International Journal of Geographical Information Science

ISSN: 1365-8816 (Print) 1362-3087 (Online) Journal homepage: https://www.tandfonline.com/loi/tgis20

The ‘Incense Road’ from Petra to Gaza: an analysis using GIS and Cost functions

Motti Zohar & Tali Erickson-Gini

To cite this article: Motti Zohar & Tali Erickson-Gini (2020) The ‘Incense Road’ from Petra to Gaza: an analysis using GIS and Cost functions, International Journal of Geographical Information Science, 34:2, 292-310, DOI: 10.1080/13658816.2019.1669795

To link to this article: https://doi.org/10.1080/13658816.2019.1669795

INTERNATIONAL JOURNAL OF GEOGRAPHICAL INFORMATION SCIENCE
2020, VOL. 34, NO. 2, 292–310
https://doi.org/10.1080/13658816.2019.1669795

RESEARCH ARTICLE

The 'Incense Road' from Petra to Gaza: an analysis using GIS and Cost functions

Motti Zohar[a,b] and Tali Erickson-Gini[c]

[a]Department of Geography and Environmental Studies, University of Haifa, Haifa, Israel; [b]Department of Physical Geography, The Freie University of Berlin, Berlin, Germany; [c]Research Division, The Israel Antiquities Authority, Jerusalem, Israel

ABSTRACT
As early as the fourth century BCE, the Nabateans established the Incense Road to facilitate the transport of aromatic substances (frankincense and myrrh) from the Arabian Peninsula to the Mediterranean basin. An important part of this road was the segment between Petra and Gaza. Although studied before, the accurate route of parts of this segment is still vague since evidence of Roman milestones are scarce and significant portions of the landscape have changed dramatically in modern times, essentially wiping out the tracks of ancient roads. In this study, we use Geographic Information Systems (GIS) and Least Cost Path (LCP) analyses for reconstructing the original path of the Incense Road as well as verifying the factors influencing its establishment. The implemented analyses support the archeological evidence of two travel phases between Petra and Oboda (Avdat): During the first phase the Nabateans used the *Darb es-Sultan* route; during the second phase, from the first century BCE onwards, they passed through the Ramon Crater. This is the first time such reconstruction is made in the southern Levant. It was found that slope degree and the distance to water resources are dominant factors in reconstructing the accurate path of the Incense Road.

ARTICLE HISTORY
Received 31 March 2019
Accepted 16 September 2019

KEYWORDS
Historical GIS; Least cost path; Incense Road; Nabateans; Geographic Information Systems

Introduction

Trading and trade routes were key factors in the economic development of ancient societies in the southern Levant during historical times. As early as the fourth century BCE, the Nabateans established a branched network of roads to facilitate the transport of aromatic substances (frankincense and myrrh) from the Arabian Peninsula to the Mediterranean Sea. These substances were widely used as incense, perfumed oils used in religious ceremonies, and for personal hygiene, as well as for medicinal and culinary purposes (Erickson-Gini and Israel 2003). One of the important trails, leading along c. 1500 miles from Marib in South Arabia to the port of Gaza on the Mediterranean coast, was the Incense Road (Figure 1). In the first century CE, Pliny the Elder reported the existence of 65 road stations along that road, which provided the trade caravans with water, food, fodder, and shelter from violent raids, as well as from the extreme

CONTACT Motti Zohar mzohar@geo.haifa.ac.il

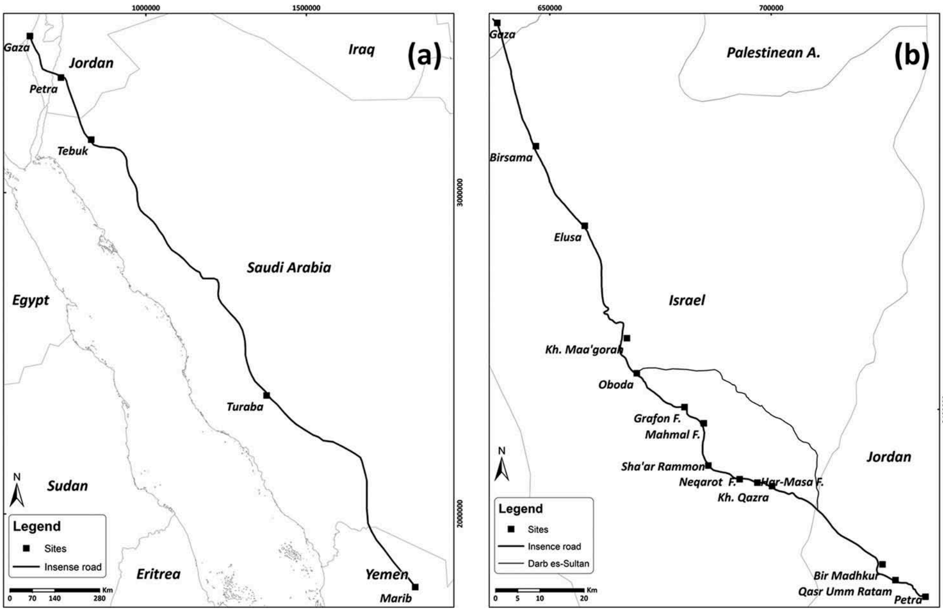

Figure 1. (a) The Incense road from Marib (present-day Saudi Arabia) to Gaza (Roll 2005) (b) The segment of the Incense road between Petra and Gaza. This segment was compiled using Tsafrir *et al.* (1994); McCormick (2008) and the locations of Roman milestones (Meshel and Tsafrir 1974, Ben-David 2018 – Person. comm.). Note also the *Darb es-Sultan* route north of the Incense Road compiled using the maps by Newcombe (1914) and Armstrong (1890) (Figure 2), rectified to the UTM zone 36 N (datum WGS84) Coordinate Reference System (CRS).

climatic conditions prevailing in the desert (Pliny 12.32.63–65). Part of the Incense Road leading from Petra to Gaza was an important link connecting the ports of Aila (Aqaba in present-day Jordan) and Gaza (Negev 1983, Ben-David 2012). The other significant link connected Aila via Petra with the northern cities of Damascus (present-day Syria) and Bostra (present-day Jordan) (Ben-David 2005) (Figure 1(a)).

The caravans traveling from Petra to Gaza faced two major obstacles. The first is the climb from the Arava Valley to the Negev Highlands, over 800 m above sea level. The second was the Ramon Crater, a deep erosion cirque, whose northern face is sharply steeped. Until the late first century BCE – first century CE, the route from Petra to Gaza appears to have passed north of the Ramon Crater, along an Early Bronze Age route referred to as *Darb es-Sultan* (the King's Way) (Figure 1(b)). This route connected the copper mines of the Faynan region in the eastern Arava with the lower Negev Highlands along the Zin Basin. The Arabic names of the Zin Basin (Wadi Murra, meaning the Myrrh Channel) and Ein Oraḥot ('Ain el-Gattar', meaning the Spring of the Camel Trail) attest to their presence along the route used for transporting incense resins (Erickson-Gini and Israel 2013). Part of the path of this route also appears in the Newcombe map (Newcombe 1914) (Figure 2(a)). During the Roman period, the Nabateans established a new route, cutting a pass along the north face of the Ramon Crater, the Maḥmal Pass (Erickson-Gini and Israel 2013) while establishing a few road stations between the earlier stations of Orḥan Mor (Moyat 'Awad) and Oboda (Avdat) (Figure 1(b)). In 106 CE, the Romans annexed the Nabataean kingdom and created the *Provincia Arabia* (Negev

