the DN network.

7 CONCLUSION

The factors determining the routes used by travelers can be diverse and numerous (Murrieta-Flores 2010) and assessing their influence is a difficult exercise when modeling ancient routes. In the context of least cost analysis, it is necessary to spatialize these factors at the same spatial resolution, and assign them a cost function and weighting. Some social criteria or navigation are more difficult to take into account, and give a weighting to, than other factors. Even if topography remains the predominant factor for camels in the largely mountainous area of the Eastern Desert, the approach of this study has the advantage of being able to integrate more factors than just the slope, provided that they can be mapped at a similar resolution and that sufficiently accurate and reliable historical routes are available to serve as a basis for modeling. An analysis of the movement factors and routes carried out under similar conditions to those of Antiquity can produce a significant result without the need for a cost function specific to the means of transportation studied. Nevertheless, this approach shows greater uncertainties in lowland regions due to wider traffic areas and a lack of friction layers more specific to these areas, a bias that has already been pointed out for LCP modeling by van Lanen et al. (2015).

However, the semi-empirical approach presented here, original in that the model is fed via the analysis of modern journeys, has successfully determined various displacement factors. It also offers multiple network analysis possibilities to archaeologists studying the ancient Egyptian Eastern Desert, which will allow work to be carried out on ancient networks that was previously totally unthinkable. Since calibration is based solely on the ability of the routes to reproduce real itineraries without any underlying physical law or control experiments, this approach of analyzing the elements governing travel and calibrating from known routes can be replicated in other areas, although it remains specific to the mode of transport (camels) and the environmental particularities of the region (arid desert). A region with many watering places in wetter areas could lead to the creation of numerous unnecessary paths. Even if these locations may correspond to necessary stops, travelers may skip them in favor of a more strategic and higher quality resource profile. The navigation and terrain surface conditions lead the routes traced by the model particularly towards the wadis bottom. A navigation driven by infrastructures and/or more convenient mountainous terrain for camels will allow the model to produce paths on steeper slopes, and would probably require a new calibration with a more relevant slope influence.

APPENDIX A

Movement factor cost calibration parameters.

SLOPE ASPECT (DEGREES)	SLOPE COST	SLOPE ASPECT (DEGREES)	SLOPE COST	SLOPE ASPECT (DEGREES)	SLOPE COST
–25	24.8	–8	8.7	9	9.8
–24	23.9	–7	7.7	10	10.8
–23	23.0	–6	6.6	11	11.8
–22	22.1	–5	5.6	12	12.7
–21	21.2	–4	4.7	13	13.7
–20	20.3	–3	3.7	14	14.7
–19	19.4	–2	2.8	15	15.7
–18	18.5	–1	1.8	16	16.6
–17	17.5	0	1.0	17	17.5
–16	16.6	1	1.8	18	18.5
–15	15.7	2	2.8	19	19.4
–14	14.7	3	3.7	20	20.3
–13	13.7	4	4.7	21	21.2
–12	12.7	5	5.6	22	22.1
–11	11.8	6	6.6	23	23.0
–10	10.8	7	7.7	24	23.9
–9	9.8	8	8.7	25	24.8

TERRAIN	TERRAIN COST
Sandy-gravel deposit	1
Rough terrain	3

PLAIN NAVIGATION	NAVIGATION COST
Navigation outside of wadis	2
Easy wadi navigation	1

APPENDIX B

Illustration of the shortest path taken in the wadis, based on the remains of an undated caravan road near the Coptos–Myos Hormos road.

