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Beyond Least Cost Paths: Circuit theory, maritime mobility and patterns of urbanism in the Roman Adriatic

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ABSTRACT

Traditionally, Least Cost Paths (LCP) are used for exploring mobility across archaeological landscapes. However, LCPs only highlight optimal paths, and implementing maritime mobility is arduous. In this paper, Circuit Theory (CT) analysis is used to analyse potential mobility. Key to this is the effect of wind patterns, dependent on the month and direction of travel, on maritime mobility. This analysis is applied to the case study of urbanism in the Roman Adriatic, and it is shown that CT provides considerably more quantitative data than LCP. These data can then be used in deeper analysis of the archaeological landscape, showing the impact of potential mobility on various factors. The impact on site distribution appears to be significant, with urban centres consistently being located in areas with above average potential mobility values, particularly those in the Northern Adriatic. The impact on population hierarchy is more com-plex, and while the urban centres with the largest populations generally have higher potential mobility values, there is no straightforward correlation between the two, and so additional factors must have played a more significant role in determining this hierarchy, than in site distribution.

1. Introduction

Geographical Information Systems (GIS) have become the standard tool to explore human-environment relations, including the concept of past mobil-ity [Conolly and Lake, 2006; Bevan and Lake, 2013]. With the proliferation of detailed topographical data the geographical prop-erties of these landscapes have been utilised in modelling mobility, rather than focusing solely on the in-complete archaeological record. The most commonly used approach is Least.

Cost Path (LCP) analysis [Carballo and Pluckhahn, 2007, Doyle and Garrison, 2012, Hazell and Brodie, 2012, Llobera et al., 2011, White, 2015, Gustas and Supernant, 2017, Martínez Tuñón et al., 2018, Rose-nswig and Martínez Tuñón, 2020]. LCP requires a cost surface map, usually derived from a Digital Eleva-tion Model (DEM) or slope. LCP uses this surface to calculate the optimal path between two given points. The value of such analysis is considerable, allowing for a deeper un-derstanding of which sites could be more efficiently accessed, as well as, through comparison with the archaeological data, if the LCP was actu-ally exploited or not [Rosenswig and Martínez Tuñón, 2020].

As with any research tool, LCP presents challenges and limitations. The most pertinent, being that only a single optimal route is defined. If the LCP is blocked, this basic analysis cannot offer insight into alternative routes that would, realistically, have been regularly used. Additionally, LCP analysis func-tions best with set points. It clearly shows the LCP between two points, but the choice of points invariably influences the results, exacerbating archaeolog-ical biases. Some ap-proaches define grids or perimeters of points and perform pairwise LCP analysis to reveal natural paths across a given region [Murrieta-Flores, 2012, Yubero-Gómez et al., 2015], but this approach is still limited to an optimal path and suffers additional issues with border effects. With LCP analysis in archaeology seldom integrating maritime or fluvial move-ment, per-spectives of mobility may be distorted. Finally, LCP results are affected by the choice of the algorithms defining the path and the cost map, which is particu-larly important for the binary route vs non-route output of the analysis. These issues are certainly not new and have been extensively discussed, but they are yet to be entirely overcome [Herzog, 2014; Seifried and Gardner, 2019]. Some approaches such as probabi-listic cost values [Verhagen et al., 2019] or the use of multiple algo-rithms [Güimil-Fariña and Parcero-Oubiña, 2015] may mitigate the issues, but LCP is still ultimately focused on identifying a single path between two points.

The work presented here highlights the potential of a different method, namely Circuit Theory (CT), to overcome some of the limita-tions of LCP. We argue that this approach is readily applicable to

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modelling mobility, and pro-vides richer, more relevant results for archaeologists, beyond a simple cost value between two points derived from LCP. In order to demonstrate the utility of this approach, we present here an example of its application to mobility and patterns of urbanism in the Adriatic region in the Roman period. We first explore the challenge of modelling maritime mobility and outline the Adriatic study region. The concept of CT itself is then introduced. The specific methods and materials used in this research are then discussed and the results outlined. This is followed by an in-depth discussion and possible interpretations of the results. Finally, concluding remarks on the limits of this model and future steps are provided. All of this highlights CT as a promising method for expanding mobility analysis in archaeology beyond LCP, and assesses the extent to which mobility can explain the distribution and population of urban centres in the Roman Adriatic.

1.1. Maritime mobility

Studies modelling mobility across archaeological landscapes are often re-stricted to terrestrial environments, and so rarely provide a complete picture. With most LCP analysis being reliant on DEM and slope data, the inclusion of seascapes in any model is difficult. Attempts have been made to overcome this by using the slope data of the coast to highlight better landing locations [Gustas and Supernant, 2017] or by using wind patterns to generate cost surface maps for the sea itself [See examples in Indruszewski and Barton, 2008; Leidwanger, 2013; Arcenas, 2015; Jarriel, 2018]. The effect of these wind patterns on sailing vessels is arguably the main factor influencing ancient maritime mobility. How-ever, a widely applicable model for this is yet to be proposed, particularly one combining both land and sea. Indruszewski and Barton model a single sea voy-age, for which relatively robust historical and experimental archaeological data was accessible [Indruszewski and Barton, 2008, 61–62]. Such data are rarely available. Jarriel uses seasonal wind patterns to understand the changing travel costs of vessels with experienced paddlers moving between certain Aegean is-lands [Jarriel, 2018]. Ranges of one, two, three or more than three days are used, which is not very precise, particularly when considering larger regions. Safadi and Sturt offer one of the most compelling attempts to advance our understand-ing of modelling maritime mobility, with a focus on seasonal wind speeds and re-conceptualising maritime space-time [Safadi and Sturt, 2019].

All of these cases are focused on maritime mobility, but a full integration of seascapes and terrestrial landscapes is seldom seen in any archaeological-based model [for an exception to this trend see Scheidel, 2015], and the issues associated with LCP outlined above remain. Such reliance on LCP limits the extent to which the challenges of modeling maritime mobility can be effectively addressed.

1.2. The Adriatic Sea during the roman period

The Adriatic Sea during the Roman period provides an excellent study re-gion in which to test alternative mobility analysis in a combined maritime and terrestrial context. By the 1st century AD, much of the Mediterranean was firmly under the control of the Roman Empire, ushering in a period of relative peace and stability for the region during which unprecedented economic activity and communication flourished. The Mediterranean Sea itself acted to connect the geographically distant provinces of the Empire. The Adriatic, at the centre of the Mediterranean world, connects the east and west and acts as a gateway between the Mediterranean and central Europe (see Fig. 1). It is generally accepted that the sea connected the various peoples inhabiting the opposite coasts over much of its history [de Vivo, 2003; Abulafia, 2005; Hodges, 2010; Reill, 2012; Phelps, 2013]. Nevertheless, there have been few studies specifically concerned with modelling mobility in the Adriatic, and the notable qualitative studies focus mainly on prehistoric periods [Gaffney et al., 1997; Forenbaher, 2009] with only one study for the Roman period [Jurišić, 2000]. Only during this period, following the Roman conquest of the Illyrian coast [Glicksman, 2005], was the entire Adriatic region under the direct control of a single political en-tity. Following the fall of the Empire, this would never again be the case. While the sites and populations considered in this study were all present during the Early Empire, the data is otherwise largely non-historical, with developments and more minor population shifts at the sites over this period not accounted for. This approach helps to reduce archaeological bias in the initial analysis.