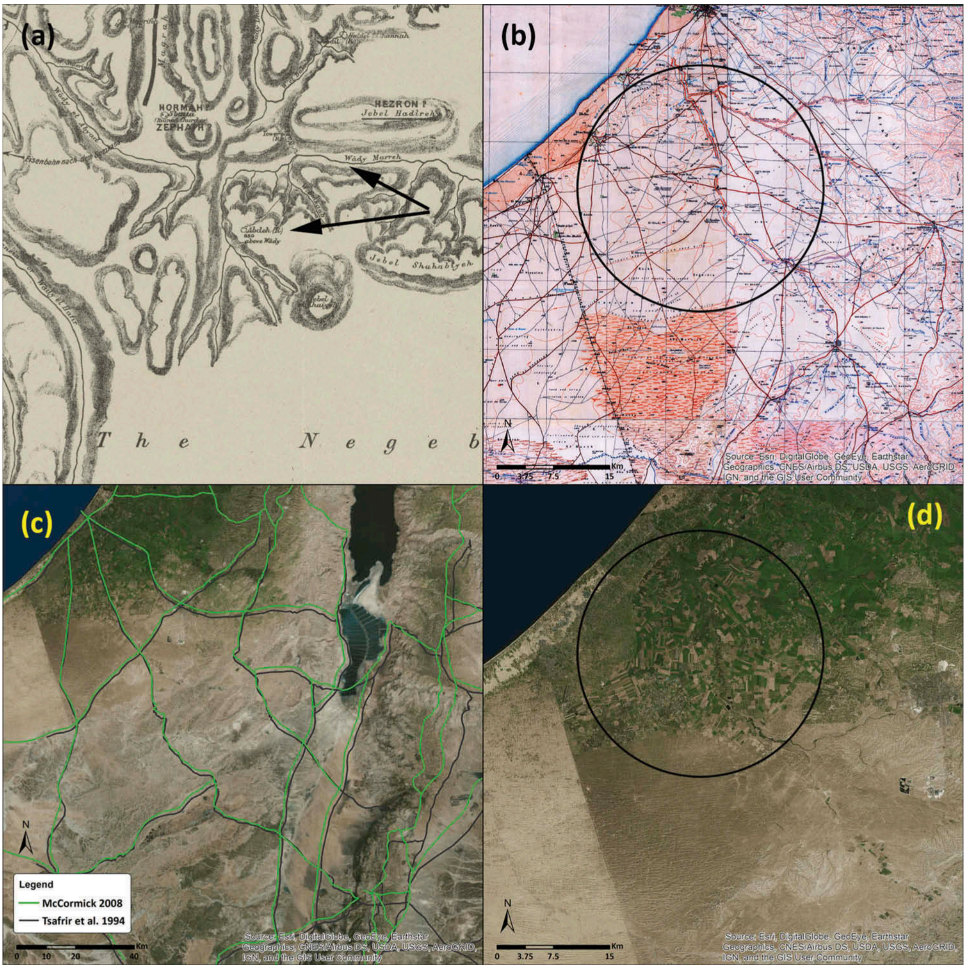

Figure 2. (a) Armstrong's map portraying the road from the east (noted by arrows) leading to Oboda (Armstrong 1890); (b) The early 20th century landscape between Elusa and Gaza as reflected in the Newcombe (1914) map; (c) The network of Roman roads following Tsafrir *et al*. (1994) and McCormick (2008). (d) Present-day landscape between Elusa and Gaza. Note the landscape difference between (b) and (d) (noted by black outline circles) because many unpaved tracks in the early 20th century were obliterated by the development of agricultural fields, modern roads, and settlements.

1983). After the annexation, the Romans built new roads and paved existing ones as part of their imperial network, aimed primarily for military and economic purposes in continuing the international trade along the Incense Road throughout the entire Middle Roman period (Roll 2005, McCormick 2008). Recently discovered milestones along a newly discovered leg of the road north of the Ramon Crater bear inscriptions of Roman emperors from the Severan period and the name of the city of Elusa (Ben-David 2018, person. comm.). However, due to a series of crises in the Roman Empire during the third century CE, the region was neglected for a few decades and thus many sites along the road were abandoned. A few of these stations were apparently re-used during the Early Byzantine period (fourth-early fifth centuries CE) but in general, trade along that road declined significantly during this period (Erickson-Gini 2002, Erickson-Gini and Israel 2003).

Several parts of the road have been surveyed and mapped, including those where Roman milestones were discovered (Meshel and Tsafrir 1974). These milestones were probably erected as part of Roman military activity in the Negev, and not necessarily as part of the Petra-Gaza Route (Ben-David 2012). The precise route of other parts of the road is still not resolved. A prominent example is the northern part of the road between Elusa and Gaza passing through a region whose landscape has been largely developed in recent decades and consequently, remains of the ancient track are now difficult to determine (Figure 2(a,b)). Previous mappings of the route as part of the Roman network have been proposed (Roll 1976, 2005, Tsafrir *et al*. 1994) and appear in the online database of DARMC (The Digital Atlas of Roman and Medieval Civilizations, see https://darmc.harvard.edu/data-availability) (Figure 2(c)). However, the scale of these mappings is large and thus omits high-resolution digitization of the parts comprising the road (Figure 2). To this may be added the recently discovered leg of the route north of the Ramon Crater referred to above, which includes six Roman milestones from the Severan period (Ben-David 2018, person. comm.).

The transport of the Nabateans along the Incense Road was carried out using caravans of 20 to 30 camels and riding horses (Kloner 1996, Erickson-Gini 2010). The costs of merchandising inland vary and were primarily influenced by several factors. First is the type of pack animals, their fitness and their riding equipment, such as harnesses, saddles, and shafts. Second is route infrastructure and complexity: steep slopes, boggy soils, and natural obstacles posed difficulties for heavily laden camel caravans, raising the cost of travel. Third is the velocity and timing of the trade caravans; once the trade of aromatic substances expanded and was beneficial to the Nabateans, the duration of travel between Petra and Gaza became crucial. Thus, one may assume that the trade caravans would seek the shortest and most available trail, provided it was not dangerous and could be sufficiently protected. Finally, come the cost of taxes, food, and shelter along the route (e.g. Rostovtzeff 1932, Millar 1998). The Petra-Gaza leg of the Incense Road was and is still situated in a hyper-arid region with annual precipitation of less than 200 mm/y (Goldreich 2003) such that the availability of water throughout the entire region is extremely limited. Consequently, caravans were entirely dependent on food and water resources – springs, high ground water or cisterns – along the way (Rubin 1988, Erickson-Gini and Israel 2013). To maintain trade during the Hellenistic period, the Nabateans hewed and plastered cisterns in the bedrock hidden along the main route, particularly adjacent to segments far from caravan stops (Erickson-Gini 2012). Altogether, the established road's route had to accord with the locations of the major trading centers but was also strongly subjected to the conditions prevailing in the Negev at the time. Thus, the underlying hypothesis suggests cost-effective factors in terms of travel time and energy input. In conjunction with water availability, these were the key factors in establishing and maintaining the Incense Road. Evaluation of these parameters may provide indications of the actual route and enlighten us on the limitations the Nabateans faced and how they coped with these difficult conditions while traversing the desert.

The route of the Petra-Gaza segment of the Incense Road has been mapped before by historical sources and archeological remains (Meshel and Tsafrir 1974, Ben-David 2012), although other techniques for tracing past landscape features are available (Tsoar and Yekutieli 1992, Stott *et al*. 2018). However, the exact route of much of the road is still under debate or has been previously mapped but with great uncertainties. Recently, GIS technology has become an important tool for resolving such past scenarios (e.g. Davie and Frumin 2007, Levin *et al*. 2010, Schaffer and Levin 2016, Zohar 2017). Using GIS technology, one can digitize, query, and analyze spatial historical data – a discipline more recently referred to as Historical GIS (HGIS) (Knowles 2005, Gregory and Healy 2007, Bailey and Schick 2009, Gregory and Geddes 2014). GIS also enables the reconstruction of ancient roadways, whether a pedestrian path or vehicular trails, using Least Cost Path (LCP) analyses (Herzog 2013; Herzog and Posluschny 2011). Basically, these techniques estimate the shortest distance between two sites based on the influence of topography, terrain and other natural characteristics (e.g. Batten *et al*. 2007, Matsumoto 2008, Güimil-Fariña and Parcero-Oubiña 2015). However, until now this methodology was never applied to investigate any Levantine road, including those established by the Nabateans. Furthermore, apart from the mere identification of the path, one can use LCP as a leveraging approach to resolve the historical patterns and behavior of Nabatean trade and thus contribute additional important insights to the study of the Nabateans. Accordingly, the first goal of this study is to reconstruct as accurately as possible the route of the Incense Road using the LCP technique. The second goal is to use different LCP configurations corresponding either to time or energy input in order to resolve the trading patterns of the Nabateans in establishing and maintaining the route.

