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Exploring the dynamics of transport in the Dutch *limes*

Very little is known about local scale transport in the Roman period in the Netherlands, and therefore this paper aims to reconstruct and examine local transport networks through an integrative approach, using data and research from palaeogeography, physiology, archaeology and computational archaeological approaches. This study particularly focusses on the role of different modes of transport and the role of the natural environment. Firstly, a palaeogeographic reconstruction is presented encompassing both the natural and the cultural landscape. Transport networks for several modes are then reconstructed by calculating least cost paths that incorporate functions from physiological research. These networks are analysed using standard network analytical procedures. Interesting interpretations can be inferred from the results of these procedures, including some relating to the different characteristics of the transport modes but notably also the relative important role of stone-built settlements in the networks and the relative lack of control that the Roman forts have over the transport network.

Least cost analysis; network analysis; palaeogeography; Roman *limes*; transport reconstruction.

1 Introduction

The archaeological study of Roman transport systems in the Netherlands has traditionally focussed mainly on transport of regional to imperial scales. Examples of well-studied subjects are the Roman *limes* road,¹ Roman shipping on the Rhine and Meuse² including interregional transports,³ canal construction,⁴ Roman harbours⁵ and other waterfront installations.⁶ Comparatively little research has been done on transport that occurred on local to intraregional scales. Thus little is known about how transport on these scales was organised and carried out, particularly for a ‘peripheral’ region such as the Dutch river area, which outside the main roads and rivers offered major environmental constraints for the type of transport that is known from Roman Italy and Gaul.⁷ This lack of knowledge is further increased by the limited nature of the archaeological evidence for transport, including the likelihood that most local land-based transport connections are mere routes with very low archaeological visibility, rather than constructed roads.⁸

This research was performed within the framework of the ‘Finding the limits of the *limes*’ project, funded by the Netherlands Organisation for Scientific Research (NWO, project nr. 276-61-005) through the VIDI Innovative Research Incentives Scheme. We would like to thank two anonymous reviewers for their constructive suggestions on improving this paper.

1 E. g. Modderman 1952; Luksen-IJtsma 2010.

2 E. g. Eckoldt 1980; de Weerd 1988; Jansma and Morel 2007.

3 E. g. Pals and Hakbijl 1992, 293–294; Domínguez-Delmás et al. 2014.

4 E. g. Hazenberg 2000.

5 E. g. Morel 1988; Polak and Wynia 1991; Driessen and Besselsen 2013.

6 E. g. Van Dinter 2013, 20, citing other sources; Seinen and Van den Besselaar 2014.

7 E. g. Chevallier 1988.

8 Willems 1986, 63–64.

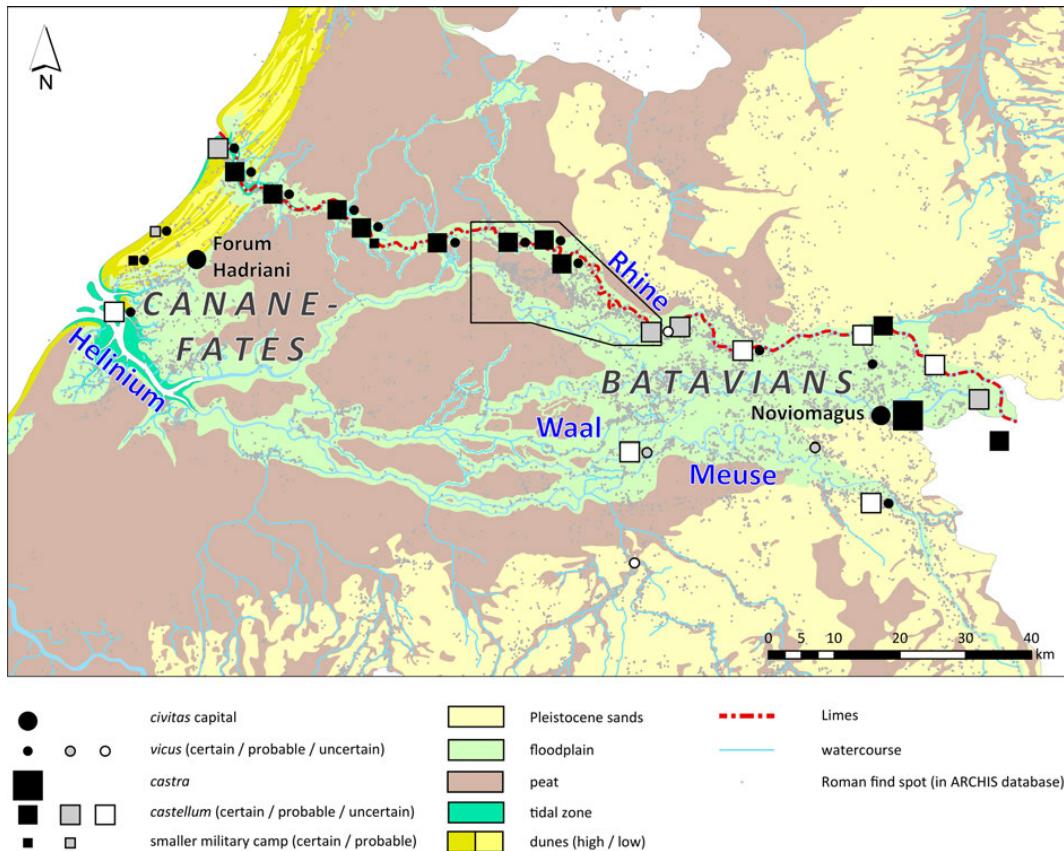


Fig. 1 | Palaeogeographic map of the Dutch river area around AD 100 with the case study area indicated. Physical palaeogeography is taken from P. Vos and de Vries 2013.

Given the limited nature of the archaeological evidence, computational approaches have become increasingly popular to study movement in archaeology,⁹ with its basic components rather well understood.¹⁰ This paper aims to reconstruct and examine Roman local transport networks using a conceptual model for transport and the application of cumulative cost paths¹¹ and network analysis.¹² To achieve this, an integrative approach was applied using datasets and research from palaeogeography, physiology, archaeology and computational archaeological approaches.