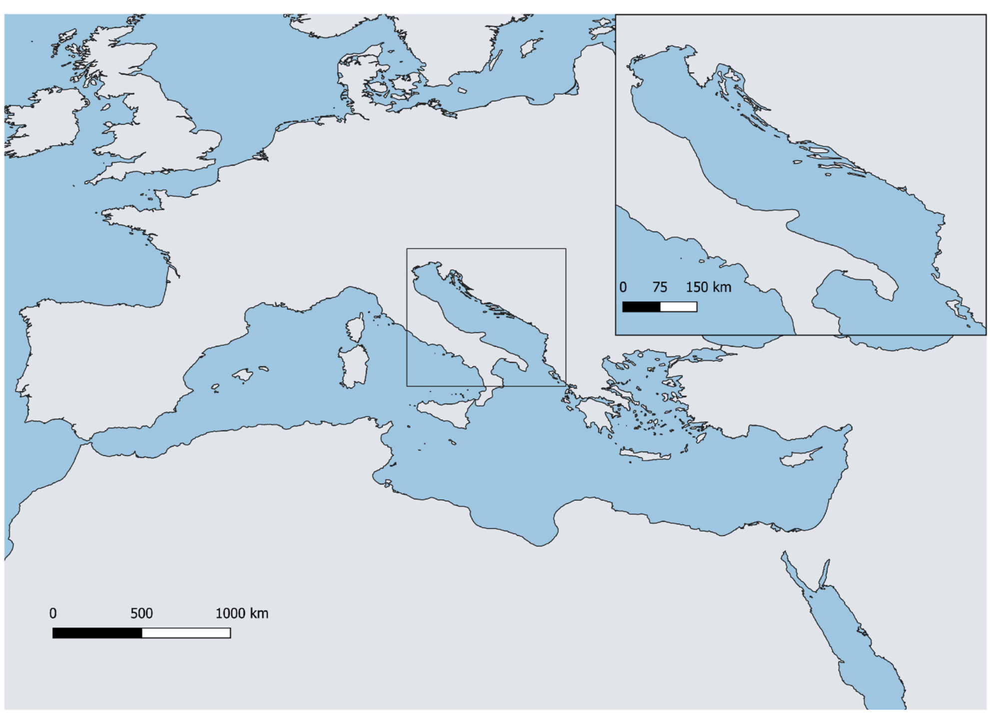

Fig. 1. View of Mediterranean World with a Close up of the Adriatic Case Study Region. (Colour to be used for all figures except 2 and 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

1.3. Circuit theory and connectivity

Circuit theory can show a complete spectrum of movement costs across land-scapes, and does not require set pairs of points for the input. This allows for far more than simple LCPs to be identified.

The theory is based on Ohm's Law outlining the electrical relation-ship be-tween current I, resistance R and voltage V under the formula ($V = IR$). Current I flows across a circuit with varying resistance R values; these resis-tance values result in greater or lesser current values. The circuit requires a source of current and resistance values for each cell of the circuit; as we focus on the relative connectivity values, voltage V is largely irrelevant for current purposes. Fig. 2 offers a basic workflow for CT which can be compared to LCP in Fig. 3.

The inclusion of specific archaeological sites is not necessary at the outset of the model. Instead, user-defined areas of any size can be used as sources between which current flows. Therefore, the results of the model are not impacted by the choice of case study itself; rather the case study, and specific sites, can be compared to the final CT output independently. Applying this to archaeological contexts, the source can be a point or an area, such as an urban centre, and the resistance values provided by cost surface maps. The manner in which current flows across this the circuit shows, at its most basic interpretation, the hierarchy of routes across the landscape, with areas of relatively high potential mobility having high current values (see Fig. 4 for an example output of the Istrian peninsula in the northern Adriatic). With closer analysis, this can provide insight into connectivity, settlement patterns and a variety of more complex aspects of the archaeological environment. CT has been used primarily

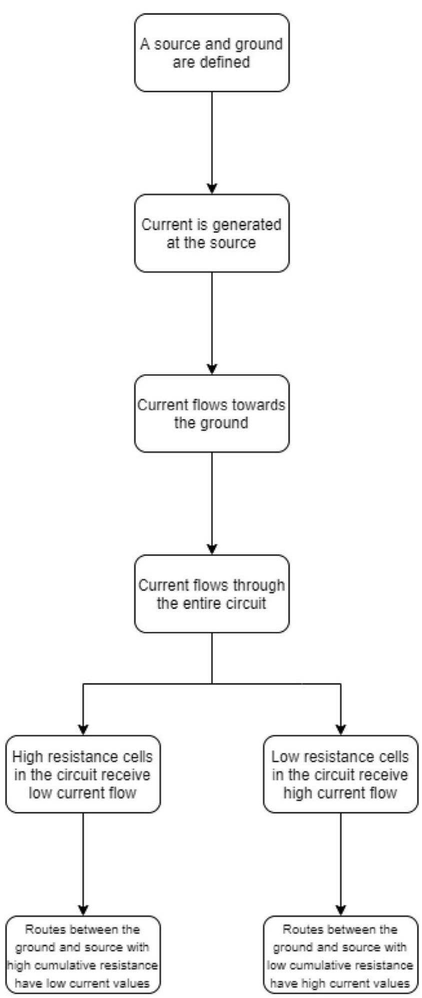

Fig. 2. Basic CT work flow.

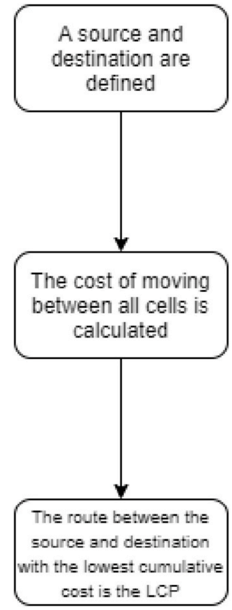

Fig. 3. Basic LCP work flow.

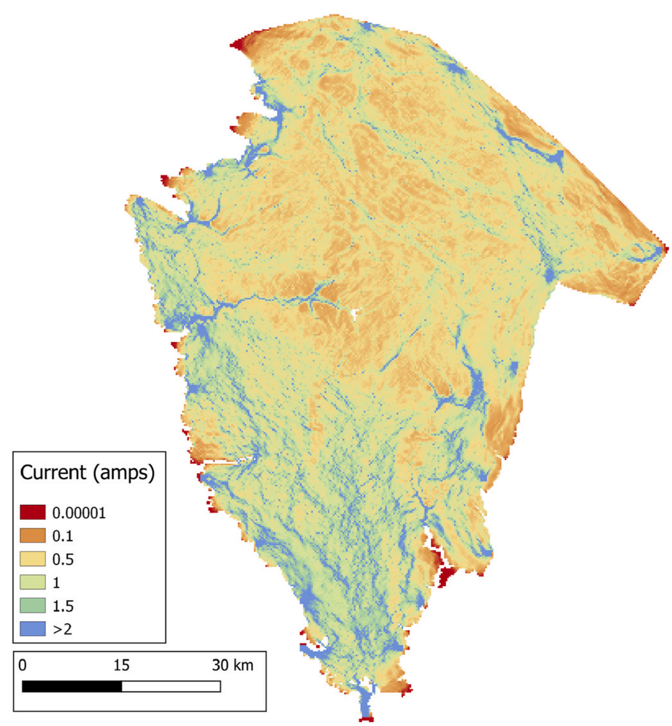

Fig. 4. Example Circuit Theory Output for Istria using random point sources along the border of the circuit. Random sources were not used for the Adriatic wide directional itera-tions.

in ecological studies to identify connectivity corridors and bottlenecks [see for example Pelletier et al., 2014; Brodie et al., 2016; Osipova et al., 2019]; it has seldom been applied to archaeological contexts, except in a few studies [Howey, 2011; Thayn et al., 2016; White, 2015].

It is important to understand what CT cannot show. The current values represent potential mobility, but an area of high current in the output does not indicate that the area was well connected in reality, as this potential mobility may not have been utilised. Moreover, areas with high current values need not necessarily be the areas with the lowest absolute movement costs; rather high current areas have relatively low movement costs compared to adjacent areas. Compare the uniformly flat southern area of Istria in Fig. 5 to the varied current values in the same area of Fig. 4. Rather than a single LCP between sites, the application of CT has the potential to show multiple low cost paths, and to reveal entire regions of potential mobility beyond a binary LCP output (see Figs. 4 and 6 as a basic comparison between CT and LCP analyses). The archaeological sites within these regions can then be analysed and one of the core concerns of computational models in archaeology addressed: the comparison between what should be expected and what the evidence suggests.

2. Materials and methods

The current methodology is centred around CT and statistical analysis of patterns of urbanism in the Roman Adriatic.

2.1. Circuitscape

The software used for running the CT model is Circuitscape [McRae et al., 2013, 2016]. The project's website and these publications offer lengthy bibli-ographies for the use of Circuitscape in varied disciplines, but none are archae-ological, despite some works not included in the bibliographies applying Circuit Theory to archaeological contexts [Howey, 2011].