Methods and materials

Input data

For the LCP analysis we have used several datasets rectified to the UTM zone 36 N (datum WGS84) CRS, as the CRS of the DEM (Digital Elevation Model) chosen as our base geographic layer. When digitization was required, it was implemented within a scale of less than 1:5000 to avoid digitization errors (Schaffer and Levin 2015). The following datasets were used: (1) **Slope**: calculated by a GIS software using a terrain DEM dataset in which the slope value is dominated by the steepest descent (Warren *et al*. 2004). The DEM used in this study is the Advanced Land Observation Satellite – Phased Array type L-band Synthetic Aperture Radar (ALOS-PALSAR) with a resolution of 12.5 m (http://www.eorc.jaxa.jp/ALOS/en/about/palsar.htm, downloaded from https://vertex.daac.asf.alaska.edu/#, April 2018). Although the PALSAR data may be biased (Shimada 2010), it is still the highest resolution available for our use. The footprints of the PALSAR dataset were pieced together and clipped to the extent of the study area (Figure 1). Before calculating slope, we used the 'Fill' function in the ArcGIS Desktop software to fill sinks and remove anomalous peaks;[1] (2) **Sites**: the location of late antiquity Petra and Gaza, as well as other sites (e.g. towns, road stations, villages, forts) along the Incense Road, were digitized using the *'Tabula Imperii Romani'* (Tsafrir *et al*. 1994) and pinpointed according to the DEM dataset and modern maps; (3) **Water resources** and **ancient routes** were digitized using the Newcombe map (Newcombe 1914), rectified as the other datasets to the UTM zone 36 N (datum WGS84) CRS, which is probably the earliest available map that meets the demands of accuracy and completeness in the southern Levant (Zohar 2019) (Figures 1 and 2); in light of the absence of air photos from the beginning of the twentieth century in this region, this map is probably the best available source (Gavish 1978). Created primarily for British military purposes, the map includes routes, as well as water supplies categorized by quality, quantity and indications whether they are temporary or permanent water holes.

As stated above, the definite route of large portions of the Incense Road between Petra and Gaza is an enigma. Nevertheless, in order to compare the results of the LCP analyses to a route as accurately as possible, a compiled *true* route was evaluated using previous maps (e.g. Tsafrir *et al*. 1994, McCormick 2008),[2] late nineteenth and early twentieth century maps (e.g. Armstrong 1890, Newcombe 1914) (Figures 2(a,b)), and the locations of known Roman milestones as the only resources exactly indicating the true route (Meshel and Tsafrir 1974) (Ben-David 2018, person. comm.).[3]

Least Cost Path analysis

Being aware of the potential political conflict involved in qualitative GIS-based analyses initiated worldwide (Aitken and Kwan 2010), we chose the LCP approach for the reconstruction of an ancient road. LCP analysis is an intuitive method used recently in archeology in order to reconstruct roads and trails (Llobera *et al*.2011, Verhagen and Jeneson 2012) or to identify the principal factors governing the construction of routes (Bell and Lock 2000, Kantner and Hobgood 2003). The underlying assumption is that the initial travel routes were determined by the least cost in energy or time spent between the journey's start and end points. Pedestrian or camel-laden caravans are likely to follow this principle, allowing for the identification and reconstruction of ancient routes. LCP is used also for the chronological dating of sites. For instance, Batten *et al*. (2007) suggest that the location of sites along routes between two other sites implies that the midpoint sites were established only after the establishment of the endpoints.

We have used the slope and water resources as two factors governing the established path of the Petra-Gaza segment of the Incense Road. On the way to Petra, the caravans also traded in Oboda (Avdat) and Elusa (Ḥalutza), (Figure 1) thus dividing the route into three major legs: (1) Petra-Oboda; (2) Oboda-Elusa; and (3) Elusa-Gaza. These legs were then analyzed using two types of LCP models, based on two Cost functions (Figure 3). The first is the Cost Distance function reflecting the cost-effective path in terms of the minimal cost to travel from the start to the end points, regardless of the travel time (Douglas 1994, Siljander *et al*. 2015). Using this method, a Cost surface was created by a weighted overlay of datasets representing classifications of slope degree and Euclidean proximity to water resources (Table 1).

The second function is the Path Distance method, which expresses the travel along a route in terms of time spent (Herzog 2013, Güimil-Fariña and Parcero-Oubiña 2015) while considering the direction of movement. A movement along a flat surface is isotropic; that is, similar progress is made regardless of direction. However, a movement along hilly or steep surfaces is different in each direction (anisotropic movement) and is dependent on the topographical characteristics along the way (White and Surface-Evans 2012). In other words, the estimated time required to travel a given distance is based on the surface slope, assuming that the steeper the slope, the longer the travel time.

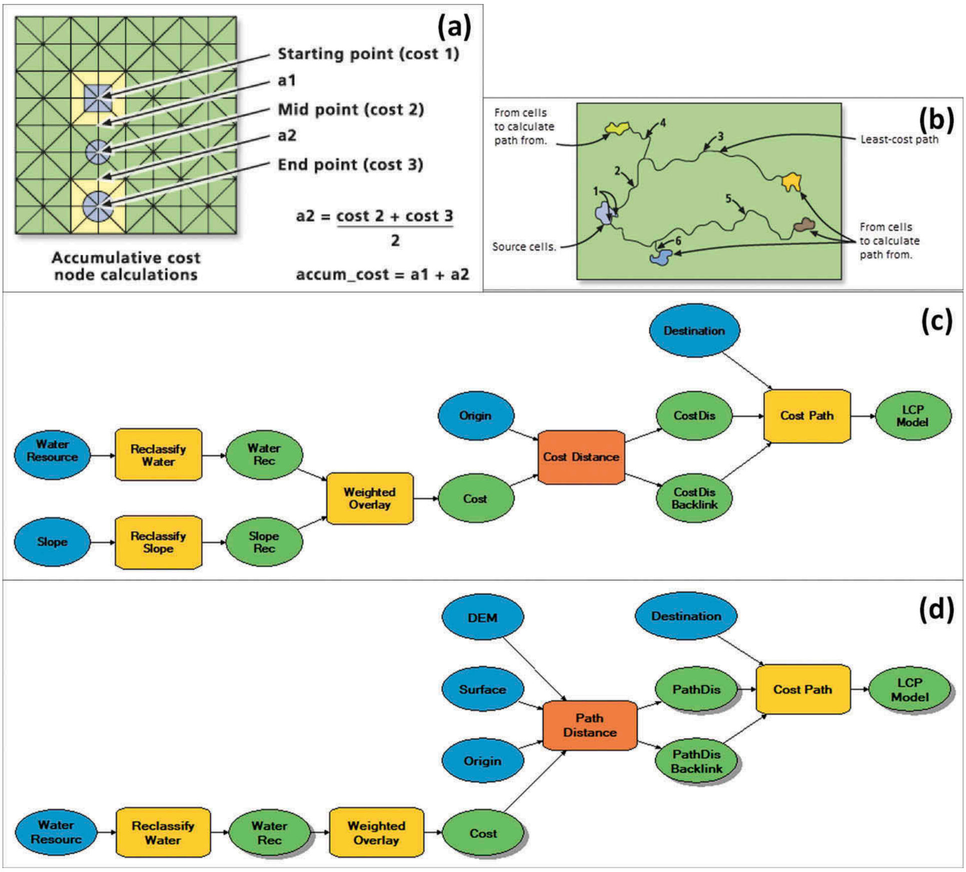

Figure 3. The LCP analysis: (a) calculation of accumulated cost when moving along cells of cost raster (source: https://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-the-cost-distance-tools-work.htm, last accessed: March 2019); (b) schematic representation of LCP analysis from several source cells (source: https://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/creating-the-least-cost-path.htm, last accessed: March 2019); (c) LCP model based on Cost Distance function. Note the equally weighted overlay between the factors of slope and distance to water resources; (d) LCP model based on Path Distance function. Note the surface input representing movement in terms of velocity (after the hiking function of Tobler 1993). Both models were established using the ArcGIS model builder tool.