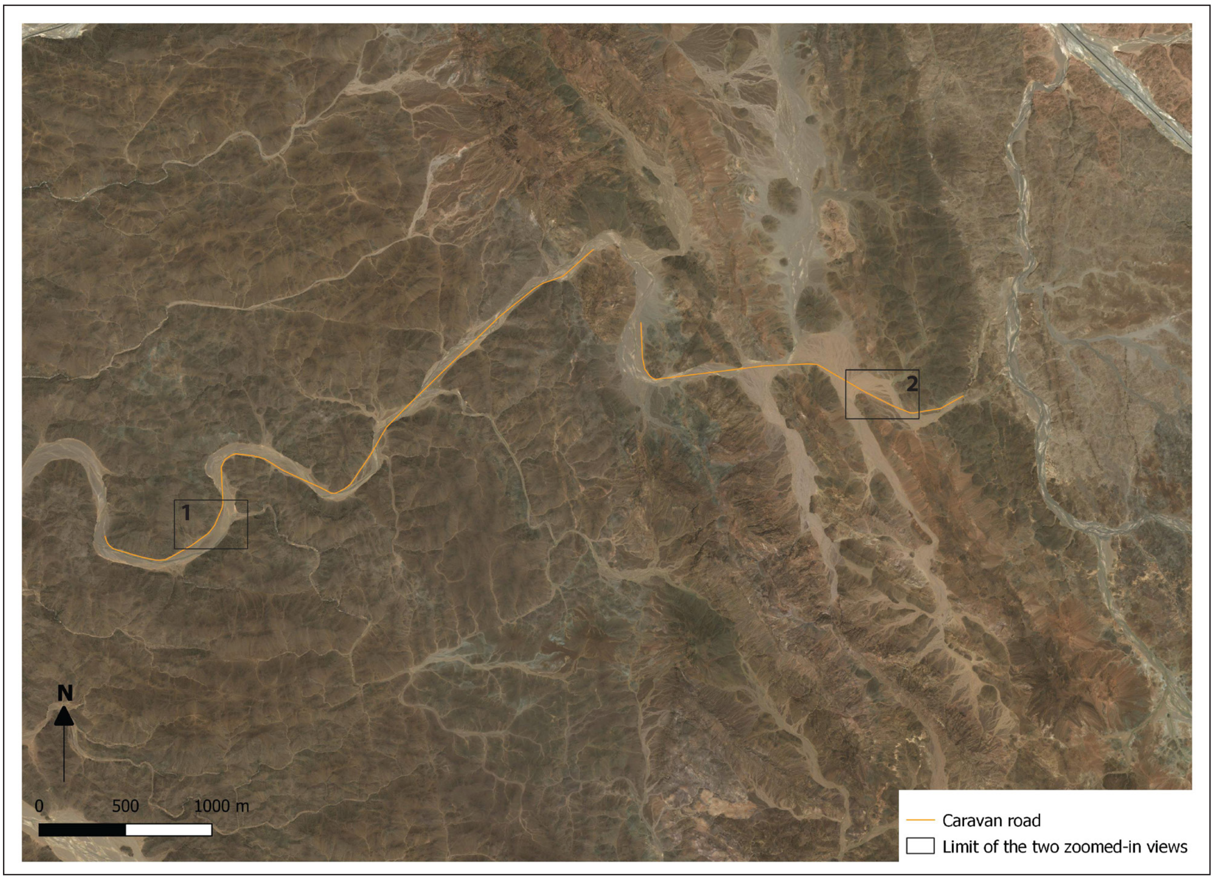

Figure 16 Caravan road near the Coptos–Myos Hormos road.

Figure 17 Caravan road near the Coptos–Myos Hormos road, zoomed section 1.

Figure 18 Caravan road near the Coptos–Myos Hormos road, zoomed section 2.

DATA ACCESSIBILITY STATEMENT

Data Paper: Manière, L, Crépy, M and Redon, B 2020. Geospatial Data from the "Building a Model to Reconstruct the Hellenistic and Roman Road Networks of the Eastern Desert of Egypt, a Semi-Empirical Approach Based on Modern Travelers' Itineraries" Paper, Journal of Open Archaeology Data, 8: 7. DOI: *https://doi.org/10.5334/joad.71.*

Zenodo data repository DOI: *https://doi.org/10.5281/zenodo.4063249.*

Theoretical hydrological networks construction on the Desert Networks blog (French version): *https://desertnetworks.hypotheses.org/920.*

Trismegistos website: *https://www.trismegistos.org/index.php.*

Desert networks database website *https://desertnetworks.huma-num.fr/.*

NOTES

1 The term "camel" will be used in this article to refer to animals of the species *Camelus dromedarius* that roamed the Egyptian Eastern Desert from the 1st millennium BC onwards. On camel vocabulary and the roots of the words "camels" and "dromedaries", see Agut-Labordère and Redon 2020: introduction.

2 Their arguments are nevertheless questionable and the data is insufficient to draw an unequivocal conclusion, see Crépy (2016: 33–34).

3 Studies on donkeys are even more complicated, as we do not have any useful data to reconstruct their routes (from the dawn of the Pharaonic era, at the end of the 4th millennium BC) prior to the introduction of the camel. However, given that donkeys are much more adaptable than the camel on many terrains and can travel on steeper slopes we are currently working on reconstructing their network with less constrained movement factors and an approach based on physiological studies. Itinerary data are still very rare, though, or not accurate enough to be used.

4 MAFDO (French archaeological mission in the Eastern Desert), the main partner of our project, is directed by Th. Faucher. It is supported by the IFAO, the French Ministry of Foreign Affairs, and the CNRS.

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The authors have no competing interests to declare.

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