Different inputs and scenarios can be used in Circuitscape. The most perti-nent combination is raster inputs with the 'advanced' scenario. This allows for the direction of current to be controlled. It requires a source, ground and resis-tance map, all of which must be in ASC Grid format and of the same size and resolution [for basic examples of this, see McRae et al., 2013]. Each cell in the resistance grid has a value corresponding to a cost/resistance value, and each is connected, by default, to eight adjacent cells, from which average resistance values are calculated. Current can then be generated at the source and flows across the grid towards the ground. The relationship between current and re-sistance dictates the manner in which current flows and therefore, the

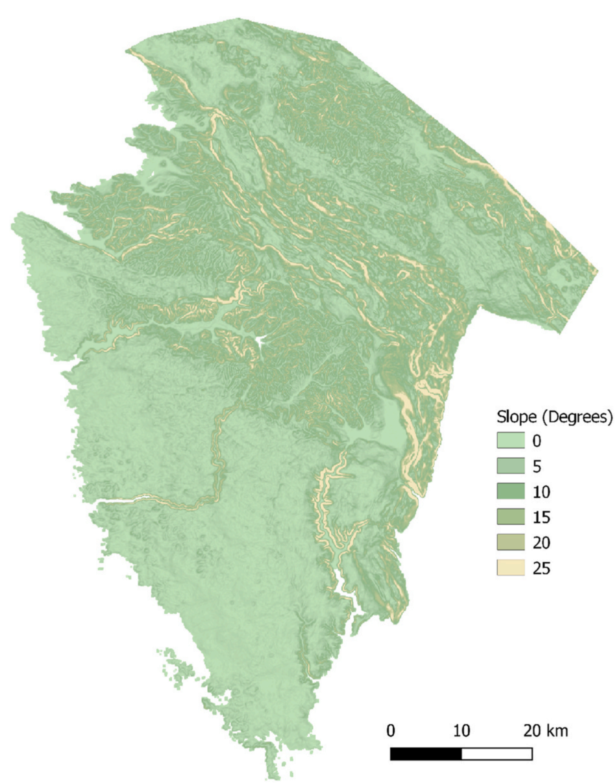

Fig. 5. Slope raster for istria.

Fig. 6. Example Output for LCP analysis for Istria, with LCP between all main Roman urban centres shown.

output of the model. If, for example, the eastern border of the grid is used as the source, and the western border the ground, the output models how current would flow from east to west. By then comparing the location of known archaeological sites with the current values in the output grid we can determine if the archaeological sites are located in regions of high potential mobility.

2.1.1. Land-based mobility cost

The materials used for CT, like with LCP, are cost surfaces and specific points/sources between which current flows. In the present analysis, the sources are relatively straight forward, being the northern, southern, eastern and west-ern borders of the study region. These are all weighted equally, though Cir-cuitscape has the functionality to implement weighting. Additionally, these sources and grounds could be anywhere across the grid, in the north-east and south-west for example, depending on the direction of movement being re-searched.

The cost surface maps themselves are more complicated, terrestrial surfaces are based on the DEM available from the Copernicus Land Monitoring Service. Slope can be calculated from this and, using a common equation $s = 0.033i + -1.357$ to calculate how the incline of a slope i affects speed s, a raster for speed is produced [based on Bosina and Weidmann, 2017]. This function does not require direction of travel to be accounted for, and so was chosen over others. However, this is not the only suitable way to calculate movement cost, and terrestrial direction of travel can be accounted for by using more complex functions if required. Transforming the result of this function into time provides a cost surface map for the terrestrial Adriatic region as seen in Fig. 7. With a resolution of 250m, the numerical values of each cell represent the time taken, in seconds, to cross 250m at the given incline. The number of uncertainties involved in the model, given the ancient context and regional scale, mean that a resolution of 250m is more than sufficient, with tests using a 100m resolution producing similar outputs at much higher computational costs. Additionally, while movement down a

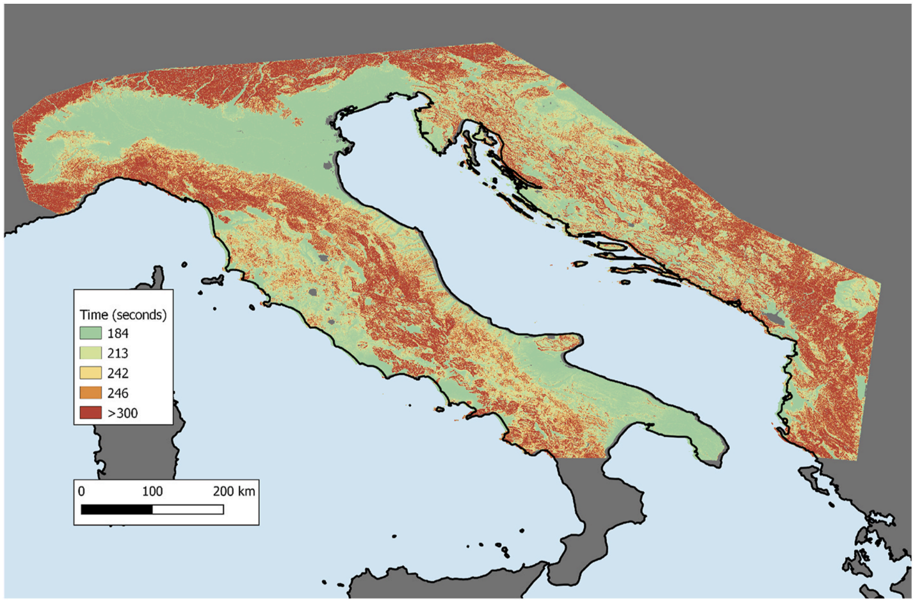

Fig. 7. Terrestrial Cost Surface, based on slope, in time.

gentle slope is more efficient than movement up the same slope, this becomes increasingly negligible and even reverses as the incline of the slope increases, which this specific equation accounts for [Hunter et al., 2010; Meeder et al., 2017; Bosina and Weidmann, 2017]. This, combined with the scale of the current study region, means that direction of travel does not have a significant impact on terrestrial mobility, particularly when compared to its effect on maritime mobility.

2.1.2. Maritime mobility cost

Generating a cost surface map for the sea itself is vital to fully understand mobility in the Adriatic. Wind patterns had the greatest single effect on sailing times, and so a cost surface map based on these patterns is used. ERA5 hourly Datasets from the Copernicus Project were retrieved [Hersbach et al., 2020], which contain both u and v components of wind at 10m. The coordinates for the extent of the Adriatic used are a latitudinal and longitudinal range of 39.5–46.0 and 12.0–20.0° respectively. These components were taken hourly from 1979 through to 2020, before being averaged for every month. Using Pythagorean Theorem, the u and v components were transformed into wind speed (m/s) ($ws < sqrt(u^2 + v^2)$) (Fig. 8) and using the atan2 function in the R package 'raster', into wind direction in degrees ($wd < 180 + (180/pi)$ $atan2(u, v)$) (Fig. 9). The resolution of available wind data is limited to ~

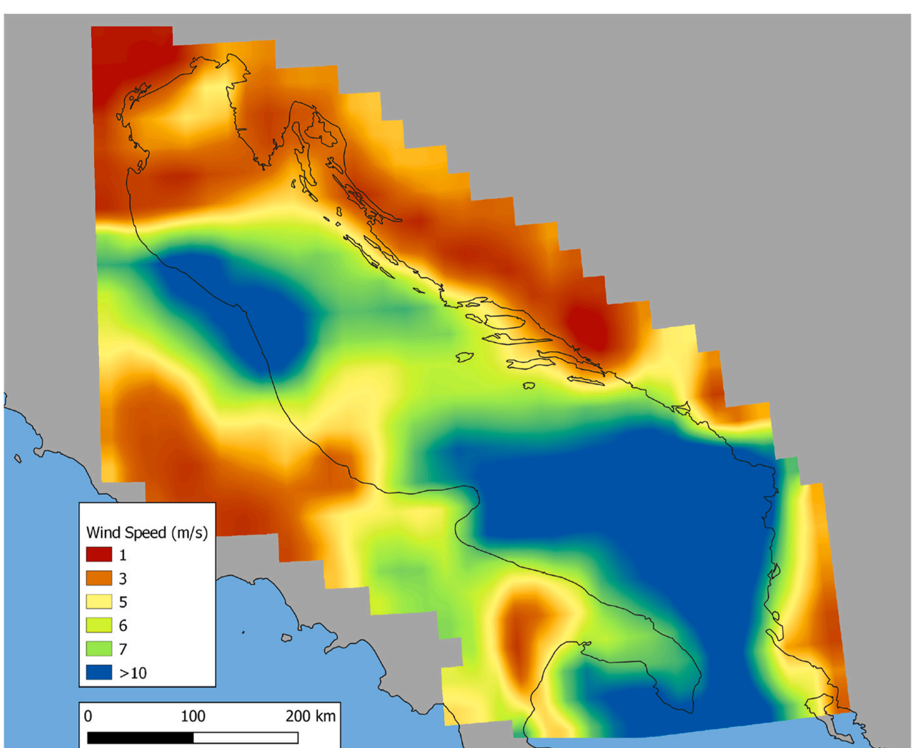

Fig. 8. Average Wind Speed Raster for January (1979–2020). An equivalent for each of the 12 months was used in the model.