This paper will present part of a project¹³ that focusses on the cultural landscape of the Dutch part of the Roman *limes* encompassing the Batavian and Cananefatian *civitates* (Fig. 1), and in particular the spatial and economic relations between the local population and the Roman military population that inhabited the area starting from around 15 BC (Fig. 2). The paper will focus on the Kromme Rijn-Hollandse IJssel region within this area (Fig. 1), located immediately to the south of the Rhine which formed the northern border of the Roman Empire. The *limes* was dotted with military forts (*castella*) during the Roman occupation, including four forts within the current study area. This region is considered an ideal testing ground for reconstructing and examining Roman local trans-

9 E.g. Bell and Lock 2000; Llobera 2000; Bell, Wilson, and Wickham 2002; Fábrega-Álvarez and Parcero-Oubiña 2007; Zakšek et al. 2008; Murrieta-Flores 2014.

10 See e.g. Murrieta-Flores 2010 for an overview of influences on prehistoric movement.

11 Verhagen 2013.

12 Verhagen et al. 2014.

13 “Finding the limits of the *limes*”, <http://www.limeslimits.wordpress.com/> (visited on 06/05/2015).

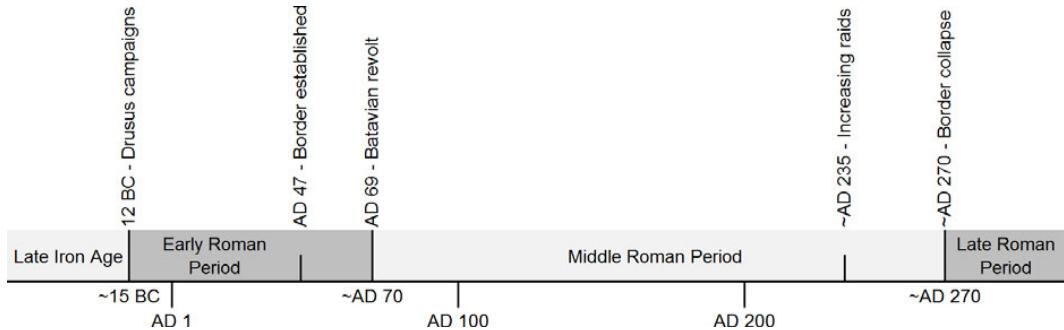


Fig. 2 | Timeline considered in this study, with the relevant archaeological periods and some notable events indicated.

port networks owing to the extensive archaeological studies¹⁴ and other sources available for palaeogeographical research.¹⁵

2 Methods

2.1 Transport modelling

Modelling transport networks is not straightforward; there are many influencing factors that change the way a transport network materialises. Murrieta-Flores names a number of factors that influence movement on foot, which can generally be subdivided in independent factors (topography, terrain, time, human physical properties, carried loads and access to resources) and social factors (social conceptions or ideas regarding places, geographical knowledge, social networks, territoriality and visibility).¹⁶ For our study, a conceptual model for transport decisions was created (Fig. 3). Important factors that determine the nature of transport and thus transport variability are the agents that are involved, the purpose for which the transport is undertaken and the mode of transport that is used. Besides these inherent elements of transport, external influences play a role as well. They can range from abstract factors such as (imperial) political pressures to very concrete features such as the natural environment. For the purpose of this paper, the dynamics of transport will be examined through two elements of this transport model, namely the mode of transport that is applied and the role of the natural environment.

2.2 Palaeogeography

In order to fully grasp the role of the natural environment on local transport networks, a detailed palaeogeographic map of the study area is required. One of the major difficulties in the study area and in the delta landscape of the Netherlands in general is the vast amount of landscape change that has occurred since the Roman period, primarily through river channel migration and avulsion and to some extent also peat extraction and drift-sand activity. Exemplary detailed palaeogeographic work has been performed for the western river area in the Netherlands,¹⁷ which also covers the northern edge of the current study area. We reused the methodology applied by Van Dinter to extend this

14 Particular for the Kromme Rijn region is W. Vos 2009; for the larger Batavian *civitas* also Willemse 1986; Roymans 2004; Heeren 2009.

15 Listed in 3.2.

16 Murrieta-Flores 2010.

17 Van Dinter 2013.

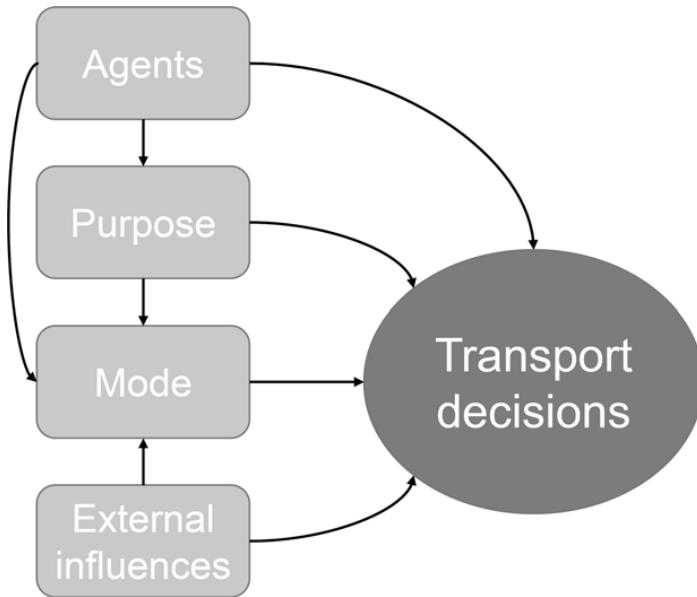


Fig. 3 | The conceptual transport model.

palaeogeographic reconstruction to the whole study area. It involves the combination of existing datasets including geomorphological,¹⁸ pedological,¹⁹ palaeogeographical²⁰ and historical maps, LIDAR elevation data²¹ and local information from archaeological research²² to construct a palaeogeographical map on a scale of 1:50,000 (Fig. 5). This map represents the landscape in the Middle Roman Period, although the only significant landscape change in this area in comparison with the earlier periods is the river avulsion at Wijk bij Duurstede which marks the onset of the Lek river. Due to its position on the southern edge of the research area this has little influence on the following spatial analysis.

During the reconstruction areas of uncertainty were identified, which can be attributed to the presence of urban development, sand or clay extraction sites or areas of natural post-Roman erosion, primarily through river activity. For the purpose of this study the most likely palaeogeographical unit was assigned to each uncertain area based on expert judgement, but through the explicit recognition of uncertainty further studies can also include more elaborate testing of the influence of the natural landscape by applying variation in the interpretation of the uncertain areas.