To estimate the travel time from one point to another we have used the hiking function developed by Tobler (1993):

$$W = 6^{(-3.5*|(S+0.05)|} \quad (1)$$

Whereas W is the walking velocity (km/hour) and S is the slope degree.[4] For flat surfaces, for example, this relation yields a velocity of 5.036 km/hour while for a slope of 10° the velocity is 2.71 km/hour. The yielded velocities are for foot-walking. Although horseback or camels are sensitive to steep slopes their velocities are greater than of pedestrians and thus were multiplied by 1.25 (Tobler 1993). The two LCP models instruct the Nabateans' limitations and considerations for using the Negev routes for the shortest path in length is not necessarily the easiest or shortest in time. Both Cost Distance and

Table 1. Cost classification of (1) Euclidean distance to water resources used for generating Cost surface in both LCP models; and (2) Slope degree used for generating cost surface in the Cost Distance LCP model only (the slope factor for the Path Distance LCP model, is evaluated using the hiking function (by Tobler 1993). Regions assigned with 'Restricted' classification (whether distance to water resources or slope) represent extreme values that do not participate in the LCP analyses as potentially passable areas.

	Distance to water resources (m)		Slope (degrees)	
Cost classification	From	To	From	To
1	0	1000	0.0	2.0
2	1000	2000	2.0	5.0
3			5.0	10.0
5	2000	5000	10.0	15.0
9	5000	15,000	15.0	25.0
Restricted	15,000	100,472	25.0	79.9

Path Distance LCP functions were constructed using the ArcGIS Desktop Model Builder of ESRI© and are presented in Figure 3. Once reconstructions were made for the legs between Petra-Oboda-Elusa-Gaza, they were compared to route segments where Roman milestones exist and also to the compiled *true* path (Figure 1(b)) based upon geometric similarity (e.g. Goodchild and Hunter 1997, Beeri *et al*. 2005).

Results

The first major station of the Nabateans after leaving Petra on the way to Gaza was the town of Oboda (Figure 1). Before the late first century BCE, the Nabateans used the route established in the Early Bronze Age, called *Darb es-Sultan* (Glueck 1960, 1965), a route that connected the copper mines of Faynan in the eastern Arava Valley with the central Negev by skirting the Ramon Crater from the north (Erickson-Gini 2006). Then, with the expansion of perfume production and trade toward the end of the first century BCE (Johnson 1987), the Nabateans constructed the Maḥmal Pass along the northern face of the Ramon Crater and the route was diverted southwards (Erickson-Gini 2006, p. 160–163, Fig. 12;4). The newly created route facilitated the aromatic trade from Petra to the Mediterranean basin until the first half of the third century CE and continued to link the Negev towns with Petra until c. 363 CE (Erickson-Gini 2010, p. 191–194). Accordingly, the implemented LCP models examined two phases of the route between Petra and Oboda: (1) A single route segment between Petra and Oboda, active until about the late first century BCE-first century CE; and (2) Two separated segments divided by the Maḥmal Pass acting as an obligatory pass: the first, between Petra and the Maḥmal Pass while the second, from the Maḥmal Pass to Oboda. For both phases LCP models, based on Cost Distance and Path Distance, were constructed using topographic slopes and distance from water resources. These two functions represent cost-effective routes in terms of expenditure energy spent and travel time, respectively. The resulting routes of each phase along with their characteristics are presented in Table 2 and Figure 4. Accordingly, the LCP models associated with Phase 1 are A1, A2 and B as alternatives to the route segment between Petra and Oboda. Models C and D represent the segments associated with Phase 2 between Petra-Maḥmal and Maḥmal-Oboda,

Table 2. LCP models (labeled A1-F) of potential route segments between Petra to Gaza comprising the Incense Road. The models use Cost Distance and Path Distance (after Tobler's hiking function, 1993) functions representing the cost-effective best-fit route in terms of energy and travel time, respectively. **A1** and **A2** implement the Cost Distance function, whereas **A1** uses only slope while **A2** equally weights (i.e. 50% for each factor) the slope and the distance to water resources. Models **B-F** implement the Path Distance function by equally weighting slope and distance to water resources. Note that the A1, A2 and B models are alternatives to the route segment between Petra and Oboda. The rest of the table fields represent the characteristics of each proposed route: **Seg –** the segment between two nodes (whether a Nabatean city or obligatory pass); **Tp** – LCP model type (CD for Cost Distance and PD for Path Distance, both using slope/dem); **Ln** – length to the segment (in km); **Lnt** – the length of the equivalent true Incense Road segment (in km); **LnDiff** – the difference between the LCP route and the true segments; **Lnd** – the length of the direct (straight) path (in km); **Slp** – mean slope along the path of the segments (in degrees); **Wt1** – the number of water resources along the way within a buffer of 1 km; **Wt2.5** – the number of water resources along the way within a buffer of 2.5 km; **S0.5 –** total length of the segments located within a buffer of 0.5 km of the 'true line'; **Sim0.5** – the ratio between S0.5 and Ln; **S1** – total length of the segments located within a buffer of 1.0 km of the 'true line'; **Sim1** – the ratio between S1 and Ln**;** **T** – time to travel between origin and destination of the segment (in hours, after the hiking function of Tobler 1993).

Model	Seg	Tp	Ln (km)	Lnt (km)	LnDiff (km)	Lnd (km)	Slp (°)	Wt1	Wt2.5	S0.5 (km)	Sim 0.5 (%)	S1 (km)	Sim1 (%)	T (HH)
Prior to late first century BCE–first century CE (phase 1):														
A1	Petra-Oboda	CD	100.3	91.2	9.1	82.4	2.5	2	5	12.5	**12.5**	17.6	**17.5**	–
A2	Petra-Oboda	CD	103.4		12.2		4.3	8	11	18.7	**18.0**	22.9	**22.1**	–
B	Petra- Oboda	PD	88.9		2.3		5.1	2	5	27.0	**30.4**	35.5	**39.9**	20
First century CE onward (phase 2, with Maḥmal Pass as an obligatory passageway):														
C	Petra-Maḥmal	PD	71.9	70.9	1.0	63.5	5.3	5	5	42.3	**58.8**	53.9	**74.9**	16
D	Maḥmal- Oboda	PD	20.2	20.3	0.1	18.8	6.0	2	3	14.4	**71.3**	19.3	**95.5**	4
Both phases:														
E	Oboda – Elusa	PD	37.8	39.7	1.9	35.2	3.7	8	12	18.7	49.5	34.3	**90.7**	7–8
F	Eluza-Gaza	PD	54.4	51.8	2.6	51.0	2.1	10	16	14.4	26.5	28.2	**51.8**	11

respectively. Models E-F are relevant for both phases whereas the route from Oboda to Gaza was similar throughout the whole period.

For Phase 1, Routes A1 and A2 bypassed the Ramon Crater from the north while Route B 'cuts' the northern cliffs of the crater, very close to the actual pass of the Maḥmal Pass (Figure 4). Thereby, the shortest route is Route B at 88.9 km while the longest is A1 and A2 with 100.3 km and 103.4 km, respectively. However, Routes A1 and A2 are easier than Route B in terms of mean slope (2.5° and 4.3°compared to 5.1°). That is, there is a preference for Route B over Routes A1 or A2 since the track is shortened significantly but it would most likely require more energy along the way. Both Routes A1 and B share a similar number of water resources along their path while Route A2, which accounts for distance from water resources, is the most abundant in terms of water availability. The difference in length from the true line is 9.1 km, 12.2 km and 2.3 km for Routes A1, A2, and B, respectively. For line-feature-matching, a buffer zone of 0.5 km and 1 km was set around the true segment to verify which portion of the modeled route it is falling within (Goodchild and Hunter 1997, Li and Goodchild 2011). Accordingly, Routes A1 and A2 are less matched than Route B where they present only 12.5% and 17.5% matching for a buffer of 0.5 km and 18% and 22.1% for a buffer zone of 1 km, while Route B has 30.4% and almost