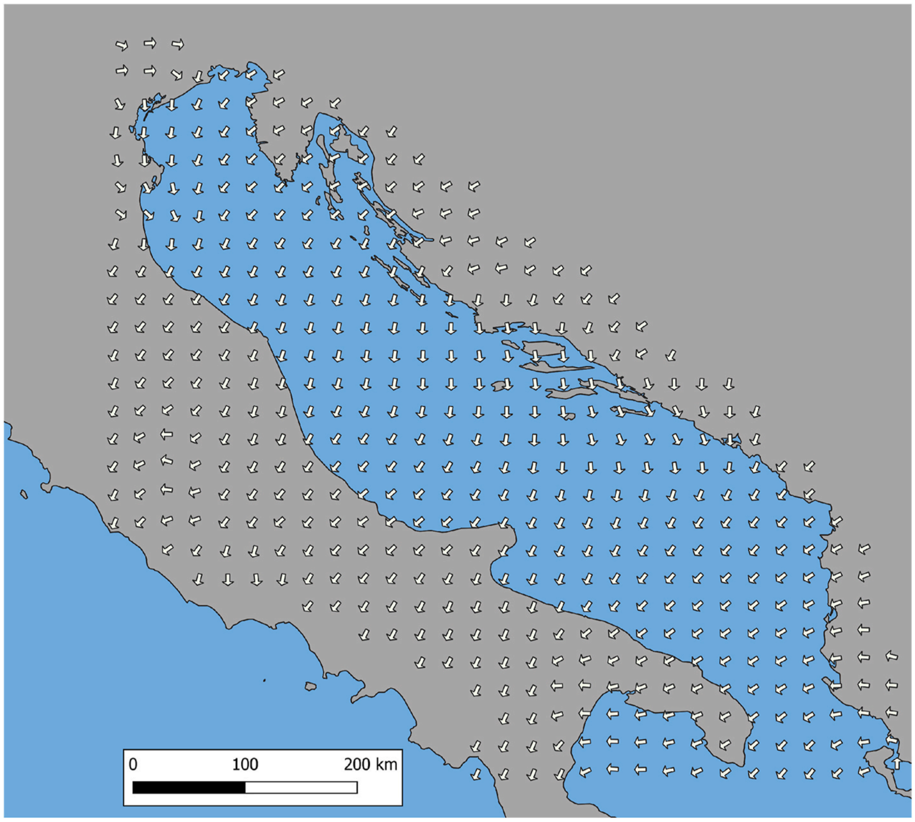

Fig. 9. Average Wind Direction Raster for January (1979–2020). An equivalent for each of the 12 months was used in the model.

— * 0.25°/25 km, so in order to be functional with the terrestrial, the wind data was translated into 250m resolution rasters, though each pixel in a given 25 km^2 area will all have the same value. Again, due to the uncertainties inherent in calculating the impact of modern wind patterns on speeds of ancient sailing vessels, this resolution does not meaningfully affect the viability of the model.

Transforming wind patterns into time requires calculating movement speed. There have been numerous discussions focusing on the possible sailing speeds of ancient vessels [Casson, 1950, 1995; Arnaud, 2005, 2016; Bilić, 2012; Beresford, 2013; Leidwanger and Knappett, 2018] and it is beyond the scope of this paper to expand on the work already undertaken. As such, the values for sailing speeds used in this study (primarily derived from [Casson, 1950, 1995; Bilić, 2012; Arcenas, 2015]) are not meant to represent infallible real sailing speeds, rather simply provide comparable averages which can be readily adjusted over multiple iterations of the model. A combination of wind speed and direction ranges provide the sailing speed values. Six ranges are used for wind speed as defined in Table 1 and sixteen for wind direction (Table 2). These ranges can then be put into reference grids where depending on the relative sailing direction, different sailing speeds result. These reference grids can be found in Appendix A, as well as those with slower sailing speeds which were tested, but produced unrealistic results where much of the sea was impossible to sail across for most of the year. In reality, techniques such as tacking would have allowed ancient sailors to make slow, but steady progress even under unfavourable conditions [Casson, 1995]). 48 different scenarios are considered, sailing in one of the four cardinal directions for each of the 12 months. The end result is 48 cost surface maps. After converting speed into time, the terrestrial and maritime cost surface maps can be combined, providing continuous cost surfaces with each 250m cell containing a value for the relative cost, in seconds, that it would take to traverse this cell, as seen in Fig. 10. These raster maps can then be used as resistance maps in Circuitscape.

Table 1
The Six Wind Speed Ranges Used for Calculating Sailing Speed. (Note, m/s were used in calculations).

Range	Wind Speed (knots)	Beaufort
1	0–1	Calm
2	1–3	Light Air
3	3–6	Light Breeze
4	6–10	Gentle Breeze
5	10–16	Moderate Breeze
6	>16	Strong Breeze and Above

Table 2
The Sixteen Wind Direction Ranges Corresponding to Cardinal Directions and used for Calculating Sailing Speed.

Range	Wind Direction (°)	Cardinal
1	348.75–11.25	N
2	11.25–33.75	NNE
3	33.75–56.25	NE
4	56.25–78.75	ENE
5	78.75–101.25	E
6	101.25–123.75	ESE
7	123.75–146.75	SE
8	146.75–168.75	SSE
9	168.75–191.25	S
10	191.25–213.75	SSW
11	213.75–236.25	SW
12	236.25–258.75	WSW
13	258.75–281.25	W
14	281.25–303.75	WNW
15	303.75–326.25	NW
16	326.25–348.75	NNW

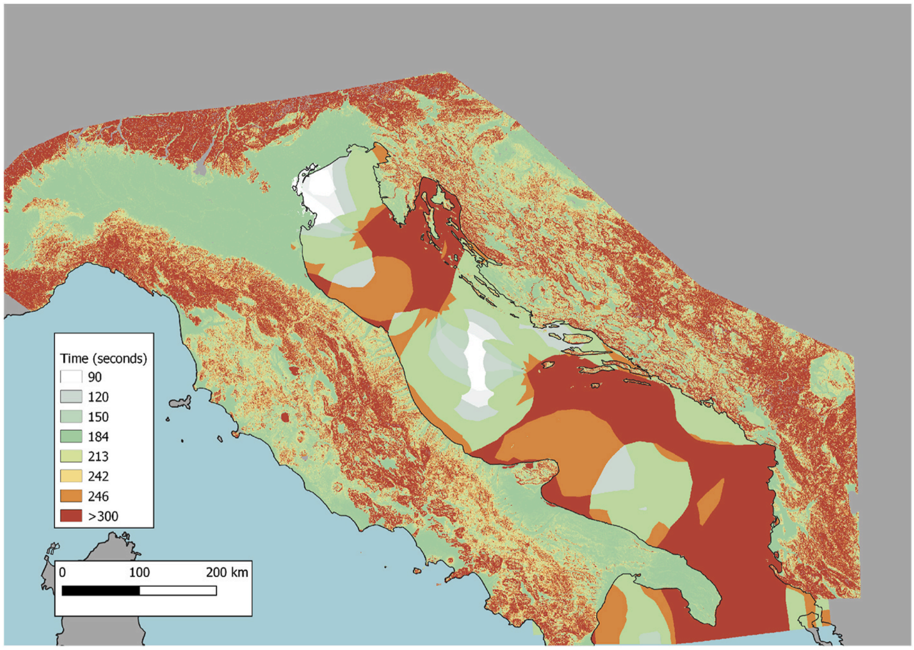

Fig. 10. Example Cost Surface for Sailing East in April. This is Derived from Combining Terrestrial and Maritime Cost Surfaces.