Fig. 4 | Reconstruction of the landscape around a typical rural settlement (Tiel-Passewaaijse Hogeweg) in the Dutch river area, situated on the levee of an abandoned stream bordering on marshy floodplains. Drawing by Mikko Kriek (VUhbs).

18 Berendsen 1982; Alterra 2008.

19 Alterra 2006.

20 Especially important is the research on the palaeogeographical development of the Rhine-Meuse delta by Cohen et al. 2012.

21 Rijkswaterstaat-AGI 2013.

22 E. g. Van Es 1994; W. Vos 2000.

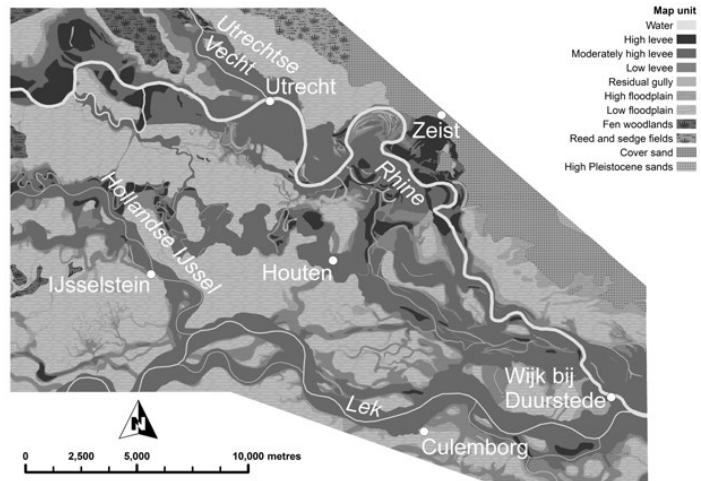


Fig. 5 | Simplified palaeogeographical map of the research area during the Middle Roman Period with modern place and river names shown as reference.

Another important aspect of palaeogeography is the cultural landscape, or the landscape created by man, in this study consisting of the settlements and the connections between peoples. The study area has a rich archaeological research tradition, which allows for a detailed reconstruction of the cultural palaeogeography. This is achieved through a reinterpretation of the existing archaeological evidence, which largely consists of entries in the Dutch national archaeological database²³ supplemented with data from other surveys.²⁴ The reinterpretation is done by following a standardised set of rules for assigning an interpretation to archaeological finds. For example, through a minimum number of sherds within a radius of a specific distance, along with characteristic evidence for a certain archaeological activity, a find spot can be interpreted e.g. as a settlement, burial place or military site. The reinterpreted settlements are stored in an archaeological site database that also includes information on chronology, uncertainty of interpretation and references. Such a methodology has been applied in previous research,²⁵ and was updated and extended to the current study area (Fig. 6). It must be noted that stone-built settlements only appear in the Middle Roman Period, although they may exist as post-built settlements in earlier periods.

2.3 Network reconstruction

A frequently used approach to study movement in archaeology is least cost path (LCP) modelling.²⁶ One of the most important aspects of LCP modelling that makes it useful for this kind of research is the ability to incorporate information about the natural environment to model routes of movement between places. The cost surfaces required for LCP modelling can be calculated using different approaches,²⁷ often using functions from physiological research on energy expenditure of movement on foot that take into account the effects of slope, and for that reason result in directional LCPs²⁸ that may follow different routes depending on whether movement is uphill or downhill. However, since we

23 Archis, <https://archis.cultureelerfgoed.nl/>.

24 In particular W. Vos 2009, including datasets from Roymans 2004; Nicolay 2007 and unpublished work by Ivo Vossen and Linda Verniers.

25 W. Vos 2009; Van Dinter et al. 2014.

26 E. g. Bell, Wilson, and Wickham 2002.

27 See Herzog 2013 for a discussion.

28 I. e. LCPs which are only valid for one-way movement, since the costs are dependent on the direction in which one is moving.

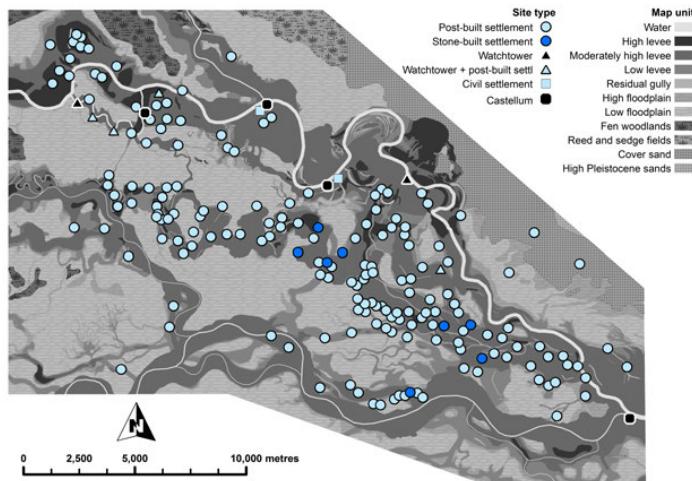


Fig. 6 | Simplified palaeogeographical map including a diachronic overview of the archaeological site database. Note that the sites identified as stone-built settlements in the database may appear in all archaeological periods, but prior to the Middle Roman Period are actually regular post-built settlements.

only find very small elevation differences in the study area²⁹ the main cost component that we need to take into account is the terrain surface. In the 1970s an American research group did extensive testing on the role of terrain surface on energy expenditure during movement while carrying varying loads,³⁰ making it the most useful method to apply given our research focus on transport across a differentiated landscape. The cost function from this research is adapted to calculate velocity (V in m/s) over a terrain surface with a certain cost coefficient (η) by a subject of a certain weight (W in kg) carrying a load (L in kg) while maintaining a constant metabolic rate (M in W) suited to travel large distances:

$$V = \sqrt{\frac{M - 1.5 W - 2 (W + L) \left(\frac{L}{W}\right)^2}{1.5 \eta (W + L)}}$$

Terrain coefficients were taken from Soule and Goldman³¹ and adapted to fit the environmental units identified in the research area (Table 1). For this study, a constant subject weight of 60 kg and a constant metabolic rate of 340 W³² were used. The effects of load and terrain surface on the velocity are given in Figs. 7 and 8.