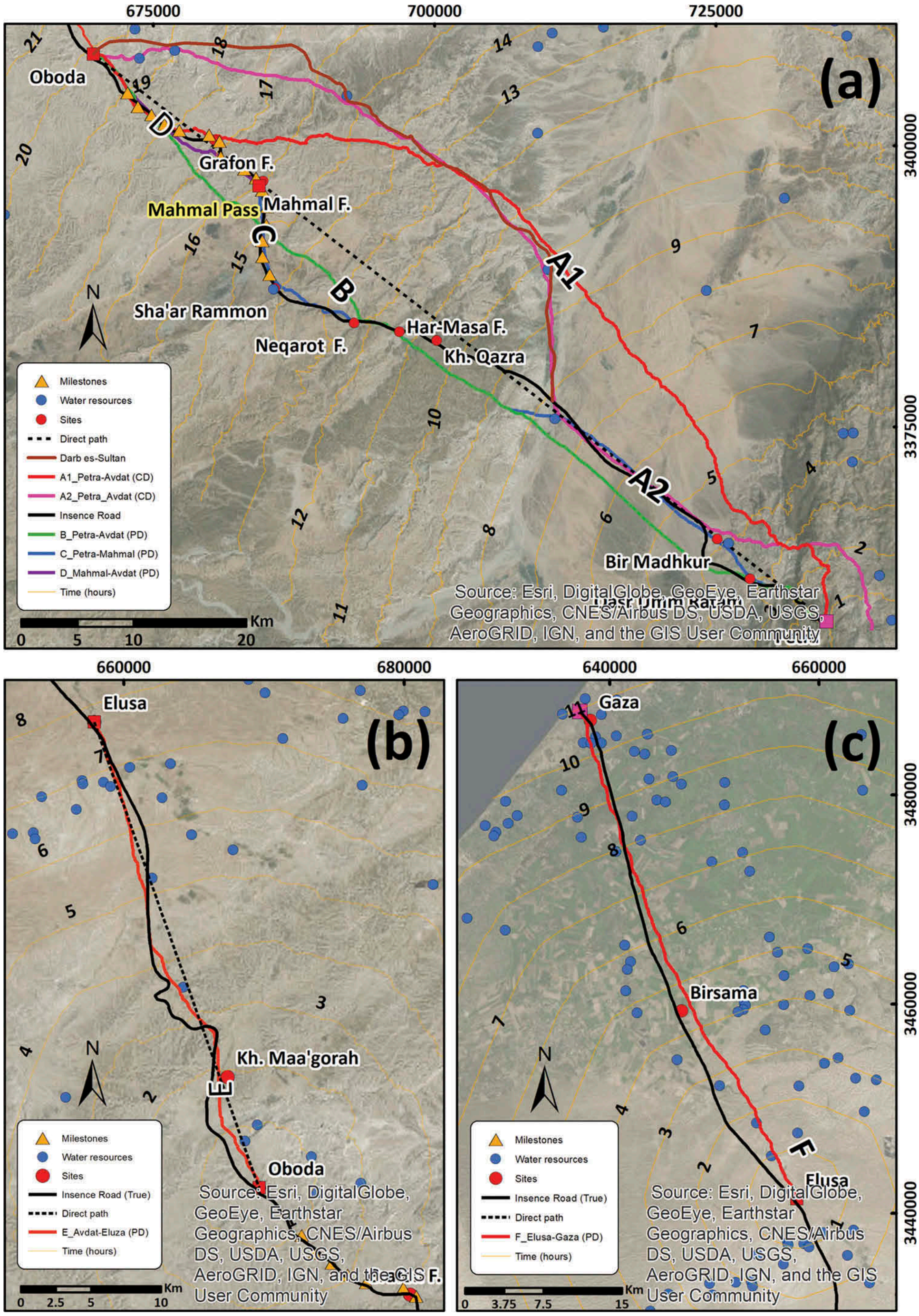

Figure 4. LCP models as potential routes of the Incense Road: (a) Models A1, A2, and B-D representing route analyses between Petra and Oboda; (b) Model E representing route analyses between Oboda and Elusa; and (c) Model F representing route analyses between Elusa and Gaza. For more details of the models, see also Table 2.

40% within a buffer of 0.5 km and 1 km, respectively. That is, Route B is more similar to the analogs of the Incense Road's true route. On the other hand, Route A1 and A2 follow at least parts of the *Darb es-Sultan* Route as it appears in the old maps of Newcombe (1914), Armstrong (1890) (See also Figure 2).

For Phase 2, the segment between Petra and Oboda was divided into two parts, while the Maḥmal Pass became an obligatory passageway. This resulted in two segments: the first between Petra and the Maḥmal Pass and the second between the Maḥmal Pass and Oboda. Milestones have been discovered along this track and they enable an accurate portrayal of the road in the area in which they were found. The rest of the Incense Road, from Oboda to Gaza, was in use during the two phases, thus allowing equal analysis. Along the route between Petra and Maḥmal (noted by Route C in Figure 4), two springs are located. The first is located in the western Arava Valley next to Orḥan Mor (Moyat 'Awad), the second (Shaa'r Ramon) is located on the southern edge of the Ramon Crater (Figure 4). On the other hand, the route between the Maḥmal Pass and Oboda (Figure 4, noted by the symbol D) does not have any springs at all. The length of both routes (C and D) almost equals the length of their true segment analogs (within a buffer zone of up to 1 km) and both have a mean slope between 5° and 6°. The feature-matching ratios are significantly higher than those of Routes A1, A2 and B, while Route C has a similarity ratio of 58.8% and 74.9%, and while Route D has a ratio of 71.3% and 95.5% for buffer zones of 0.5 km and 1 km, respectively. Notable is Route D, validated by milestones (Ben-David 2018 – Pers. comm.), which presents a high accuracy level. Travel time is estimated to be 16 h and 4 h by Route C and D, respectively.

The remainder of the Incense Road, in use during the first and second phases, is composed of the routes between Oboda to Elusa and Elusa to Gaza (legs E and F in Table 2 and Figure 4, respectively). The length difference between these routes and their true segment analogs is less than 3 km with a mean slope of 3.7°, and 2.1° for the Route E and F, respectively. The latter is significantly lower than the others due to its proximity to the southern Mediterranean coastal plain. As these two routes head north, the number of water sources also increases because of the existence of springs and high ground water in the northern Negev and a larger amount of precipitation (close to 200 mm/year) in this region (Goldreich 2003). Feature-matching of the segments are 49.5% and 90.7% for leg E, while 26.5% and 51.8% for Model F for a buffer zone of 0.5 km and 1 km, respectively. It is to be stressed however, that the true path of the later route (leg F, between Elusa and Gaza) is not sufficiently clear because the landscape in this region has changed dramatically during the twentieth century (Figure 2), due to modern development particularly after the establishment of the state of Israel in 1948 (Zohar 2019). Perhaps this is the reason why its geometric feature-matching is less than Route E. Along the way, the individual travel time between two hosting sites (whether a caravanserai, fort, town or city) did not exceed 10 h. Taking into consideration 6–8 h of caravan travel per day, the travel between Oboda and Gaza would have taken between 2 and 3 days. This value also equals the travel time between Petra and Oboda. Altogether, the total caravan journey between Petra and Gaza must have taken between 5 and 6 days(Table 2 and Figure 4).