2.1.3. Quantitative analysis and patterns of urbanism

Quantitative analysis is required in order to understand the relationship be-tween the CT outputs and patterns of urbanism. Two case studies are analysed, the first focusing on site distribution of urban centres, the second on the hier-archy of the urban population. In both cases, mean current values from all circuit theory outputs are used. 3 km radii are taken around each site and the mean values of current generated in these areas are calculated. This radius is based on over 80% of known sites in central Italy being within 3 km of an ur-ban centre [Goodchild, 2007]. Using larger radii did not significantly impact the results. For site distribution, the mean current values for each site's 3 km radius are combined to provide a single city mean current value (cmcv) for each scenario. A one sample *t*-test is run against these cmcvs in order to reject the null hypothesis of random site distribution. Further, by subtracting the total mean current value (tmcv) of the CT output from the corresponding cmcv, a difference value is produced. A high difference value indicates that sites are mainly distributed in locations of higher than expected current.

The hierarchy of the urban population can also be explored by analysing mean current values around specific sites. Rather than combining all of the sites mean current values to get a cmcv for each scenario, the current mean value of each individual urban centre can be used. These individual mean current values (imcv) can then be compared to the tmcv of a scenario by subtracting the tmcv from the relevant imcv. This produces 48 difference values for every urban centre, corresponding to each of the scenarios, which can be combined to get a single difference value for every site. Again, a higher difference value would suggest that the individual site is in an area of higher than expected current. By comparing the difference values of sites with different populations we can begin to understand how potential mobility might have impacted the hierarchy of the urban population.

2.1.4. Urban database

The data for the urban centres of the Adriatic region is largely derived from Hanson's work [Hanson, 2016] and supplemented with additional material as necessary [especially de Ligt, 2012; Wilkes, 1969]. The population figures are based on the area covered by the sites and relevant expected population densities (see Table 3). Where the size of the site is not known, and so the population cannot be estimated, it is

Table 3
Site size and density relationships. After [Hanson, 2016].

Size (ha)	Density (p/ha)
<50	100
50–100	150
100–150	200

assumed that the site was relatively small, with a population of 1500. Including or excluding these sites does not affect the main conclusions drawn. The sites can be observed in Fig. 11 and accompanying Appendix B. There are a total of 169 urban centres in the Adriatic region. Of these, just under 57% have estimates for their size.

As with any synthesis of archaeological data, Hanson's database, though the most complete available, is not without issue. It has been criticised for inaccuracies concerning individual sites and for the omission of smaller urban centres [Pfuntner, 2017, Donev et al., 2017]. Many of these issues are negated by the large-scale approach, which is extremely valuable for regional analysis such as the current study. Accepting that some of the smaller sites may be missing from the data and that population figures cannot be exact, the main conclusions drawn here should not be affected, as we focus on relative values rather than absolute. As a consequence, we strongly believe that the imperfect nature of the data does not affect the outcome in any significant way.

3. Results

The 48 maps showing the results of the Circuitscape model on the Adriatic can be found in Appendix C, and we focus here on only the most relevant results. The 'middle' values for sailing speeds were used in the discussions here, but the results using faster and slower sailing speeds are also included in Appendix C. The CT analysis clearly shows that the time of the year and direction of travel have an effect on mobility. For example, sailing north results in high current values in the north-east corner of the region for every month (January in Fig. 12, August in Fig. 13 and April in Fig. 14). This is particularly apparent in colder, wetter months.

On the other hand, when sailing south (Fig. 15), the high current

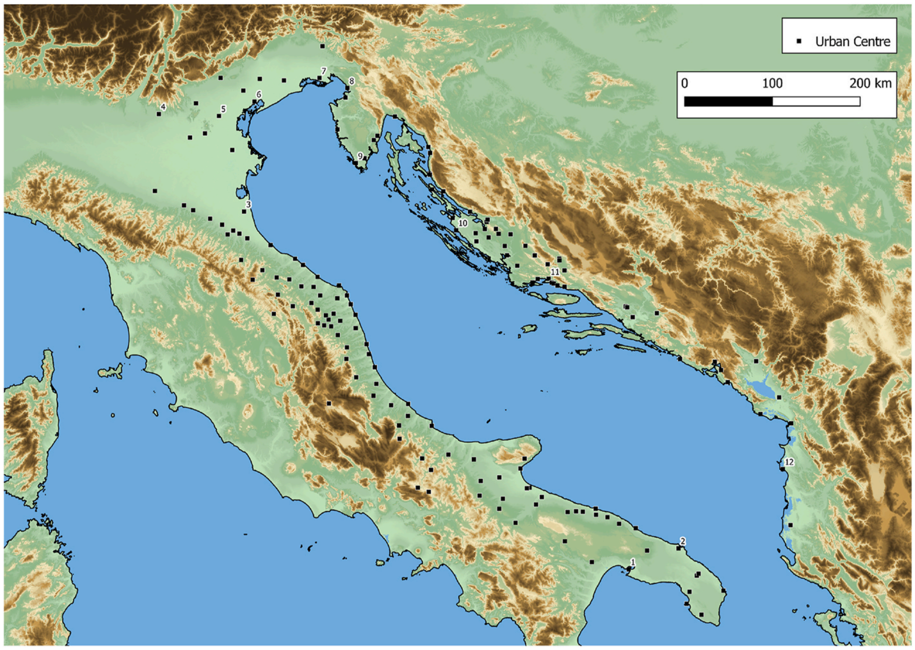

Fig. 11. Urban centres of the adriatic, with major sites highlighted. 1 tarentum; 2 brundisium; 3 ravenna; 4 verona; 5 patavium; 6 altinum; 7 aquileia; 8 tergestum; 9 pola; 10 iader; 11 salona; 12 dyrrachium/epidamnos.

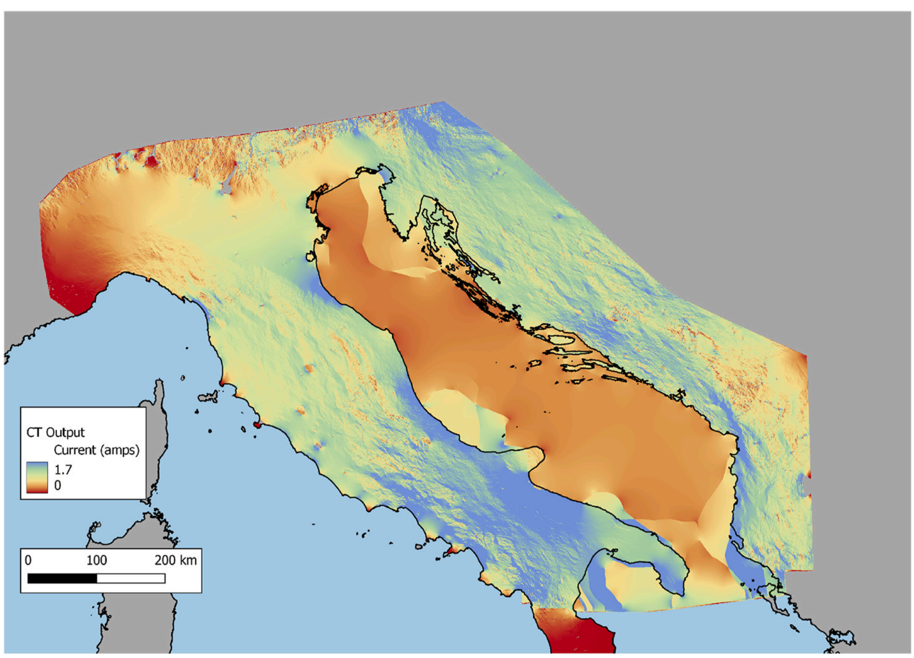

Fig. 12. Circuit theory output for sailing north in January.

values of the north-east are less pronounced, with higher values apparent in the north-west and south-west, though high values along the eastern coast are still present. When considering movement east, the northern Adriatic has considerably higher current values than the south (Fig. 17). For movement west in January (Fig. 16), the current values are considerably lower than for other directions. Notably, the north east still has relatively high current, though so too does the south west, suggesting less of a focus on the northern Adriatic for movement west than for movement east. This is largely true for every month.