It is more difficult to model movement of vehicles such as mule carts. Research on the movement of vehicles has so far only considered the effects of slope,³³ or has only been performed for hand carts³⁴ and thus does not include animal traction. Estimates of average mule cart speed over long distances³⁵ have therefore been used to set the travelling time on paved roads. Furthermore, the terrain coefficients were modified (Table 1) to reflect the greater effort required to move a wheeled vehicle through difficult terrain compared to walking, because of rolling resistance, momentum loss due to terrain undulations and efficiency loss due to the movement of the centre of gravity on uneven terrain.³⁶ Another uncertain factor which is difficult to account for is the effect of the terrain surface on the locomotion of traction animals.

29 The research area is generally flat and gradually sloping westward, covering an elevation difference of approximately three metres.

30 Soule and Goldman 1972; Pandolf, Givoni, and Goldman 1976.

31 Soule and Goldman 1972, 708.

32 The average metabolic rate that a person of 60 kg maintains while walking normally; Pandolf, Givoni, and Goldman 1976.

33 Herzog 2013, 377–378.

34 Haisman and Goldman 1974.

35 Roth 1999, 211, who sets it at 30 km/day, which excluding breaks is approximately 6 km/h.

36 Haisman and Goldman 1974, 547.

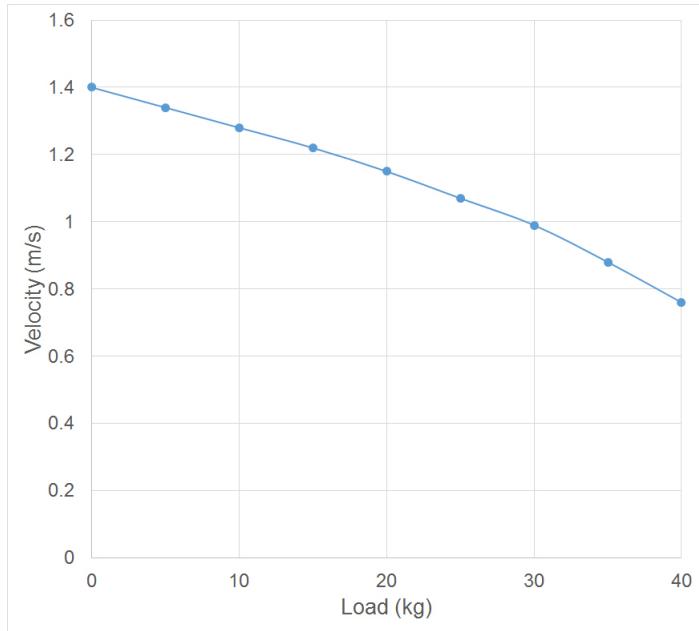


Fig. 7 | Load versus velocity with terrain coefficient set at 1.

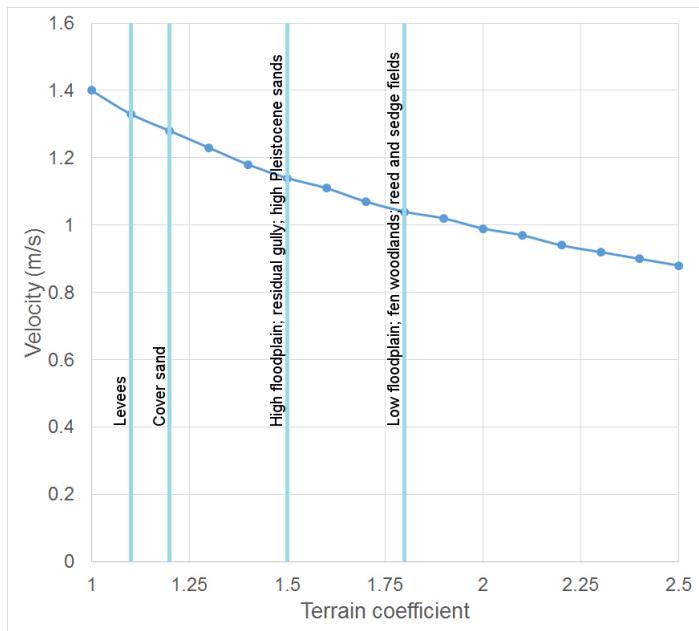


Fig. 8 | Terrain coefficient versus velocity with load set at 0.

Using the aforementioned cost function and variables and after introducing a random noise factor to promote concentration of paths and avoid countless parallel paths,³⁷ cost surfaces were created for the following scenarios: walking without load (W₀); walking with a load of 20 kg (W₂₀); walking with a load of 40 kg (W₄₀), which is meant to represent the maximum that an average person can achieve when absolutely necessary; and mule cart transport (MC). LCPs were then calculated between all possible sources and destinations in the archaeological site database of the research area, to arrive at a cumulative cost path map of the region (Fig. 8).³⁸ Simultaneously, every route that was

37 See Verhagen 2013, 385–386.

38 Cost surfaces and LCPs were created using the *Cost Distance* and *Cost Path* tools in the ArcGIS 10.2 package.

Surface terrain	Walking coefficient	Mule cart coefficient
Water	20	134
Military road	1	1
High levee	1.1	1.7
Moderately high levee	1.1	1.7
Low levee	1.1	1.7
Residual gully	1.5	4.5
High floodplain	1.5	4.5
Low floodplain	1.8	6.6
Fen woodlands	1.8	6.6
Reed and sedge fields	1.8	6.6
Cover sands	1.2	4.5
High pleistocene sands	1.5	2.4

Tab. 1 | Terrain coefficients.

created during the LCP modelling was saved to a database storing its source, destination, length and travel time, in order to be used for network analysis.