Discussion

The LCP models presented in Table 2 and Figure 4 reflect cost-effective routes in terms of energy spent (Cost Distance function) or travel time (Path Distance function). The later models, although shorter in length and time, are more strenuous than the former, while the mean slope along the resulting path is relatively higher. Model A1, based only on the cost of slope, partially comply with the 'early' Incense Road (the Darb es-Sultan Route) connecting Petra and Oboda by skirting the Ramon Crater from the north. When evaluating also the Euclidean distance of the route to the nearest water resources (A2), the route almost entirely follows the *Darb es-Sultan* Route as it appears in older maps (Armstrong 1890, Newcombe 1914). From archeological surveys and excavations, we learn that the shift to the 'new' road through the Ramon Crater occurred only toward the end of the first century BCE (Ben-David 2012, Erickson-Gini and Israel 2013) and the sites of Khirbat Qatzra, Har Massa, Meẓad Neqarot, Sha'ar Ramon and Meẓad Maḥmal were not settled before the late first century BCE (Table 3). Thus, the LCP models of Phase 1 reinforce the alternation between the old route and the new one. At the beginning of their consolidation, the Nabateans used routes for local use; i.e. for the needs of the Nabataean kingdom based in Petra. Most likely, they used pre-existing routes between Petra and Oboda. To avoid unnecessary ascents and waste of energy in the heated desert along the road, these routes probably followed accumulated knowledge of the best convenient route following a topographic rule of moving along a common height. Routes A1 and A2 follow this rule reflecting cost-effective route in terms of energy conservation. These routes, particularly Route A2, fit well with the route of the *Darb es-Sultan* (Figure 4). That is, the major consideration taken by the users of these routes was convenience and energy reduction regardless of the travel time and length of the route. This explanation suits a local, perhaps seasonal behavior, aimed for travel from one site to the other as an inter-community network. However, when the Nabateans started producing and trading perfumed oils in significant quantities, they required a faster and economically based route to transport the goods from Petra to the Mediterranean basin. They also had to compete with faster land and marine Roman trading routes leading from the eastern coast of Egypt to the Mediterranean basin (Johnson 1987). Thus, they probably searched for a better cost-effective route that would have shortened travel time. The shortest distance between Petra and Oboda passes through the Ramon Crater, very close to the actual Maḥmal Pass (see the direct path and Route B in Figure 4). Accordingly, the Nabateans leveled a way through the northern face of the crater and established a new, shorter track that obligated all caravans to pass through this narrow passageway. The shorter time and distance required for using the Maḥmal Pass allowed a higher degree of security at a very vulnerable point along the road, a well-known factor that prompted the accompaniment of guarding forces (Maraqten 1996). (Table 3).

The construction of the Maḥmal Pass required the establishment of caravanserais along the road (Table 3) since the travel time from Petra to Oboda exceeded 16–18 h, approximately 2 days of caravan travel. The construction of caravanserais next to the only two springs along this leg at Moyat 'Awad and Shaa'r Ramon ('En Saharonim), was necessary in order to provide shelter and fodder as well as road services such as meals and bathing facilities. Not surprisingly, in the hyper-arid region between Petra and

Table 3. The major archeological finds at the sites along the Incense Road.

Period	Orḫan Mor (Moyat ʻAwad)	Khirbat Qatzra	Har Massa	Meẓad Neqarot	Sha'ar Ramon ('En Saharonim)	Meẓad Maḥmal	Ḥorbat Ma'agurah
Early Hellenistic 3rd c. BCE	Nabatean fort	–	–	–	–	–	Cistern (Pre-existing?)
Late Hellenistic 2nd –1st c. BCE	Nabatean fort	–	–	–	–	–	Cistern; Nabatean; caravanserai; Hasmonean fort
Early Roman 1st c. BCE–1st c. CE	Fort (re-occupied); Caravanserai; Pool, Irrigation system		Dwelling complex	Dwelling complex; Cistern	Caravanserai	Nabatean dwelling; Cistern	Caravanserai (partial re-occupation)
Middle Roman 2nd –3rd c. CE	Fort with production facilities; Caravanserai; Pool, Irrigation systems	Open shrine; Middle Roman fort	Dwelling complex	Middle Roman fort Cistern	Caravanserai	Middle Roman fort Cistern	–
Late Roman – Early Byzantine Late 3rd–4th c. CE	–	–	Dwelling complex	–	Caravanserai (partial occupation)	Fort (re-occupied); Cistern	

Oboda, water sources were a key factor. This is also reflected in the LCP analyses. The first is Route A2 between Petra and Oboda (Phase 1, when the Maḥmal Pass has yet to be established and the cost was not inspected in terms of travel time) based on a Cost Distance function equally weighing the dominancy of slope and the distance to water resources. Route A2 better fits the actual path of the *Darb es-Sultan* (Figure 4(a)) than Route A1 (based only on slope), thus implying that the utilization of these factors may serve as a close approximation of the actual route. The second implication is when using Path Distance function with slope and distance of water resources to reconstruct the route from Petra to the Maḥmal Pass. When omitting the water factor, the path of the route is a poorer match than of using both slope and water (Figure 5). This is particularly evident along the track in the Ramon Crater where the milestones accurately the actual path. Altogether, excluding other considerations for road construction in ancient times (Roll 1976), slope and water sources appear to be dominant factors although the other factors may contribute and improve for accuracy in the reconstruction of the routes.

The route between the Maḥmal Pass and Oboda (Figure 5) deserves special attention. Until recently, the path of this segment was considered to be about 1 km further east, as shown in the map of Newcombe (1914) and also demonstrated in Tsafrir *et al*. (1994). More recently, a research expedition led by Haim Ben-David found six new milestones and accordingly revealed a previously unknown leg of the road. Interestingly, the route generated by the LCP model (Figure 4(a), 5, noted D) follows this exact discovery with nearly 95% line-matching within a buffer zone of 1 km. The only exception is the path close to the Grafon Fort where the model route does not correspond with the actual route. One possibility for this anomaly may be a pre-existing track that connects the ‘En

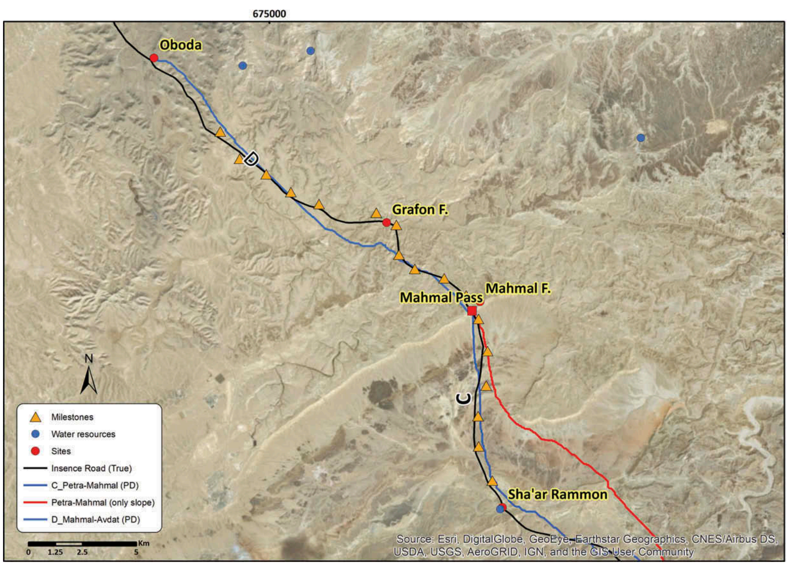

Figure 5. The region between Sha’ar Ramon and Oboda, where milestones exist. Path Distance LCP model using the slope and distance to water resources as factors are portrayed in blue while the model using only the slope is portrayed in red. Note the similarity of the blue line to the path marked by the milestones except at the Grafon Fort.

Aqev Spring with the *Darb es-Sultan* southwest of ‘En Oroḥot, which ran close to the Grafon Fort as indicated by Early Bronze Age road markers.

The routes from Oboda to Elusa and from Elusa to Gaza reflect a line-matching of 90% and 51% within a buffer zone of 1 km, respectively, along abundant water resources. According to the model, the point where the road crosses the Naḥal Besor is 653,463 E, 3,451,024 (UTM CRS); that is, nearly 3 km east of the crossing-point indicated on the Newcombe map. This was an important location along the Incense Road because from this point the road followed the Besor through the Western Negev all the way to Gaza. Unfortunately, the landscape of this region has changed dramatically and thus tracing the accurate route in this region is difficult. However, a Nabataean-Roman site (1st-3rd century CE) of significant proportions was discovered by Erickson-Gini in early 2019 (Person. comm). The site is situated approximately 4 km. southwest of Elusa in an important drainage basin located west of Naḥal Besor. The location of this site is important in determining the line of the track of the Incense Road north of the modern highway (Highway 211) as far as Elusa. The presence of such a large settlement within 4 km of Elusa was probably necessary for providing water and pasturage for larger amount of accompanying pack animals, mainly camels, for caravans traveling through Elusa when the international trade in aromatics was at its peak.

Summary and conclusions

In this paper, the track of the Incense Road was reconstructed using Cost Distance and Path Distance LCP models. It reveals that when using slope and distance to water resources as factors to determine the location of the track, the reconstruction provides a close approximation of the actual path. The accuracy of the LCP models that accords with the Petra-Maḥmal Pass, the Maḥmal Pass-Oboda, the Oboda-Elusa and the Elusa-Gaza within a buffer zone of 1 km, was found to be 74.9%, 95.5%, 90.7% and 51.8%, respectively. The latter is of a route segment located within a region whose landscape has changed dramatically since the early twentieth century. Therefore, the reconstruction may not be fully completed.