Differences can also be observed between seasonal current values. If we take sailing north as an example, coastal sailing is relatively favourable in January (Fig. 12), with the deeper open waters having lower current values. Addition-ally, there is not a marked difference in current between some terrestrial and maritime areas, with much of the terrestrial landscape actually having higher current values. On the other hand, for travelling the same route in August (Fig. 13), maritime movement is clearly preferable, though movement across southern Italy seems relatively efficient. Comparing sailing north in April (Fig-ure 14), the maritime current values are less uniform than in January or August, with the eastern coast having significantly higher current values. Importantly, though the terrestrial cost surface is the same for every scenario, changing the maritime cost surfaces significantly impacts the potential mobility across the terrestrial landscape in every case.

The difference values for the 48 different scenarios and 169 sites can

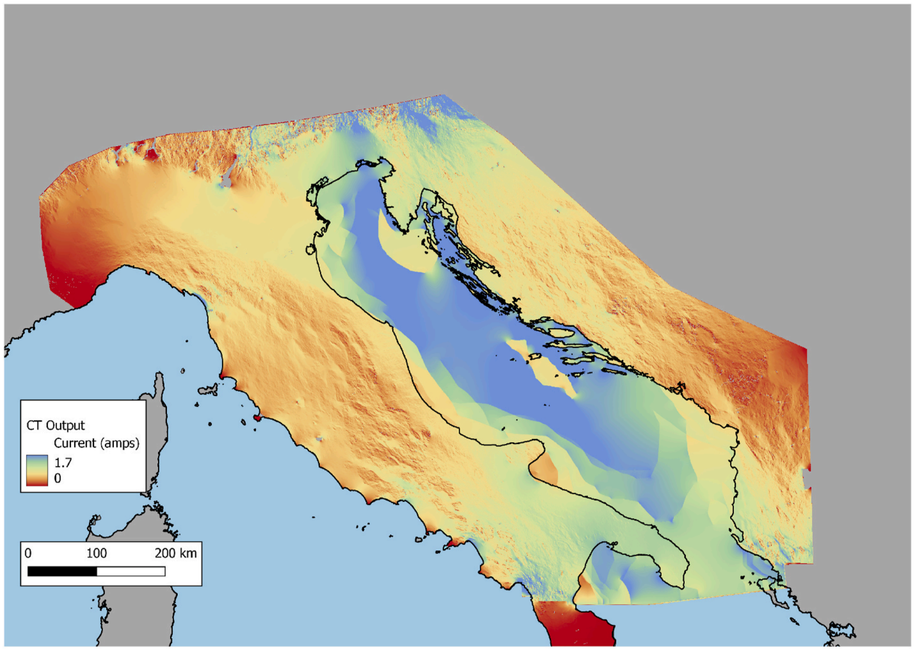

Fig. 13. Circuit theory output for sailing north in August.

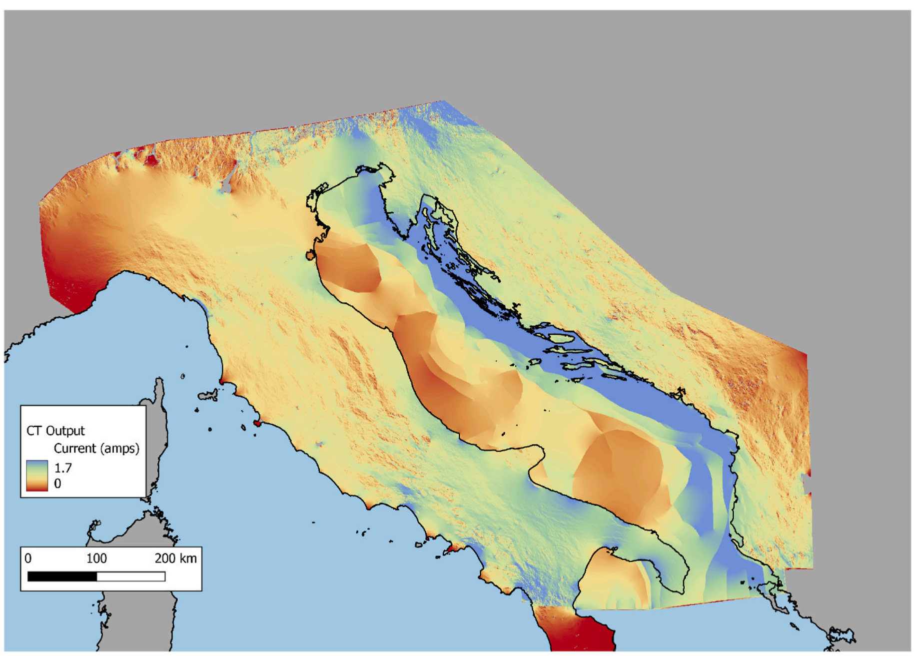

Fig. 14. Circuit theory output for sailing north in April.

be found in Appendices Dand Brespectively. The results for the one sample *t*-test run for the cmcv and imcv difference values consistently produced p values of < 0.001, using a *mu* value of the tmcv. As such, the null hypothesis, that site distribution is not in some way affected by current values, is rejected. Additionally, the difference value of all 48 cmcv and all 169 imcv are positive. This suggests that site distribution favoured areas of high current. However, the situation with site hierarchy is somewhat more complicated (Fig. 18). While all sites have positive total difference values, there is not a straightforward correlation between these difference values and population size. However, only 2 of the sites with known populations significantly above the mean value have difference values significantly below the mean of the difference value. Furthermore, the largest sites do generally have high difference values (Table 4), though the sites with the highest difference values (Table 5) are not all those with higher populations. As such, the impact of potential mobility on population hierarchy seems to have been more complex than on site distribution.

4. Discussion

Comparing these basic results with the archaeological record allows for a much deeper understanding of potential mobility in the region.

4.1. Maritime movement

The higher current values in the east and west for sailing north and

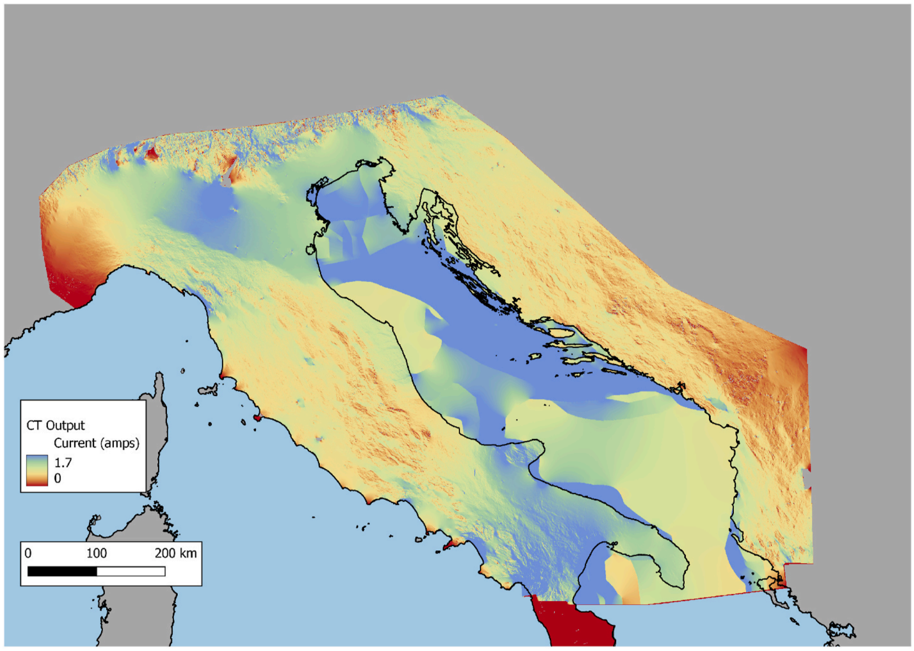

Fig. 15. Circuit theory output for sailing south in January.