2.4 Network analysis

The use of network analysis techniques in LCP modelling has only recently been explored.³⁹ Since there is no directionality in this case study and other possibly important factors such as population size and production/consumption in settlements are not yet incorporated, the route network could be analysed using techniques for simple node-based networks with unweighted and undirected edges. Among the measurements investigated are global network measurements such as number of connected components, clustering coefficient, network centralisation, characteristic path length, average degree, network density and network heterogeneity, and the local measurements of closeness centrality, betweenness centrality and neighbourhood connectivity.⁴⁰

An analysis of a completely connected network is pointless, as there would be no difference between the different networks. Therefore, the amount of edges, i. e. the routes between sites, was reduced to include only those that can be travelled within 20 minutes. This critical point was chosen as most networks in this study show major fracturing at lower cut-off points. Although choosing a critical point is arbitrary, it can be partly justified by studies on human navigation and wayfinding which argue that a route towards a destination often consists of a number of smaller routes between known landmarks that the traveller is familiar with and that are part of his so-called cognitive map.⁴¹ Given the low relief and assumed significant amount of deforestation in the Roman Period, other settlements may have functioned as important landmarks while travelling. One aspect that is not taken into account but should be explored in further studies is a similar role for burial sites in the cognitive map, as archaeological research has shown that cemeteries dating to the Roman period are often situated alongside prehistoric burial sites, indicating that prehistoric and contemporary burial sites were recognised and consciously incorporated in the Roman cultural landscape.⁴²

39 Verhagen et al. 2014.

40 All network analyses were performed using the *Network Analyzer* plugin in Cytoscape 3.1.0.

41 Murrieta-Flores 2010, 260–261.

42 Roymans 1995, 5.

We analysed a number of different networks derived from the LCP modelling. The networks were based on the different modes of transport (walking with loads of 0, 20 or 40 kg and mule cart transport) and were filtered for three different time slices, namely the Late Iron Age,⁴³ the Early Roman Period and the Middle Roman Period (Fig. 2), based on the chronological information in the archaeological site database.

3 Results

Through the combination of LCPs between all sites in the archaeological database, a cumulative cost path map was created (Fig. 9), which gives some indications of the main transport corridors. As can be expected from the cost map inputs, most transport movements occur on the high levees that are positioned centrally in the study area. The shape of the different networks based on the mode of transportation can be compared visually. However, through the application of network analysis additional information on the structures of the various networks can be obtained.

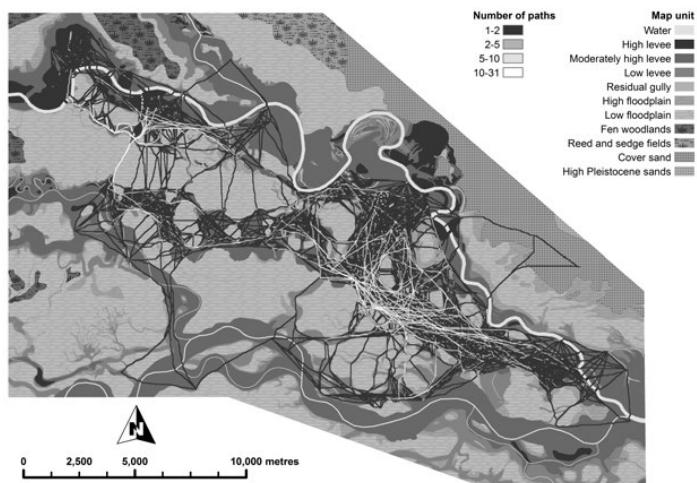


Fig. 9 | Cumulative cost path map of mule cart transport between all sites in the archaeological site database.

A number of global network measurements were calculated for the twelve networks, representing four different modes across three different time slices (Table 2). The terminology used will be shortly explained here:⁴⁴

- Firstly, the number of nodes represents the number of unique sources and destinations of routes in the network, which equals the number of sites known from that period in the archaeological site database.
- The number of connected components is the number of groups of nodes (i. e. containing at least two nodes) which are not connected to other groups of nodes. A completely connected network would thus have only one connected component. The networks analysed in this study often consist of one very large component and a number of minor components located around the edges of the research area. In addition, a number of isolated nodes can exist, which are not connected to any other node and are therefore not counted as part of the number of connected components.

⁴³ It must be noted that the dataset on Late Iron Age sites is incomplete, as it only includes sites that were also continuous into at least the Early Roman Period. Any comparison between Late Iron Age networks and other networks must therefore be made with caution.

⁴⁴ Based on the documentation accompanying Cytoscape 3.1.0.

- The average clustering coefficient is an average of the measurements of the extent to which the neighbours of a node in the network are also neighbours themselves.
- Network centralisation is a measurement of how central its most central node is in comparison to all other nodes. A decentralised network will therefore have a low network centralisation.
- The characteristic path length, also known as the average shortest path length, is the average of all path lengths (number of edges) between any two connected nodes.
- The average degree is the average of the number of neighbours each node has.
- The network density is a normalised version of the average degree, so that network density is highest (equal to 1) when the network is completely connected and lowest (equal to 0) when all nodes are isolated.
- Network heterogeneity represents the tendency of a network to contain a few highly connected (hub) nodes, while the majority of nodes have very few connections. A more inhomogeneous network thus contains fewer hub nodes and more nodes with a relatively equal amount of connections.

Besides the global network measurements, network analysis also encompasses local network measurements on nodes. One interesting measurement is the betweenness centrality (Figs. 10–15). For each node this equals the ratio of shortest paths between any other pair of nodes that pass through this node against the total number of node pairs excluding this node. It is often interpreted as reflecting the amount of control that this node has over the interactions within the network. Another local measurement is neighbourhood connectivity, which for each node is the average number of neighbours of its neighbours (Fig. 16). Other local network measurements, such as closeness centrality, did not yield as striking results.

Time period	Mode	Number of nodes	Number of connected components	Average clustering coefficient	Network centralisation	Characteristic path length	Average degree	Network density	Network heterogeneity	Number of isolated nodes
Late Iron Age	Walking w/ 0 kg (W ₀)	84	7	0.538	0.135	5.142	8.071	0.097	0.611	5
	Walking w/ 20 kg (W ₂₀)	84	12	0.629	0.108	3.605	6.238	0.075	0.665	7
	Walking w/ 40 kg (W ₄₀)	84	19	0.468	0.073	4.003	3.284	0.041	0.724	14
	Mule cart	84	9	0.603	0.152	5.419	7.667	0.092	0.669	6
Early Roman Period	Walking w/ 0 kg (W ₀)	117	5	0.551	0.099	6.754	8.769	0.076	0.572	3
	Walking w/ 20 kg (W ₂₀)	117	12	0.604	0.082	5.403	6.759	0.059	0.599	6
	Walking w/ 40 kg (W ₄₀)	117	18	0.474	0.058	5.844	3.593	0.032	0.637	10
	Mule cart	117	7	0.627	0.113	7.598	8.241	0.072	0.627	4
Middle Roman Period	Walking w/ 0 kg (W ₀)	180	3	0.61	0.087	6.417	12.656	0.071	0.506	1
	Walking w/ 20 kg (W ₂₀)	180	6	0.66	0.07	5.235	9.787	0.055	0.484	2
	Walking w/ 40 kg (W ₄₀)	180	12	0.574	0.048	7.333	4.913	0.029	0.526	9
	Mule cart	180	3	0.678	0.082	7.497	11.697	0.066	0.524	2

Tab. 2 | Results of global network measurements.