An interesting aspect of this study is a comparison of the Phase 1 Incense Road, which bypassed the Ramon Crater during the Hellenistic period when the Nabateans were mainly middlemen, transporting raw materials between southern Arabia and the Mediterranean coast and particularly to Egypt, and the Phase 2 Incense Road, established toward the end of the first century BCE when the Nabateans began to produce perfumed oils in Petra, an industry that required intensive marketing and the year-round transport of products. In this later phase, the construction of the Maḥmal Pass along the northern face of the Ramon Crater was a crucial factor in shifting the Orḥan Mor (Moyat ‘Awad) – Oboda leg southwards through the Ramon Crater and across the Nafḥa ridge to Oboda. In order to facilitate transportation along this new leg, caravansaries were established by the Nabateans next to springs at Orḥan Mor and ‘En Saharonim, as well as stations and cisterns at Neqarot and Maḥmal. During the Severan period, ‘tower-forts’ were constructed along the same route by the Romans at Khirbat Qatzra, Meẓad Neqarot and Meẓad Maḥmal and possibly, the Grafon fort.

The LCP analyses supported by GIS techniques are a prominent example of how combination of technology and traditional disciplines such as archeology can be implemented in order to resolve past scenarios. On the one hand, the implemented LCP analyses reinforce the archeological knowledge of the Nabateans as shrewd traders while, on the other hand, provides a technique for accurate reconstruction of the Incense Road. Although LCP models were already used in other parts of the world, this is the first time they are utilized for the reconstruction of routes in the southern Levant. As opposed to other regions under Roman rule such as the northern Levant, Asia Minor and parts of Europe the southern Levant is extremely dry. Therefore, the aridity and the total dependency of the caravans on water, forces the inclusion of water availability characteristic as a dominant factor within the models in order to trace the exact route of the Nabateans, as well as explaining their trading patterns along the route. When inspecting ancient routes, partial archeological remains and historical records occasionally cannot assist in determining which LCP model is preferred for tracing the routes. In dry lands, water resources, as a crucial factor can compensate for the absence of information. This study presents an additional approach for the study of past societies behavior and lays the foundation for further analyses of routes in other dry regions in and off the Levant region. Such digital mapping and accurate GIS-based analyses, when combined with historical evidence and ongoing archeological excavations are the front end of the current innovative research and promise new insights concerning past trading routes as well as better understanding of the associated local and global economy at the time.

Notes

1. After using the ‘Fill’ function of ArcGIS: 89.72% of the DEM values were not altered at all; 9.45% were altered by values of 5 m and below; 0.78% were altered by values equal or greater than 5 m.
2. Part of the routes portrayed by Tsafrir *et al*. (1994) may be inaccurate as they state (p. 40): ‘some hypothetical roads whose traces are yet to be discovered are also indicated’.
3. The technique for building the Roman roads is discussed in Roll (1976). Along the road the Romans placed milestones within similar distances from each other. Meshel and Tsafrir (1974) suggest a distance ranging between 1475 and 1795 m for the milestones found in the Ramon crater and the Nafha ridge while Roll (1976), based on measurements close to the Beit-Guvrin-Hebron road, suggests a distance of 1635 m.
4. We have used Excel to produce corresponding velocities for slopes between −70° to 70° within intervals of one degree (or tenth of a degree between −10° to 10°). Accordingly, the walking velocity was calculated as W = 6*(EXP(−3.5*(ABS(TAN(RADIANS(Slope)) + 0.05)))). See also http://mapaspects.org/book/export/html/3743/and http://www.geodyssey.com/papers/tobler93.html.

Acknowledgments

We wish to acknowledge Adi Ben Nun, Krina Doekes-Brandt and Dr. Dov Gavish (the Hebrew University in Jerusalem) for their assistance in acquiring the data used in the study; Dr. Yulia Meister, Prof. Brigitta Schutt and Vincent Haburah from the Freie University of Berlin for their assistance and support; Oren Shmueli (Israel Antiquities Authority) for his guidelines in resolving the location of the ancient track northwest of ‘En Orohot; Moshe Devere for language editing and the three anonymous reviewers for their useful comments and suggestions, which improved the manuscript significantly. The study was funded by the Rothschild and Minerva post-doctoral fellowships.

Data and Codes Availability

The base data and results (in GIS format) along with the code of the implemented models that support the findings of this study are available in 'Zenodo' with the identifiers 10.5281/zenodo.3413625 and 10.5281/zenodo.3415325

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Minerva Foundation [Post-doctoral fellowship];Rothschild Foundation [Post-doctoral fellowship].

References

Aitken, S.C. and Kwan, M.-P., 2010. GIS as qualitative research: knowledge, participatory politics and cartographies of affect. *In:* DeLyser, D., et al. eds. *The SAGE Handbook of Qualitative Geography*. SAGE Publications Inc., 287–304.

Armstrong, G., 1890. *Palestine from the surveys conducted for the committee of the palestine exploration fund and other sources [Map]. Compiled by George Armstrong and revised by Colonel Sir Charles W. Wilson and Major C.R. Conder. Sheets 13, 19, 20 and 21*, 1:168960. London: Stanford's Geographical Establishment.

Bailey, T.J. and Schick, J.B.M., 2009. Historical GIS: enabling the collision of history and geography. *Social Science Computer Review*, 27 (3), 291–296. doi:10.1177/0894439308329757.

Batten, D.C. 2007. Least-Cost Pathways, Exchange Routes, and Settlement Patterns in Late Prehistoric East-Central New Mexico. *In:* Clark, J.T., and E.M. Hagemeister, eds. *Proceedings of the 34th Conference*, Fargo, United States, April 2007. Archaeolingua, Budapest, pp. 151–158.

Beeri, C., *et al.*, ed. 2005. Finding corresponding objects when integrating several geo-spatial datasets. *in 13th annual ACM international workshop on Geographic information systems*. Bremen, Germany, 87–96.

Bell, T. and Lock, G., 2000. Topographic and cultural influences on walking the ridgeway in later prehistoric times. *Nato ASI Series A Life Sciences*, 321, 85–100.

Ben-David, C., 2005. The paved Roman road from Petra to the Arabah. *Cathedra*, 116, 31–48.

Ben-David, C., ed. 2012. Nabataean or late Roman? Reconsidering the date of the built sections and milestones along the Petra-Gaza road. *Special Session of the Seminar for Arabian Studies*. London, England, 17–25.

Ben-David, C., 2018. *New discoveries along the Insence Road*. Personal communication.

Davie, F.M. and Frumin, M., 2007. Late 18th century Russian navy maps and the first 3D visualization of the walled city of Beirut. *e-Perimetron*, 2 (2), 52–65.

Douglas, D.H., 1994. Least-cost path in GIS using an accumulated cost surface and slopelines. *Cartographica: the International Journal for Geographic Information and Geovisualization*, 31 (3), 37–51. doi:10.3138/D327-0323-2JUT-016M

Erickson-Gini, T., 2002. Nabataean or Roman? Reconsidering the date of the camp at Avdat in light of recent excavations. *Bar International Series*, 1084 (1), 113–130.

Erickson-Gini, T. and Israel, Y., 2003. Recent advances in the research of the Nabatean and Roman Negev. In: R. Rosenthal-Heginbottom, eds. *The Nabateans in the Negev*. Haifa: Muzeʾon Reʾuvan ṿe-ʻIdit Hekhṭ, 10–14.

Erickson-Gini, T., 2006. Down to the sea. Nabataean colonisation in the Negev Highlands. *In:* Bienkowski, P. and Galor, K. eds. *Crossing the rift. Resources, routes, settlement patterns and interaction in the Wadi Arabah*. Oxford: British academy monographs in archaeology, 157–166.

Erickson-Gini, T., 2010. *Nabataean settlement and self-organized economy in the central Negev: crisis and renewal*. Oxford: Archaeopress.