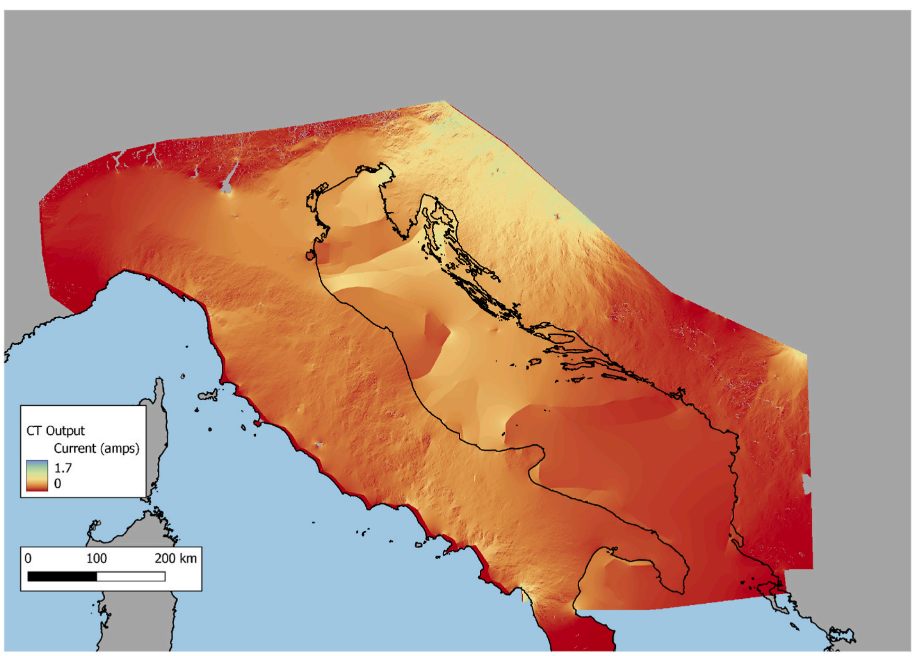

Fig. 16. Circuit theory output for sailing west in January.

south respectively suggest that an anti-clockwise route around the Adriatic would have been preferred for much of the year. Indeed, the relatively good natural harbours of the eastern coast and a modern preference for this coast have previously led some to argue that the eastern coast was the main route, at least for sailing north [Jurišić, 2000; Glicksman, 2005]. The archaeological evidence seems to support this, as Roman shipwrecks are found frequently along the eastern coast, and ships with cargoes from the western Mediterranean appear to have rounded the heel of Italy before crossing over to the central Dalmatian coast, rather than using the closer western coast [Jurišić, 2000, 48–51].

Looking at this evidence, a model can be proposed. The eastern coast was the main route for sailing north in the Adriatic, and frequently used for sailing south. The western coast experienced less traffic overall, and vessels sailing north would have been particularly rare. This is primarily due to wind patterns making the eastern coast significantly more efficient for northward movement, and only somewhat more efficient for southward movement. The natural har-bours of the eastern coast would have been important for movement north and south, further reinforcing this eastern focus. Relying on the shipwreck evidence can be complicated (See Parker, 2008; Rice, 2016; Leidwanger, 2020, 110–153). However, the CT analysis suggests that the western coast was a less naturally efficient route, and so less shipwreck data here could indeed be due to less actual traffic.

The model suggests that movement east was far more preferable in the north-ern Adriatic. This is much less pronounced for movement west. This is at odds with what the general anti-clockwise surface

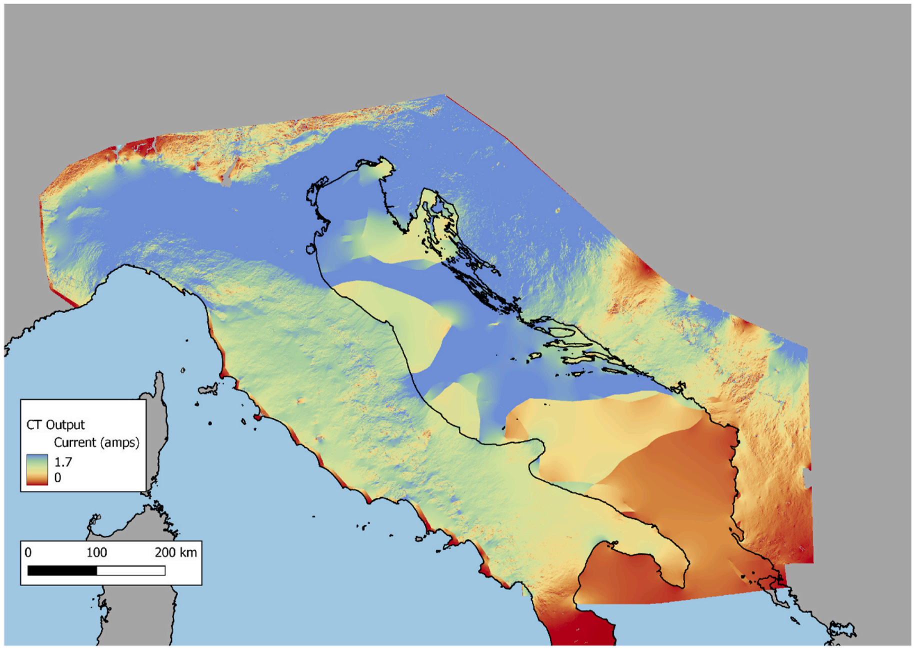

Fig. 17. Circuit theory output for sailing east in January.

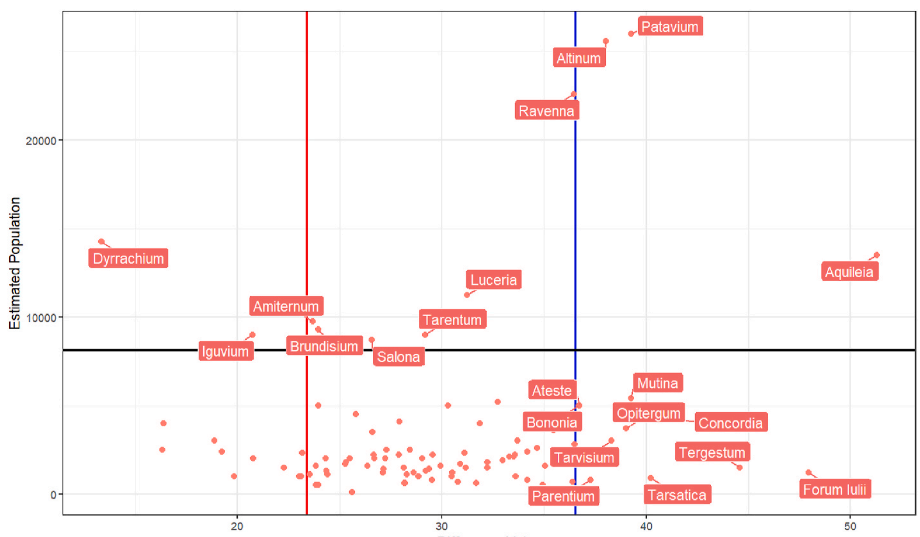

Fig. 18. Estimated Population Figures Against Total Difference Values for Urban Centres with Known Sizes, with 1 Standard Deviation (sd) Above (Blue) and 1 sd Below (Red) the Mean Difference Value, and 1 sd Above the mean Population (Black) all Shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Sites with populations more than one standard deviation over the mean.

Site	Population	Difference Value
Patavium	26,000	39.25
Altinum	25,600	38.03
Ravenna	22,600	36.46
Dyrrachium/Epidamnos	14,250	13.34
Aquileia	13,500	51.29
Luceria	11,250	31.23
Amiternum	9750	23.7
Brundisium	9300	23.95
Iguvium	9000	20.74
Tarentum	9000	29.2
Salona	8700	26.58

currents suggest (Orlić et al., 2007; Skegro, 1999; Thompson and Thompson, 2004, 7; Glicksman, 2005; Pandžić and Likso, 2005; Book et al., 2007, 1). However, the movement of Roman bricks from northern Italy, east into Istria and parts of Dalmatia is well documented in the archaeological record, with more than a third of all stamped bricks found in Dalmatia coming from northern Italy [Wilkes, 1979; Glicksman, 2005]. In- deed, while the northerly and southerly winds are often strong, the easterly and westerly winds are generally weaker (Skegro, 1999; Thompson and Thomp-son, 2004, 7, Glicksman, 2005). As such, this trend observed for sailing east and west in the CT outputs must have more to do with the geography of the Adriatic than the wind and current patterns; the terrestrial landscape, which does not change so dramatically month to month, made eastward movement in the north, and westward movement in the south relatively more efficient. It is clear from the CT analysis that the direction of travel drastically affects the

Table 5
Sites with difference values more than one standard deviation over the mean.