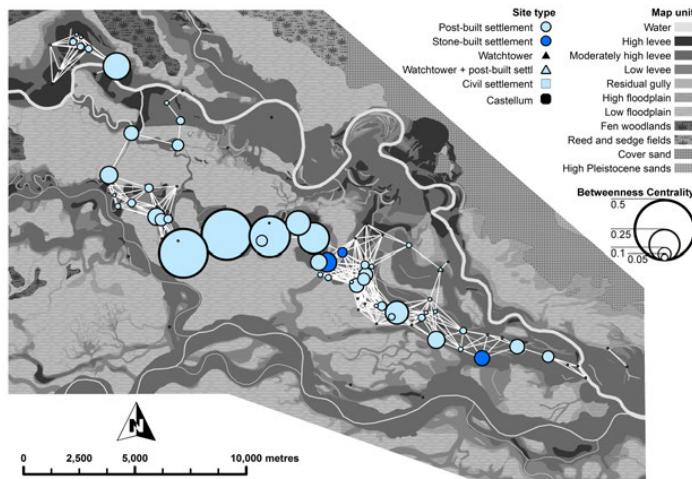


Fig. 10 | Betweenness centrality measurements of all sites in the Late Iron Age mule cart network.

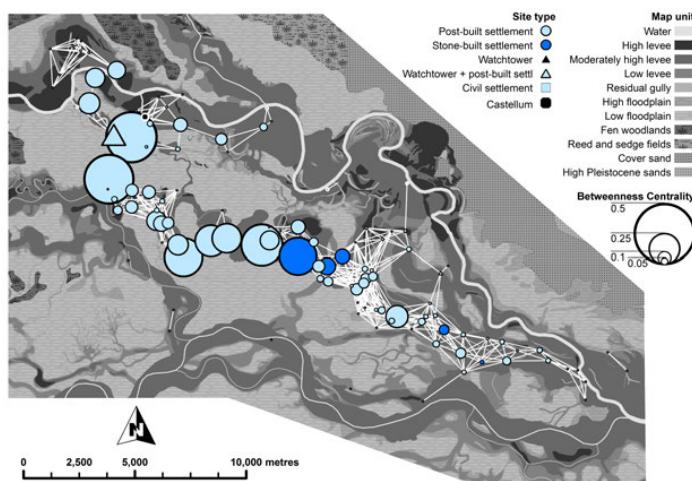


Fig. 11 | Betweenness centrality measurements of all sites in the Early Roman mule cart network.

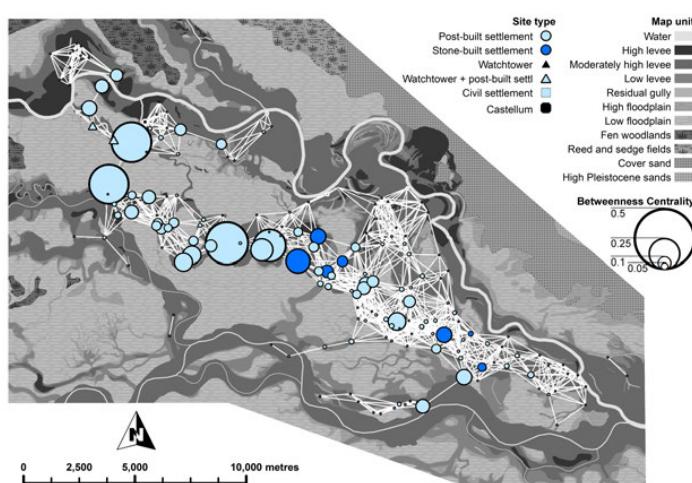


Fig. 12 | Betweenness centrality measurements of all sites in the Middle Roman mule cart network.

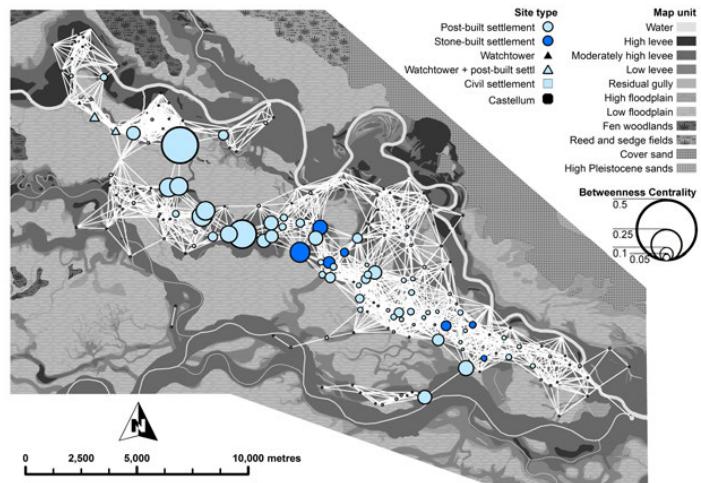


Fig. 13 | Betweenness centrality measurements of all sites in the Middle Roman network of walking without a load.