Erickson-Gini, T., 2012. Nabataean agriculture: myth and reality. *Journal of Arid Environments*, 86, 50–54. doi:10.1016/j.jaridenv.2012.02.018

Erickson-Gini, T. and Israel, Y., 2013. Excavating the Nabataean Incense road. *Journal of Eastern Mediterranean Archeology & Heritage Studies*, 1 (1), 24–53. doi:10.5325/jeasmedarcherstu.1.1.0024

Gavish, D., 1978. Air photographs by first world war pilots in Eretz-Israel. *Cathedra*, 7, 119–150.

Glueck, N., 1960. Archeological exploration of the Negev in 1959. *Bulletin of the American Schools of Oriental Research*, 159 (1), 3–14. doi:10.2307/1355614

Glueck, N., 1965. Further explorations in the Negev. *Bulletin of the American Schools of Oriental Research*, 179 (1), 6–29. doi:10.2307/1356346

Goldreich, Y., 2003. *Israel climate: observations research and applications*. New York: Springer.

Goodchild, M.F. and Hunter, G.J., 1997. A simple positional accuracy measure for linear features. *International Journal of Geographical Information Science*, 11 (3), 299–306. doi:10.1080/136588197242419

Gregory, I.N. and Geddes, A., 2014. *Toward spatial humanities: historical GIS and spatial history*. Bloomington: Indiana University Press.

Gregory, I.N. and Healy, G.R., 2007. Historical GIS: structuring, mapping and analysing geographies of the past. *Progress in Human Geography*, 31 (5), 638–653. doi:10.1177/0309132507081495.

Güimil-Fariña, A. and Parcero-Oubiña, C., 2015. "Dotting the joins": a non-reconstructive use of least cost paths to approach ancient roads. The case of the Roman roads in the NW Iberian Peninsula. *Journal of Archeological Science*, 54, 31–44. doi:10.1016/j.jas.2014.11.030.

Herzog, I., 2013. Review of least cost analysis of social landscapes. Archeological case studies. *Internet Archaeology*, 34. doi:.org/10.11141/ia.34.7

Herzog, I., and Posluschny, A. 2011. Tilt–slope-dependent least cost path calculations revisited. *Proceedings of the 36th CAA Conference*, vol. 2, pp. 6.

Johnson, D.J., 1987. *Nabateans trade: intensification and Culture Change*. (PhD). Univendity of Utah.

Kantner, J. and Hobgood, R., 2003. Digital technologies and prehistoric landscapes in the American Southwest. *Bar International Series*, 1151, 117–124.

Kloner, A., 1996. Stepped roads in Roman Palestine. *Aram*, 8, 111–137. doi:10.2143/ARAM.8.1.2002189.

Knowles, A.K., 2005. Emerging trends in historical GIS. *Historical Geography*, 33, 7–13.

Levin, N., Kark, R., and Galilee, E., 2010. Maps and the settlement of southern Palestine, 1799–1948: an historical/GIS analysis. *Journal of Historical Geography*, 36, 1–18. doi:10.1016/j.jhg.2009.04.001.

Li, L. and Goodchild, M.F., 2011. An optimisation model for linear feature matching in geographical data conflation. *International Journal of Image and Data Fusion*, 2 (4), 309–328. doi:10.1080/19479832.2011.577458.

Llobera, M., Fábrega-Álvarez, P., and Parcero-Oubiña, C., 2011. Order in movement: a GIS approach to accessibility. *Journal of Archeological Science*, 38 (4), 843–851. doi:10.1016/j.jas.2010.11.006.

Maraqten, M., 1996. Dangerous trade routes: on the plundering of caravans in the Pre-Islamic Near East. *Aram Periodicals*, 8 (1), 213–236. doi:10.2143/ARAM.8.1.2002195.

Matsumoto, G., ed. 2008. Availability of least-cost pathway analysis for the study of Inka Road system. *The 36th Annual Midwest Conference on Andean and Amazonian Archaeology and Ethnohistory*, 23–24. doi:10.1007/s11084-007-9115-0.

McCormick, M. 2008. *The Digital Atlas of Roman and Medieval Civilizations (DARMC)*. Massachusetts, USA: Harvard University.

Meshel, Z. and Tsafrir, Y., 1974. The Nabataean road from 'Avdat to Sha'ar-Ramon. *Palestine Exploration Quarterly*, 106 (2), 103–118. doi:10.1179/peq.1974.106.2.103.

Millar, F., 1998. Caravan cities: the Roman near east and long-distance trade by land. *Bulletin of the Institute of Classical Studies*, (71), 119–137. doi:10.1111/j.2041-5370.1998.tb01697.x.

Negev, A., 1983. *Masters of the desert*. Jerusalem: Keter Publishing.

Newcombe, S.F., 1914. The survey of Sinai and South Palestine. *Palestine Exploration Quarterly*, 46 (3), 128–133. doi:10.1179/peq.1914.46.3.128

Pliny, 1962. Natural history. *In:* Jones, W.H.S. and Rackham, H. eds. London: W. Heinemann.

Roll, I., 1976. The Roman road network in Eretz-Israel. *Qadmoniot*, 2/3 (34/35), 38–50.

Roll, I., 2005. Imperial roads across and trade routes beyond the Roman provinces of Judaea-Palaestina and Arabia: the state of research. *Journal of the Institute of Archeology of Tel Aviv University*, 32 (1), 107–118. doi:10.1179/tav.2005.2005.1.107.

Rostovtzeff, M., 1932. *Caravan cities*. Oxford: Claredon Press.

Rubin, R., 1988. Water conservation methods in Israel's Negev desert in late antiquity. *Journal of Historical Geography*, 14 (3), 229–244. doi:10.1016/S0305-7488(88)80220-2.

Schaffer, G. and Levin, N., 2015. Challenges and possible approaches for using GIS as a tool in historical geography landscape research: a meta-analysis review. *e-Perimetron*, 10 (3), 94–123.

Schaffer, G. and Levin, N., 2016. Reconstructing nineteenth century landscapes from historical maps-the survey of Western Palestine as a case study. *Landscape Research*, 41 (3), 360–379. doi:10.1080/01426397.2015.1078454.

Shimada, M., 2010. Ortho-rectification and slope correction of SAR data using DEM and its accuracy evaluation. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 3 (4), 657–671. doi:10.1109/JSTARS.2010.2072984

Siljander, M., *et al*., 2015. GIS-based cost distance modelling to support strategic maritime search and rescue planning: a feasibility study. *Applied Geography*, 57, 54–70. doi:10.1016/j.apgeog.2014.12.013.

Stott, D., *et al*. 2018. Mapping an ancient city with a century of remotely sensed data. *Proceedings of the national academy of sciences*, 15 (24), E5450–E5458.

Tobler, W., 1993. *Three presentations on geographical analysis and modeling*. Santa Barbara: National Center for Geographic Information and Analysis.

Tsafrir, Y., Di Segni, L., and Green, J., 1994. *Tabula Imperii Romanii: Iudaea, palaestina. Eretz Israel in Hellenistic, Roman and Byzantine Periods: maps and gazetteer*. Jerusalem: Israel Academy of Sciences and Humanities, 263.

Tsoar, H. and Yekutieli, Y., 1992. Geomorphological identification of ancient roads and paths on the loess of the Northern Negev. *Israel Journal of Earth Science*, 41, 209–216.

Verhagen, J. and Jeneson, C.F., 2012. A Roman puzzle. Trying to find the Via Belgica with GIS. doi:10.1094/PDIS-11-11-0999-PDN

Warren, S.D., *et al*., 2004. An evaluation of methods to determine slope using digital elevation data. *Catena*, 58 (3), 215–233. doi:10.1016/j.catena.2004.05.001

White, D.A. and Surface-Evans, S.L., 2012. *Least cost analysis of social landscapes: archeological case studies*. Utah: University of Utah Press.

Zohar, M., 2017. A city hit by an earthquake: an HGIS approach to reconstructing the damage in Tiberias (Israel) in 1837. *International Journal of Geographical Information Science*, 31 (1), 81–99. doi:10.1080/13658816.2016.1188933.

Zohar, M., 2019. Follow the road: historical GIS for evaluating the development of routes in the Negev region during the twentieth century. *Cartography and Geographic Information Science*, 46 (6), 532–546.