Site	Difference Value	Population
Aquileia	51.29	13,500
Forum Iulii	47.94	1200
Tergestum	44.57	1500
Concordia	41.46	4200
Tarsatica	40.21	900
Mutina	39.26	5400
Patavium	39.25	26,000
Opitergum	39.01	3700
Tarvisium	38.29	3000
Altinum	38.03	25,600
Parentium	37.27	800
Ateste	36.73	5000
Bononia	36.72	5000

entire landscape of mobility and that there is no single dominant route across the Adriatic; rather specific routes see high current in specific directions. More-over, the weaker easterly and westerly winds appear to have had less impact on patterns of movement, unlike the significant influence of the northerly and southerly winds.

4.2. Urban centres case studies

CT models produce quantitative results which allow for meaningful compar-ative analysis. With the rejection of the null hypothesis, it is clear that the combined potential connectivity of land- and sea-based mobility impacted the distribution of urban centres. All scenarios having a positive cmcv difference suggests that site distribution very strongly favoured areas of high potential mobility. Notably, there are 7 scenarios with difference values more than one standard deviation above, and 12 below the mean. The 7 above are for sailing east and/or south in March, August, September and December, and north in January. The 12 below are for sailing west, whatever the season. This clearly shows the huge impact that direction of travel as well as seasonal wind patterns have on mobility across the region, with sailing in late Spring and Summer clearly being particularly preferable, while movement west across the Adriatic appears to have been relatively less influential in dictating settlement distribu-tion. However, even for sailing west, urban centres are located in areas of higher than expected potential mobility values (*ie.* have positive difference values).

Similarly, while sailing South generates particularly high cmcvs for March, August and September, the rest are relatively low. It might be suggested that traffic sailing west or south out of the Adriatic region was of less con-cern than that sailing in other directions, perhaps indicating that imports from the Mediterranean were more important in urban centres than exports. This further plays into the concept of the primacy of the eastern route in the Adri-atic. Moreover, it has long been argued that the export of wine and oil south out of the Adriatic was minimal, particularly in Dalmatia (Matijašić, 1993, 258–259; Glicksman, 2007). Indeed, most traceable exports, particularly in the northern Adriatic and Istria, appear to have been more commonly sent north beyond the Alps (Matijašić, 1993, 258; Cipriano, 2009, 183). The distribution of urban centres does indeed appear to have been influenced by mobility, with distribution favouring areas where movement north and east is efficient, more than movement south or west.

Moving beyond general patterns of urbanism, we can assess some specific sites and the relationship between their estimated populations and place within the landscape of mobility. As the sites with the greatest positive difference values are not the same as the sites with the largest populations, it could be suggested that mobility did not affect population hierarchy. However, the largest total difference value is 51.3 for Aquileia, in the north east of the study region. Aquileia is one of the largest Adriatic cities, and one of the main ports of the entire region. Patavium and Altinum similarly have very high difference values, and are also amongst the largest urban centres, both again being important northern ports. However, some sites with high difference values are not par-ticularly populous. While Tergestum has a small population, it was another important port city in the north East [Hanson, 2016, 553–554]. Iader, a Ro-man *colonia*, again has a particularly high difference value and relatively low population but was one of the main Dalmatian ports [Jurišić, 2000, 52][Wilkes, 1969]. This suggests that while high potential mobility does not necessarily lead to large populations, the important ports of the region are generally in areas of high potential mobility. Two particularly interesting anomalies can be found in Iguvium and, in particular, Dyrrachium. These are the only sites with very high populations and very low difference values. Iguvium is land locked, and on the very edge of the study region, so access to the Adriatic is unlikely to have been as major a concern for the location of this site as it would be for the port cities on the Adriatic. Dyrrachium, on the other hand, is a very large city, with a population over 10,000 on the eastern coast at the southern limit of the region. Explaining this is more difficult. However, we might view this in relation to the consistently low cmcvs for sailing west, and for the relatively low current values for sailing east in the southern Adriatic. Dyrrachium is particularly well placed for movement east and west between Italy and the East [Degrassi et al., 2012]. As such, we might expect a lower imcv for a southern site from which movement would primarily have been east and west. Although even with Dyrrachium, the imcv difference value is still positive.

There is a clear focus on the sites of the Northern Adriatic in terms of potential mobility. Aquileia appears to have been preeminent among Adriatic cities in this model, with it, Patavium and Altinum (all in the northern Italian Adriatic) having estimated populations exceeding 10,000 and difference values greater than 35. The archaeological record has long alluded to Aquileia being one of the most important sites on the Adriatic, acting as an emporium for the re-distribution of goods (Strabo, Geography 5, 8) [Raviola, 2002; Buonopane, 2009; Carre, 2008]. While being located in an area of high potential connectivity does not guarantee that a site would be a very populous one, it is clear that the most populous sites are generally in areas with higher than average mobility. Mobility affected the population hierarchy, but additional factors also clearly played a more significant role in different parts of the region and with efficient movement in certain directions having greater impact on this.

5. Conclusion

It has been shown that CT analysis has great potential to inform our un-derstanding of patterns of connectivity and urbanism across an archaeological landscape of combined terrestrial and maritime mobility. CT allows for regions of high potential mobility to be easily identified, and the sites within these regions to be quantitatively compared. Moreover, the addition of maritime mo-bility adds numerous layers, including seasonal and directional nuances, clearly demonstrating that considering terrestrial mobility in isolation is not enough. Used in such a manner, CT analysis can provide a depth of understanding that has previously been difficult, if not impossible, when relying solely on LCPs. Nevertheless, some of the limitations of the model should be acknowledged. Comparison between directional travel is complicated by the variable position of the ground and sources, the position of which can have a major impact on the output. However, iterations of the model using different sources and grounds (still the four borders) did not produce any substantial differences while testing the model. Additionally, there is a cost associated with moving between ter-restrial and maritime landscapes, which is not included in the model. Though, again, smaller scale tests with artificially large resistance values along the coastal waters did not change the overall trends observed. Finally, the interpretations outlined in the urbanism case studies offer only a few possible conclusions to draw from early results.

Moving forward, a variety of additional case studies could be fruitfully as-sessed. Comparing the distribution of shipwrecks or olive/wine press sites are two additional possibilities for the current study region.

Closer comparison of the shipwreck data to the maritime funnel points would provide important con-text to the distribution of these often problematic data. The importance of connectivity and ecology to the distribution of press sites would help to un-derstand the organisation of the economy, and how export orientated it may have been. Moreover, this analysis is in no way restricted temporally or geo-graphically to the Roman Adriatic. The values for the impact of wind patterns on sailing speed can be readily adjusted to suit specific periods with differ-ent technological capabilities. Additionally, for any region where elevation and wind data is available, cost surface maps can be readily generated. Large scale comparison with LCP analysis using the same cost surfaces could also be inter-esting, though smaller scale tests did not provide much more information than CT alone, and the processing time required for larger scale LCP analysis proved prohibitive, unlike with CT analysis on the same scale.

It is hoped that this work will showcase how archaeological research may benefit from CT analysis as a way of pushing mobility analysis beyond the cur-rent reliance on LCP tools. Of course, this approach does not provide all of the answers, but, it does allow for considerably more nuanced analysis of the impact of mobility on terrestrial, and especially maritime, archaeological landscapes.

Declaration of competing interest

None.

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CWircuitscape http://www.circuitscape.org.

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Hanson OXREP City Database http://oxrep.classics.ox.ac.uk/databases/cities/

Datasets and Appendices https://doi.org/10.6084/m9.figshare.c.5713178.v1.

Sourcecode https://github.com/amclean6787/Circuit-Theory.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2021.105534.

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