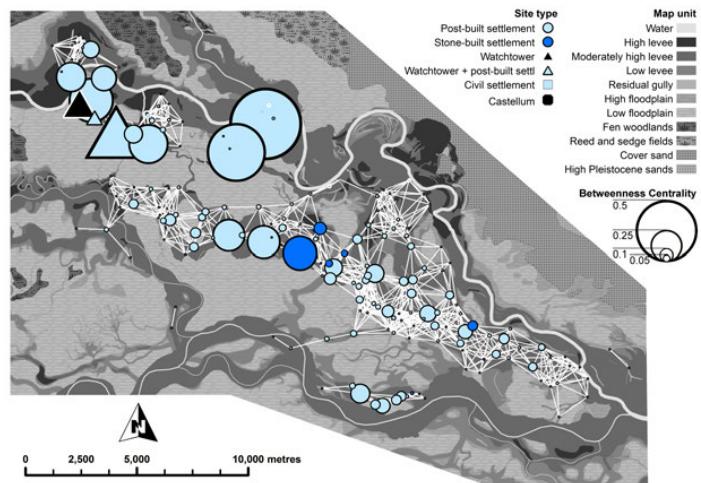


Fig. 14 | Betweenness centrality measurements of all sites in the Middle Roman network of walking with a load of 20 kg.

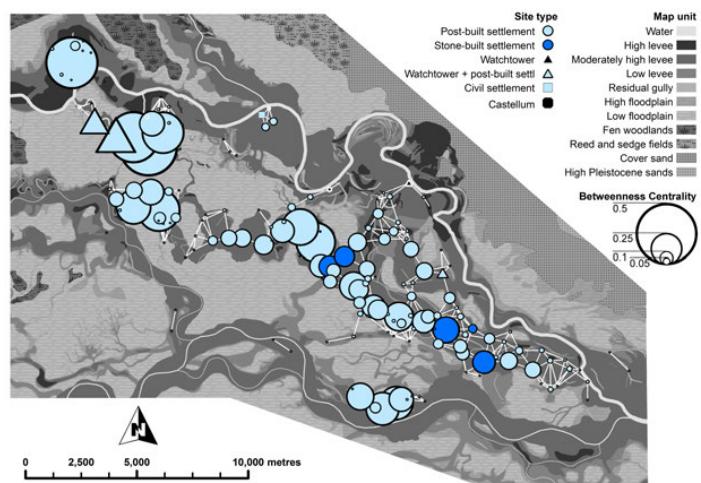


Fig. 15 | Betweenness centrality measurements of all sites in the Middle Roman network of walking with a load of 40 kg. Larger icons represent a higher betweenness centrality.

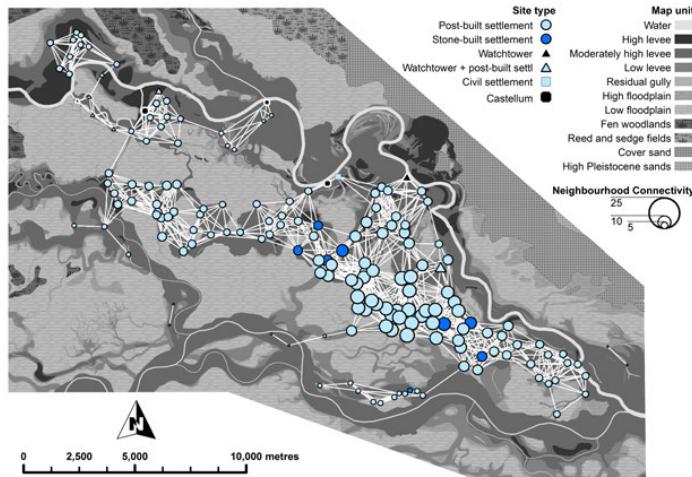


Fig. 16 | Neighbourhood connectivity measurements of all sites in the Middle Roman mule cart network.

4 Discussion

4.1 Global network measurements

Some interesting patterns can be inferred from the comparison of global network measurements (Table 2) of the transport networks based on modes (shortened here to Wo, W₂₀, W₄₀ and MC) and time periods. Such patterns can perhaps be attributed to different inherent properties of the transport mode involved, which could have played a role in the decision-making process of transport agents in the past. Chronological trends can also be attributed to developments in the transport systems, societal structure or other factors that might influence the transport network from the Late Iron Age through the Early and Middle Roman Period. However, such archaeological interpretations must be treated with caution, as there will almost inevitably be other factors influencing the results, such as incomplete datasets, uncertain interpretations and dating of archaeological sites or uncertainties in the palaeogeographical mapping.

In general, it can be stated that the Wo- and the MC-networks are most connected. This can be observed in the network centralisation, characteristic path length, average degree and network density, which are all generally highest in the Wo- and MC-networks. High network centralisation can be attributed to the fact that Wo- and MC-networks connect to components that are disconnected in the W₂₀- and W₄₀-networks. The connection to more distant components also increases characteristic path lengths. The higher amount of interconnections within the main component increases the average degree and network density for these networks. For the MC-network this also shows in the average clustering coefficient. The W₂₀-network also has a large average clustering coefficient, but this is likely due to the fact that this network does not connect to some more distant components while at the same time it retains a large number of interconnections within the main component. The results for network centralisation, characteristic path length, average degree and network density can probably be attributed to the increased difficulty for travel in the W₂₀- and W₄₀-networks, which removes a part of the interconnections. The breakdown of internal connections, leaving only the more straightforward connections, might be interpreted as an indication of the unattractiveness of carrying such heavy loads, especially when easier methods such as boat, mule (both not studied here) or mule cart transport are available. The higher average clustering coefficient for the W₂₀-network despite the disconnection to distant components might mean that this network is still viable for the densely inhabited areas such as the central levee, but is not attractive for long-range transport to more remote areas.

When we look at the networks chronologically, the appearance and disappearance of sites over the different time periods have some interesting effects. From the Late Iron Age through the Early Roman Period, more sites in the networks seem to appear around the edges of the research area, rather than on the central levee. This results in few changes in average degree and only minor changes in the average clustering coefficient when comparing Late Iron Age to Early Roman Period networks, regardless of transport mode used. At the same time, the declines in network centralisation and network density and the increase in characteristic path length are steepest over this transition. From the Early Roman Period through the Middle Roman Period, new sites appear primarily within the existing network, thereby increasing interconnectedness. This is reflected in the sharp increase in the average degree and slight increase in the average clustering coefficient, while the characteristic path length with the exception of the W₄₀-networks declines slightly. This may be interpreted archaeologically as the result of population growth and increased settlement density, which allow for more complex and more extensive social interactions.

4.2 Local network measurements

The networks can also be compared in some more detail. One interesting local network measurement is betweenness centrality, which is plotted in Figs. 10–15. In all networks an elongated group of sites forms a dense and often interconnected network on the central levee in the study area. A significant northern group is connected to the main component over a small crevasse splay that acts as a slightly elevated and traversable levee in a floodplain that is otherwise less attractive to transport. The sites directly on the edges of this corridor have a high betweenness centrality as long as this connection is intact. This northern group however disconnects in the W₂₀- and W₄₀-networks. This creates an isolated component with a number of sites of very high betweenness centrality within their own component that are otherwise not important as part of the larger network. More interestingly, no connection is made in any of the networks between this northern group and the sites towards the east across the levees of the Rhine.

A small number of sites with high betweenness centrality can be observed in the heart of the research area, connecting the western and northern groups of sites with the large concentration of sites in the eastern half of the research area. The high betweenness centrality of these central sites indicate that they likely controlled much of the east-west directed transport movements in the study area.

Several sites with high betweenness centrality are identified as stone-built in the archaeological site database, which is generally thought to represent higher status or wealth. All these sites occur in the central and eastern part of the research area. Eight out of 180 sites in the Middle Roman Period are identified as stone-built, and out of these stone-built sites seven are in the top third of highest betweenness centrality in the Wo- and MC-networks and five are in the top third in the W₂₀- and W₄₀-networks. The importance of these sites in transport networks, as well as their possible control over transport, may have allowed them to grow in status and wealth. From this point of view it is also interesting to look at the developments through time. In the Late Iron Age and Early Roman Period all settlements were still post-built. However, for example in the MC-network (Figs. 10–12) it is clear that the sites that in the Middle Roman Period would become stone-built settlements are consistently central in transport networks in the eastern part of the research area. This does not explain however why stone-built settlements only occur in the eastern part of the research area, while at the same time we also find post-built sites with high betweenness centrality and thus assumed importance for transport networks in the central and western part of the research area.

A further interesting observation is the low betweenness centrality of the four forts and the civil settlements associated with these military sites, which may indicate that these sites were not important in local transport networks. This can partly be attributed to edge effects, as one of these sites is located in the south-eastern extremity of the study area and all are bordering the Rhine, which is a relative extremity since very few sites are known from the northern bank. However, the network reconstructions show that transport is most likely to have occurred on the central levee crossing the research area, rather than on the levees of the Rhine itself, and thus local transport does not appear to need the constructed military road which runs roughly parallel to the Rhine. It must be noted that these reconstructions as of yet do not include weighting of the transport connections, as the greater population size and consumption will certainly have intensified transport from and to these sites.

To further clarify the relation between the archaeological evidence of roads, which primarily concentrates around the military *limes* road, and the transport network reconstructions, a comparison with the archaeological evidence can be made. Based on archaeological evidence and interpretations a number of road reconstructions have been published,⁴⁵ which have been combined and overlain on the Middle Roman MC-network reconstruction (Fig. 17). It is again evident that most local transport connections are found on the central levee rather than on the levees of the Rhine, where the military *limes* road is located. It can therefore be argued that this road has little importance for local land-based transport connections, but will have primarily been used for transport between the forts, the guarding of river transport and quick (inter)regional information transfer along the *limes*.

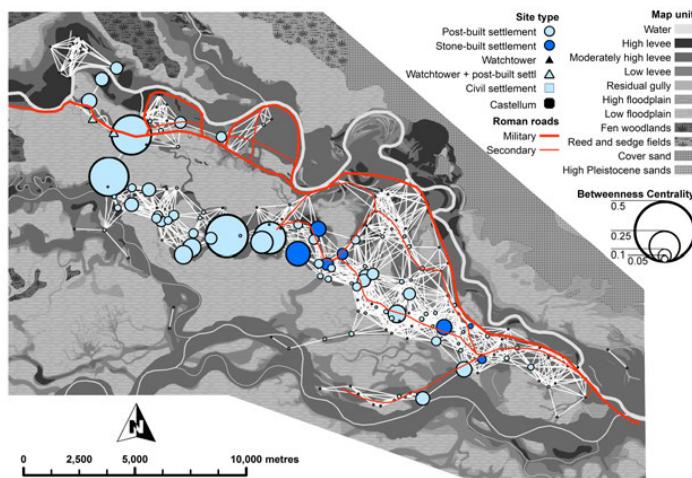


Fig. 17 | Roman road reconstruction based on archaeological evidence, overlain on the Middle Roman mule cart network.

5 Conclusion

This paper aimed to reconstruct and examine Roman local transport networks using a multidisciplinary approach, drawing on methods and data from palaeogeography, physiology, archaeology and computational archaeological approaches. A palaeogeographical map with an archaeological site database was constructed and LCP networks were calculated for various transport modes. These were subsequently analysed using network

45 Jansen and de Kort 2004; W. Vos 2009; Van Dinter 2013.

analysis, leading to some interesting observations. The global network measurements clearly showed some different characteristics of the networks, such as the breakdown of connections related to the difficulty of travel with increasing loads, while at the same time the W2o-network showed that a substantial number of connections was still maintained in more densely inhabited areas. We also analysed chronological developments and observed a site-dependent pattern of transport networks, which was characterised in the Early Roman Period by the appearance of new sites around the edges of the research area, followed by an increased site density in the Middle Roman Period, allowing for more extensive social interactions.

Looking at the transport networks in more detail, we can observe disproportionately high betweenness centrality measurements for stone-built settlements. One interpretation might be that their importance for transport networks created more wealth and status for these sites. At the other end of the spectrum, the Roman military forts and civil settlements have very low betweenness centrality measurements, indicating that they only played a minor role in the local transport movements of the research area. A comparison with a road reconstruction based on archaeological evidence also shows that the Roman military *limes* road does not play a major role in the local transport networks, as local transport is mostly concentrated on the central levee rather than on the levees of the Rhine.

In conclusion, the multidisciplinary methods demonstrated here provide a research approach to Roman local transport networks that cannot be achieved on the basis of traditional archaeological research alone. Although the results and conclusions drawn from the analysis are not set in stone and require additional archaeological interpretation and investigation, this approach provides researchers with new insights and possibly new research questions, for example concerning the absence of stone-built settlements in the western part of the research area in spite of the apparent importance of the transport corridor there, or the apparent lack of control of the Roman forts over local transport connections, despite the substantial provisioning needs of the military population.

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